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Irrigation of radiata pine with waste water: a review of the potential for tree growth and water renovation

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Irrigation of radiata pine with waste water: a review of the potential for tree growth and water renovation

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Summary

Ever-increasing quantities of waste water are being produced but legislative constraints placed on disposal to the environment are becoming more rigid. Experiments conducted over the past 60 years have shown that *Pinus radiata* has great potential for increased growth when supplied with additional water. The additional growth occurs predominantly during late summer and autumn which increases the proportion of latewood and improves wood quality.

The utilization of a forest environment for disposal and renovation of waste water has a number of advantages over other land-based methods. In particular, the need for expensive pre-treatment and disinfection could largely be avoided without an increase in the risk to public health. The possible effects of waste waters containing high concentrations of sodium, nitrogen, heavy metals and boron are discussed.

Greater attention should be given to the potential of forest environments for the utilization and renovation of waste water, and it is suggested that forests of *P. radiata* in southern Australia could utilize large quantities of waste water to produce additional timber whilst providing substantial renovation of drainage waters.

Introduction

Water has been the favoured medium for transport and disposal of human and industrial wastes since late in the 19th century when water supply and sewerage systems were developed to cope with the demand. Dramatic increases in the quantity of such wastes flowing into streams and lakes over recent years have led to massive pollution problems in many areas. Waters receiving such wastes tend to become eutrophic (excessively high in nutrients), causing proliferation of algae and other aquatic plants and subsequent oxygen depletion. For renovation of the polluted water modern treatment processes have been designed to substantially reduce the concentrations of heavy metals, pathogenic organisms and nutrients, but they require high energy inputs and produce a sludge which requires disposal. Alternatively, land-based treatment systems, e.g. crop irrigation, have the capacity to remove nutrients and absorb heavy metals, without necessarily producing a sludge and without requiring large energy inputs.

The Federal Water Pollution Control Act of the U.S.A. was amended in 1972 with the aim of eliminating the discharge of pollutants into navigable waters by 1985. More recently, the utilization of land treatment processes has been stressed to achieve this aim (Harlin 1978) and an international conference was held in Melbourne in 1978 to discuss this concept (I.A.W.P.R. 1978).

In Australia, the re-use of reclaimed water can be seen as one alternative to the development of new fresh water projects. The need for expanded investigation into the irrigation of trees and related agricultural crops with reclaimed water was stressed in two recent reports on this subject (Polin 1977, Gutteridge *et al.* 1977). Edgar and Stewart (1978) described experiments in which a number of eucalypt species have shown promise in the utilization of waste water in Victoria.

A number of land-based treatment systems using agricultural crops have operated successfully for many years, and the Melbourne and Metropolitan Board of Works (MMBW) Farm, which began operation at Werribee in 1897, is a good example (McPherson 1978). Comparatively, the use of forest land for waste water renovation should have the advantage of utilizing more waste water per unit area because the evapotranspiration rate from forest is greater than

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from annual crops or grasslands. Also, the higher soil temperatures under the canopy of a forest during winter should increase biological activity and therefore enhance the renovation process.

The irrigation of forest trees dates back to 1864 in Pakistan, and there are now several hundred thousand acres of irrigated plantations in that country (Hansen 1978, quoting Zilfiqar 1960). The use of drip irrigation in place of traditional trench or flood methods has been found to utilize 80 per cent less water but give equivalent growth (Sheikh and Masrur 1972). Irrigated plantations, mostly of eucalypts, have also been established in arid areas of Abu Dhabi (Wood *et al.* 1975), Israel (Stibbe and Kaplan 1977) and India (Lohani 1978).

One of the first projects to investigate waste water renovation by irrigating forest land was started at Pennsylvania State University in 1963 (Sopper 1975). Following the encouraging results from this venture, experiments were initiated in Michigan, Florida, Wisconsin and elsewhere (Sutherland *et al.* 1974, Hortenstine 1976, Tolsted 1976).

Two projects have been installed in Australia to investigate the use of *Pinus radiata* D. Don plantations for waste water renovation. The first was by CSIRO Division of Land Resources Management at Beenyap near Perth in a young plantation. The second was a co-operative venture involving CSIRO Division of Forest Research, the Latrobe Valley Water and Sewerage Board, the Forests Commission of Victoria and A.P.M. Ltd. and was established in a 15-year-old plantation at Dutson, near Sale, Victoria. These projects were reported briefly by Gutteridge *et al.* (1977) and subsequently by Cromer and Turton (1979) and Cromer (1979).

More than 300,000 ha has been planted with *P. radiata* in southern Australia to provide an assured supply of softwood timber (Forwood 1974). These plantations require a high capital investment for establishment and maintenance so there is clearly a need to strive for optimum productivity. Many cities and towns in southern Australia could utilize existing *P. radiata* plantations for disposal of waste water or could establish them for this purpose.

Whilst little research effort has been applied specifically to the use of waste water in *P. radiata* plantations, the substantial literature dealing with related topics is reviewed in this paper. An attempt has been made, as a result of this review, to predict the likely effects of waste water application to forests of *P. radiata* and their potential to renovate the applied water.

The effect of moisture regime on the growth and wood properties of *P. radiata*

Water requirements

The hydrology of grasslands and *P. radiata* forests in South Australia has been studied in detail (Holmes and Colville 1970 a and b). Whilst the potential evaporation from an irrigated grassland in the region was found to average 854 mm per annum, evaporation from the nearby pine forests was considerably greater and recharge of the underground aquifer, which occurred annually under pasture, occurred only rarely under the forest. Potential evapotranspiration from *P. radiata* forests in the south-east of South Australia is likely to be some 30 per cent higher than for irrigated grassland on an annual basis (Holmes[1] pers. comm.) so under conditions of adequate soil moisture, mean evapotranspiration from a mature, well-stocked forest of *P. radiata* in this environment would be in the order of 1100 mm per year.

A study by Smith *et al.* (1974) near Lidsdale in N.S.W. found that evapotranspiration from a 33-year-old *P. radiata* forest was 635 mm per year. Under conditions of non-limiting soil moisture it was calculated that this would increase to about 800 mm per year which is considerably less than the figure for South Australia.

Natural precipitation

A portion of the rain falling on a *P. radiata* forest is lost by direct evaporation from the canopy, while the remainder reaches the forest floor and is redistributed by percolation through the soil, surface evaporation or transpiration from foliage.

Results from studies on the moisture relations of *P. radiata* can be related to a generalized model expressing yield as a function of soil moisture (Figure 1). Jackson and Gifford (1974) showed that almost 50 per cent of the variation in the growth of *P. radiata* in New Zealand was due to the combined effects of precipitation and the depth and fertility of the soil. Growth was linearly related to rainfall only on deep freely-

[1] J. W. Holmes, Professor, Department of Earth Sciences, Flinders University, Adelaide.

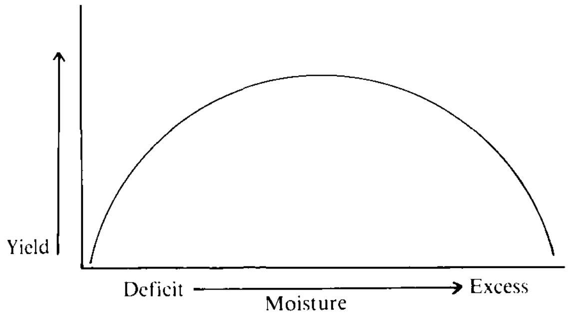

Figure 1. Model of tree growth response to soil moisture conditions. (After Hansen 1978).

draining soils with up to 2500 mm of precipitation per year (Figure 2). The relationship between Figure 2 and the generalized model in Figure 1 is clear in shallow soils in this precipitation range. The level of precipitation required for maximum growth in the deeper soils is presumably greater than 2500 mm.

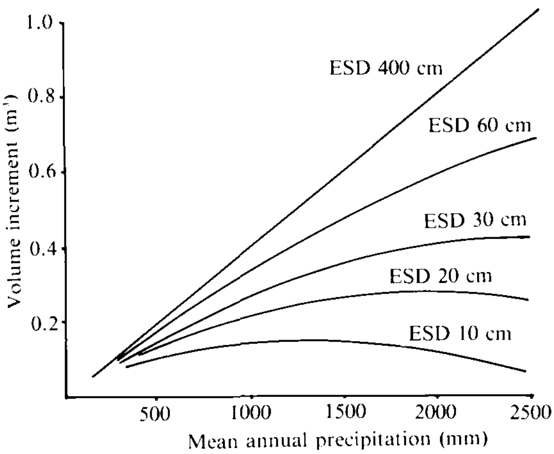

Figure 2. Interacting effects of mean annual precipitation and effective soil depth (ESD) on volume increment of *P. radiata* at age 15. (After Jackson and Gifford 1974.)

In the coastal region of California where *P. radiata* is native and where the rainfall occurs predominantly in the winter, the flush of spring growth was found to continue until soil moisture had fallen to about 6 per cent (MacDougal 1921). Whilst a single application of water resulted in a response in diameter the next day, it was probably due to recovery of cell turgor rather than cell division. Subsequent investigations elsewhere demonstrated a close relationship between basal area increment and rainfall. (Figure 3, Lindsay 1929, Laughton 1937, Millet 1944, van Laar 1967.)

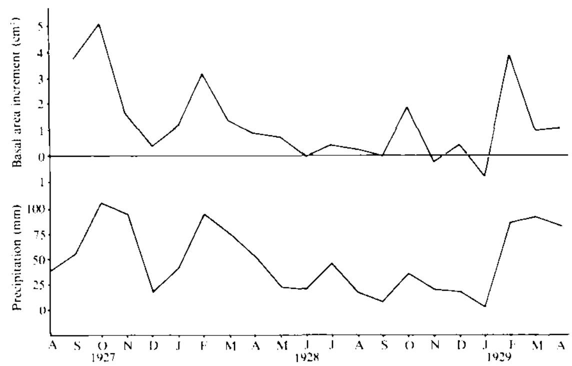

Figure 3. Relationship between monthly basal area increment of *P. radiata* and precipitation at Canberra. (After Lindsay 1929).

The vigour of *P. radiata* growing at Waarre in Victoria was found to decrease with increasing surface waterlogging (Poutsma and Simpfendorfer 1962), but trees at Second Valley in South Australia were able to withstand some seasonal waterlogging, without detriment to growth (Raupach 1967a). These observations were confirmed experimentally by Gadgil (1972) who found that complete waterlogging of *P. radiata* roots for up to 2 weeks did not reduce the uptake of phosphorus(^{32}P) by mycorrhizas. Waterlogging for 4 weeks or longer, however, significantly reduced ^{32}P uptake and after 16 weeks it was only half that of non-waterlogged mycorrhizas.

The fact that seasonally waterlogged sites can be made more productive by drainage and mounding is being used to extend the area available for planting *P. radiata* in the Donnybrook Sunkland in Western Australia (Forests Dept. W.A. 1975). Survival and early growth of *P. radiata* irrigated with waste water at Werribee has been poor and waterlogging could be partly responsible (O'Shaughnessy[2] pers. comm.).

Drought

Liquid flow through a soil-plant system occurs along gradients of decreasing water potential and as transpiration from plants in initially wet soil proceeds, soil water content (and potential) decreases. There is a concomitant decline in plant water potential and the level of stress imposed on the plant increases. Initially the period of stress is confined to the middle of the day and the effect on growth is minor but as the soil water potential decreases further and the daily

[2] P. J. O'Shaughnessy, Research Officer, Melbourne and Metropolitan Board of Works.

period of plant stress increases, the effect on plant metabolism becomes more severe (Slatyer 1967).

The rate at which soil moisture is depleted under a forest is related to the density of the crop. Butcher (1977) demonstrated that soil moisture recharge was enhanced by thinning in *P. pinaster* and that cambial growth in open stands continued for 6 months longer than in dense stands.

While the ultimate effect of drought stress is the death of individual trees, even the death of tree tops can severely reduce the amount of merchantable timber produced. The occurrence of dead trees, dead tops and heavy needle cast has been observed in *P. radiata* plantations over most of southern Australia and is worst in dry years, in dense unthinned plantations and on shallow soils (Pryor 1947, Boomsma 1949, Millikan and Anderson 1957).

Whilst *P. radiata* is more sensitive to drought stress than *P. pinaster* (Hopkins 1971) it appears to be more tolerant than some other pines (Heth and Kramer 1975). It can also maintain moderate turgidity under dry soil conditions if frequent light precipitation occurs (Johnson 1964).

Although the physiological effects of drought stress on plants may be buffered by other limiting factors in the field, it is clear that under severe moisture stress, cell division in the cambium ceases (Shepherd 1964) and that this is most strongly affected by drought imposed during the summer and autumn (Jackson *et al.* 1976). Growth in height is considerably reduced following drought imposed during winter/spring.

It has been found that "false rings" occur in the wood of *P. radiata* formed during periods of water stress (Shepherd 1964). The most prominent of these rings are formed during a summer/autumn deficit period and under certain conditions a separation zone is formed resulting in a ring shake which severely reduces wood quality (Barnett 1977).

Shrinkage in the stems of *P. radiata* is a common occurrence during droughts. The moisture content of the sapwood, which is relatively high in spring, falls during summer and is low in autumn, is directly related to previous soil moisture content (Fielding 1952, Danbury and Wolfe 1967). The dehydration of the sapwood following a reduction of soil moisture would account in part for stem shrinkage during such periods.

Irrigation

Experiments with *P. radiata* in Australia have demonstrated positive responses to additional fresh water. For example, Fielding and Millet (1941) noted substantial increases in height and diameter growth due to irrigation over a three year period near Canberra. Similarly, Waring (1971) found that basal area growth was increased by irrigation, but was reduced by partial droughting (Figure 4). In this experiment, basal areas ($m^2\ ha^{-1}$) of living trees following 11 years of treatment were: 24 (droughted), 37 (control) and 61 (irrigated). Similar results have been obtained in Victoria (Danbury[3] pers. comm.) and South Australia (Boardman[4] pers. comm.).

The close relationship between rainfall and growth in both control and irrigated treatments in the Canberra experiments suggests that additional irrigation would have increased growth further. This trend was observed in an irrigation experiment with 6-year-old *P. radiata* in Italy (Eccher and Lubrano 1969) where tree growth increased in proportion to the quantity of water applied, and experiments in which *P. radiata* was irrigated with waste water in Western Australia gave similar results (Cromer and Turton 1979).

Whilst the application of fertilizer to conifers has generally tended to slightly reduce wood density (e.g. Smith *et al.* 1971) irrigation of *P. radiata* has resulted in an increase in average density due to the production of a higher proportion of latewood (Nicholls 1971, Nicholls and Waring 1977).

Chemical aspects of waste water use

Nutrients

(i) Value to the crop.

The value of added nutrients, particularly phosphorus, to *P. radiata* plantations in Australia is well known (e.g. Raupach 1967 b). Municipal sewerage is generally an excellent source of major nutrients although concentrations are quite variable. Values given by Sandford (1977) for a number of Australian sources ranged from 15 to 128 mg L^{-1} of nitrogen (N) and 0.5 to 45 mg L^{-1} of phosphorus (P). Typical

[3] D. J. Danbury, Previously O.I.C. Gippsland Regional Station, Forest Research Institute, Traralgon, Vic.

[4] R. Boardman, Senior Research Officer, Woods and Forests Department, Adelaide.

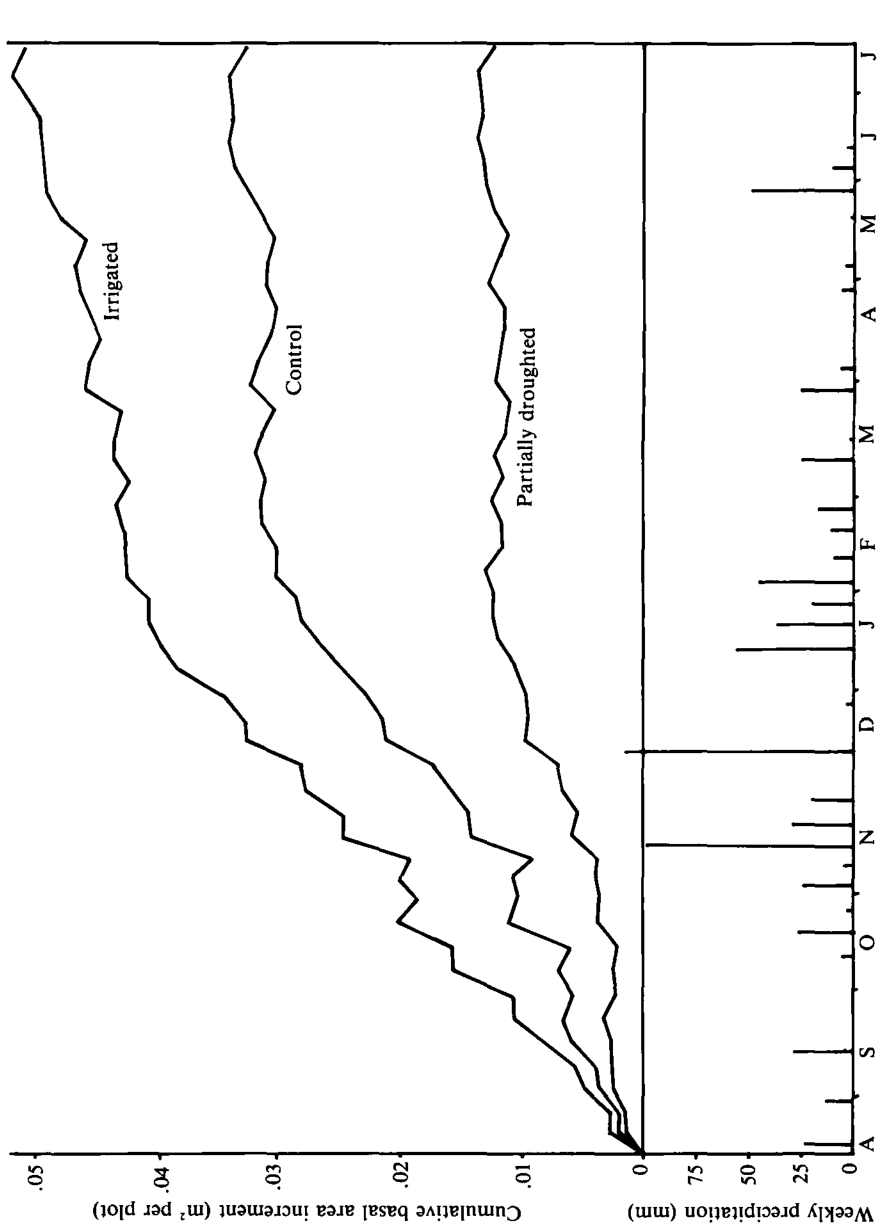

Figure 4. **Relationship between basal area increment of *P. radiata* and moisture regime at Canberra.** **(Waring 1971).**

concentrations of N and P in raw sewerage from Melbourne given by McPherson (1978) were 56 mg L^{-1} N and 9 mg L^{-1} P with nitrogen occurring predominantly in the ammonium and organic forms. Such waste waters are valuable sources of nutrients for crop or tree growth since an application of 1000 mm $year^{-1}$ would supply 560 kg N and 90 kg P ha^{-1} $year^{-1}$. Nutrient applications of this order are rarely used even experimentally but there is no doubt that the growth of *P. radiata* would be enhanced by such additions. Because undesirable side effects such as large branches and a reduction in apical dominance can occur when very high levels of nitrogen are applied (Will 1971), care may be needed to avoid an imbalance between nitrogen and other nutrients.

(ii) Renovation potential

One of the major limitations to the use of forest or croplands for waste water disposal may well be their ability to retain large quantities of nutrients within the soil-plant system. Nitrification of ammonium (NH_4 – N) to nitrate (NO_3 – N) is common following irrigation of forests with waste water, and since nitrate is very weakly absorbed on to soil particles it can be readily leached from the soil under certain conditions (Parfitt 1978). The percentage of applied nitrogen retained in the system reduces with increasing rates of irrigation (Kardos and Sopper 1973, Urie 1973, Sutherland *et al.* 1974, Urie 1979, Sopper and Kerr 1979, Brockway *et al.* 1979), and as waste water irrigation has been found to cause a significant increase in the decomposition rate of organic matter on the forest floor, this would also favour higher leaching of nitrate (Richenderfer and Sopper 1979). Nitrification is therefore seen as a major factor limiting the amount of waste water which should be applied to land (Breuer *et al.* 1979), but there is also evidence to suggest that denitrification of nitrate to nitrogen gas occurs under some circumstances and can lead to a loss of nitrogen from the system (Broadbent 1973, Hook and Kardos 1977). It is important to recognize that the movement of nitrate in ground water across an agricultural basin takes a long time. The effects may not be observed for decades in the case of medium-sized irrigation areas and even longer in the case of large catchments (Talsma 1979).

Phosphate (PO_4 – P) on the other hand is the anion most strongly absorbed by soil particles, a characteristic which is fairly independent of the crop (Parfitt 1978). Most studies with waste water have found phosphate retention in the top soil to be between 96 and 99 per cent (Kardos and Sopper 1973, Urie 1973, Hook *et al.* 1973, Sutherland *et al.* 1974, Urie 1979, Brockway *et al.* 1979, Sopper and Kerr 1979, Nutter *et al.* 1979). Whilst there are differences between soil types, all forest-soil ecosystems appear to be highly efficient in removing phosphorus from applied waste water.

Salinity

(i) Soil aspects

Although irrigation technology is now very advanced (e.g. Hagan *et al.* 1967, Yron *et al.* 1973, Schilfgaarde 1974, Ayers and Westcot 1976) and despite claims that irrigation agriculture can be conducted on a permanent basis, large areas of irrigated land go out of production yearly (Jakobsen and Wetselaar 1975). One of the major reasons for this is salinity damage to soils and crops, such as decreased soil permeability and specific ion toxicity.

The predominant ions balancing the negative charge of most soils are divalent calcium and magnesium. Under these circumstances the clay particles remain largely floculated and the soil remains permeable. Monovalent sodium may be introduced in irrigation water or be brought to the surface in high water tables formed as the result of irrigation. When sodium ions predominate, considerably greater swelling and dispersion of the clay particles may occur which leads to reduced permeability, macroporosity and poor aeration (Quirk 1971). These changes are undesirable as they will lead to a deterioration in the structure of the soil and reduce the growth of crops.

The potential for a particular irrigation water to reduce the permeability of a specific soil can be evaluated from the Sodium Absorption Ratio (SAR) of the water and the Exchangeable Sodium Percentage (ESP) of the soil (Richards 1954). It has been found that whilst these measures are useful in base-saturated, high pH ($>$7.5) soils in the western U.S.A. where they were established, they are less useful in base-unsaturated, lower pH soils in Australia (Talsma[5] pers. comm.). The effect a particular irrigation water will have on a soil can also be influenced by the presence of bicarbonate ion and various methods have been suggested to account for this (e.g. Bower *et al.* 1967). There are also important interactions between the SAR

[5] T. Talsma, Senior Principal Research Scientist, CSIRO Division of Forest Research, Canberra.

and salinity (concentration): for example, less concentrated solutions have a greater effect on hydraulic conductivity at equivalent values of SAR (Pupisky *et al.* 1979, Oster *et al.* 1979).

To have full control over the effect of irrigation water on soil permeability Bakker (1978) suggests that the threshold concentration of irrigation water for a particular soil needs to be known in addition to the SAR of the water and the ESP of the soil.

Chemical criteria for defining saline, sodic and alkaline soils in Australia were proposed by Northcote and Skene (1972). They found that soils with saline, sodic and alkaline properties were common over a large part of Australia but were mainly of significance where the land was cultivated or irrigated. They observed that the continuing problems of waterlogging and secondary salinity in many irrigation areas were due to the fact that most are situated in the predominantly alkaline sodic soil belts. Salinity profiles in the soil can be reduced to some extent by increasing the leaching fraction (Lonkerd *et al.* 1979).

(ii) Specific ion toxicity
The maximum electrolyte concentration which can be used to irrigate the crop under consideration is also of importance. Tables of tolerance to salinity have been prepared for many species (Ayers and Westcot 1976) but there are few such data for forest trees.

Mortality of *P. radiata* trees in at least one area in South Australia has been attributed to high levels of chloride (Woods 1955). Foliage from apparently unaffected trees contained up to 0.5 per cent chloride. *P. radiata* trees at Clover Hill in South Australia which contained greater than 0.07 per cent sodium in their foliage had distorted upper limbs, yellow needles and excessive branching. Distorted upper limbs were also associated with high chloride. A number of related soil, drainage and salinity problems appeared to exacerbate micronutrient problems in this forest (Raupach *et al.* 1978). Sodium concentrations in needles of *P. radiata* trees affected by salt spray in Wales ranged from 0.07 per cent for green needles on the leeward side to 0.50 per cent for yellow needles on the windward side (Potts 1978).

Although such examples of specific ion toxicity have been reported, it appears that *P. radiata* can continue to grow in soil solutions with quite low osmotic potentials. Sands and Correll (1976) found that needle elongation was reduced in direct proportion to decreasing osmotic potential of the rooting medium over the range from zero to −8 bar. Extrapolation of their data indicates that elongation would have ceased at approximately −14 bar. Sands and Clarke (1977) showed that sudden increases in salinity caused *P. radiata* seedlings to quickly degenerate and die but those gradually salinized escaped visible injury. Seedlings subject to stepwise decreases in the osmotic potential of the rooting medium with sodium chloride and polyethylene-glycol (PEG) recovered rapidly when stress was removed whereas seedlings salinized with calcium chloride did not. Seedling damage was found to be associated with chloride excess and an induced phosphorus deficiency rather than water stress.

In work associated with these studies Foster and Sands (1977) showed that chloride was precipitated in the hyphae of the mycorrhizas and between the cell wall and the plasmalemma of the outer cortical cells of the root. It was also precipitated in ray cells and tracheids of the stem. The authors suggested that chloride was in part prevented from entering the roots, and the stem appeared to provide a sink into which excess chloride could be deposited, thus removing it from cellular metabolism. Their observations support the hypothesis that, although *P. radiata* cannot tolerate high concentrations of chloride in vital tissues, it is adapted to avoid or delay its accumulation in such sites.

Heavy metals

(i) Soil accumulation
The danger of the increasing quantities of heavy metals in the environment is now well known and the mechanisms of their toxicity in man and other animals is receiving considerable attention. The need for increased research to provide more sensitive early-warning criteria of incipient or sub-clinical heavy metal toxicity in man has been stressed by Underwood (1978).

Whilst there is potential for heavy metal concentration in the food chain of a forest ecosystem when waste water is applied, the main concern is likely to be for direct plant toxicity. There does not appear to have been any research to date on the effect of heavy metals in waste water on *P. radiata* but related work provides useful data on likely trends.

Continuous monitoring of heavy metal content of Melbourne sewerage was commenced at Werribee by the MMBW in 1968 (Evans *et al.* 1978).

Table 1. Heavy metal concentration in effluent and quantity retained in soil in Werribee. (After Evans *et al.* 1978.)

	Concentration ($mg\ L^{-1}$)		Total retained in soil after 80 years ($kg\ ha^{-1}$)
	1968	1978	
Cadmium	—	0.015	5.6
Chromium	0.55	0.40	287
Copper	0.65	0.35	133
Lead	—	0.30	230
Nickel	0.20	0.15	72
Zinc	1.00	0.80	615

Standards for the acceptance of heavy metals have been tightened during that time and this trend will continue. The improvement over the 10 years 1968 to 1978 is shown in Table 1 and it can be seen that the most concentrated heavy metal in Melbourne sewerage is zinc, with chromium next followed by copper and lead.

There has been a substantial accumulation of zinc and other metals in the soil. The increases have been greatest in the top 5 cm of soil and are proportional to the length of time the area has been irrigated. Chemical analysis of pastures from irrigated and non-irrigated areas showed that concentrations of these six metals were considerably higher on the irrigated areas. The levels are still below reported levels of toxicity and no toxicity symptoms have been observed, although early signs would probably be manifest only in species composition of the pasture.

Leeper (1978) discussed the issues involved when the products of a sewerage system containing heavy metals were applied to agricultural land at Werribee. Of the 12 heavy metals which are used and discharged by industrial communities he suggested that iron and manganese were already present in the environment in such large amounts that they do not constitute a problem, but that cobalt and molybdenum are present in such small amounts that they could be disregarded. Further, he observed that chromium, lead, mercury and tin form insoluble oxides or are otherwise precipitated in the soil. However, the data presented by Evans *et al.* (1978) show that the concentrations of chromium and lead in the plant material of irrigated pastures were 6.5 and 3.5 times greater than in non-irrigated pastures. The four heavy metals which were postulated to be of most concern were: cadmium which has accumulated in some plants to levels dangerous to the consumer, zinc, copper and nickel which are recorded to have damaged certain crops when applied with sewerage sludge.

The availability of these metals is decreased by increasing pH and cation exchange capacity (C.E.C.). This effect is very marked when zinc is used as an example (Table 2). Soils which have the greatest capacity to immobilize heavy metals by complexing or absorbing them are therefore those which are high in clay and organic matter and have a high pH.

(ii) Effect on trees

Raupach (1975) reviewed the literature dealing with trace element disorders in *Pinus* and found that the foliar concentration of zinc in the upper crown of *P. radiata* trees indicating deficiency is about 5 ppm but levels of up to 80 ppm have been reported. For copper the deficiency level is around 2 ppm but concentrations up to 12 ppm occur.

Pot experiments carried out in Spain to determine deficiency and toxicity levels for certain trace elements in *P. radiata* were reported by Lanuza (1970). He suggested that the concentration of zinc in the foliage necessary to produce symptoms of toxicity was in excess of 200 ppm. Nutrient solutions containing up to 5 ppm zinc

Table 2. Suggested safe limits of zinc for sensitive crops in three soils at three pH levels (adapted from Leeper 1978).

Texture	Cation exchange capacity (meq %)	pH	Safe level of zinc in top 18 cm ($kg\ ha^{-1}$)	Years of irrigation with 1500 mm $year^{-1}$ at 1 mg Zn L^{-1}
Sand	3	6.0	110	7
		6.5	220	14
		7.0	440	27
Average	15	6.0	550	35
		6.5	1100	65
		7.0	2200	135
Clayey	30	6.0	1100	65
		6.5	2200	135
		7.0	4400	265

did not reduce yield or induce toxicity but above this concentration toxicity symptoms and decline in yield increased dramatically. It was considered that *P. radiata* is tolerant to high levels of zinc.

Lanuza (1970) set the toxicity level of copper in the foliage at greater than 8 ppm but at times it exceeded 30 ppm. Nutrient solutions containing between 0.002 and 2 ppm copper produced toxicity symptoms in some experiments. There are very complex interactions between the various trace elements which naturally influence the level of toxicity.

The concentration of heavy metals, including copper in waste water available for agricultural use will depend on the pre-treatment it receives. The activated sludge process used as a primary treatment in many effluent plants removes most of the heavy metals but not the nutrients. In an experiment in Western Australia with effluent from an activated sludge plant to irrigate a *P. radiata* plantation the removal of copper resulted in a deficiency of this element in the pines (Cromer and Turton 1979). The concentration in the effluent ranged from 0.02 to 0.10 mg copper L^{-1} and had to be supplemented to overcome the deficiency.

No published reports were found regarding the effect of nickel or cadmium on *P. radiata* trees.

Effect of boron on pines

Boron toxicity has been reported in several pine species following the application of waste water containing borax (Stone and Baird 1956, Sopper and Kardos 1973, Sinclair and Stone 1974). Neary *et al.* (1975) found that up to 26 kg ha^{-1} of elemental boron had been added to experimental plots of red pine *(Pinus resinosa)* following irrigation over two summers with water containing 0.9 mg boron L^{-1}. The boron level in the current needles rose from 27 ppm in the control trees to 75 ppm in the most heavily irrigated trees. Some trees were noted to be highly sensitive to excess boron and where toxicity caused the stand to deteriorate no alternative was seen but to cease irrigation.

Glasshouse experiments with *P. radiata* in Canberra showed that symptoms of boron toxicity developed in seedlings grown in solutions containing 10 ppm of added boron but not in those containing 5 ppm or less (Ludbrook 1942). Snowdon (1973) found that the growth of seedlings in solutions containing 5 ppm boron was only slightly restricted and that the seedlings exhibited only mild toxicity symptoms. However, Lanuza (1966) found that the growth of *P. radiata* decreased in solutions containing more than 0.5 ppm boron. These results emphasise that complex interactions between elements can occur and probably no single maximum level can be set.

It appears however that *P. radiata* is relatively tolerant to high levels of boron. Windsor and Kelly (1971) raised the average boron concentration in the foliage of *P. radiata* trees to 170 ppm following applications of 450 g borax to individual seed orchard trees to overcome suspected boron and sulphur deficiencies. The boron concentration declined to 30 ppm after 2 years and 25 ppm after 3 years.

Management of *P. radiata* under irrigation

Land area and seasonal demand

The area of land required to service various population levels will be related to rainfall, evaporation and the amount of industrial waste water produced. Experience in Pennsylvania indicates that an area of 40 ha of forest is sufficient to renovate the waste water produced by a town of 10,000 people (Sopper[6] pers. comm.). This assumes an application rate of 50 mm per week and a population producing 450 L of waste water per person per day.

The potential for a forest in southern Australia to transpire water reaches a maximum in summer but is low in winter. The quantity of waste water applied should be related to the transpirational demand for optimum growth and health of the trees but this would necessitate the construction of storages for some of the waste water produced in winter. The storages would also act as a buffer during periods of rain when irrigation was not required, but would increase the cost of disposal.

Layout and operation

Waste water could be applied to trees by flood, channel, spray or trickle irrigation methods. Spray or trickle systems could be set up in an existing forest, and whilst initial purchase of equipment would be costly, these methods would not require a large labour input to operate. Spray and trickle systems enable the water to be applied very evenly which would also provide better control over the leaching

[6] W. E. Sopper, College of Agriculture, Pennsylvania State University, U.S.A.

fraction and hence water table fluctuations. Good filtration is required to avoid blockages in drippers or sprays.

Flood or channel layouts on the other hand would have to be prepared prior to planting and would be more labour intensive to operate. They would not be suitable in hilly or rocky terrain and must be carefully designed and constructed so that slope and water flow are related to infiltration capacity of the soils.

Watering regime would be related to the transpirational demand of the crop, soil factors such as permeability and salinity and waste water characteristics including concentration, heavy metal contamination and salinity. Windthrow could be a problem in some soil types if they were allowed to remain saturated. Watering may also have to be avoided during thinning and other plantation operations as machinery can cause compaction of wet soils.

Health aspects

A number of adverse effects on human health could result from the application of waste water to land used for raising crops or live stock.

The transmission of diseases in aerosols from the use of waste water in spray irrigation and the consumption of vegetables contaminated with waste water have been noted as potential health hazards. Consequently the secondary treatment and disinfection of waste water prior to application have been suggested (Katzenelson *et al.* 1976, Sorber *et al.* 1976, Morrison and Martin 1977, Doran *et al.* 1977 and Strauch 1977). Infection of the intestine of man by the tapeworm *Taenia saginata* (beef measles) can also occur from eating undercooked beef from sewerage farms (Rickard and Adolph 1977, Rickard 1978).

Many of the health problems associated with the use of reclaimed water in agriculture do not arise where trees are the crop under cultivation. Human activities are minimal in forestry plantations compared with other agricultural crops and people can be barred from the area while spray irrigation is in progress. There is no risk of transmitting diseases to humans through a secondary animal host and the crop is not consumed directly. The World Health Organisation has suggested that waste water used to irrigate crops not for direct human consumption requires only primary treatment without disinfection (Polin 1977). For all other uses of waste water, including the irrigation of crops for human consumption, for irrigation of recreation areas, and for industrial and municipal reuse, much higher standards of treatment and disinfection are suggested.

Conclusions

This review has examined a number of factors which might be significant in proposals to utilize and renovate waste water by irrigating plantations of *P. radiata.*

While the species has the capacity to withstand limited periods of drought, it suffers from severe loss of increment due to water stress during late summer and autumn in many parts of Australia. In the most severe cases, this results in the death of tops or of complete trees. Whilst this condition can be alleviated by thinning, the stand will still suffer loss of increment.

Irrigation experiments have without exception demonstrated that the species will respond to additional water. The maximum response has not been determined, but it is likely that the response would increase up to an application (irrigation plus precipitation) of 2500 mm water per year on deep, well-drained soils. Shallow soils could be used provided waterlogging was not allowed to occur for extended periods. Drought dieback would thus be avoided and substantially higher basal areas could be carried.

Besides providing increased yields of wood, irrigation would also improve wood quality of *P. radiata* trees. For example, since irrigation permits continuous growth during spring, summer and autumn the occurrence of false rings and shakes can be avoided. Furthermore the increased growth in the latter part of the season produces a higher percentage of latewood which has higher density and greater strength than early wood.

The nutrients contained in most waste waters would enhance the growth of *P. radiata* in addition to the extra water. Very heavy applications of nitrogen can cause undesirable side effects but the concentrations of phosphorus and potassium in sewerage should be adequate to prevent an imbalance between these nutrients.

Where waste waters contain high concentrations of nitrogen, careful monitoring of nitrate in the soil solution would be required to prevent ground water pollution. Nitrate leaching can be controlled to some degree by the rate and frequency of irrigation. In most soil types phosphate adsorption should be sufficient to ensure that levels of this ion in the leachate are minimal.

Waters with high sodium adsorption ratios can reduce permeability and their use should be avoided unless the soil or waste water can be treated to maintain a balance between sodium and calcium.

Nevertheless, *P. radiata* possesses mechanisms for avoiding or delaying excessive uptake of sodium and chloride ions, and provided salinity levels build up slowly and sudden very high doses are avoided, the species should cope with moderate levels of salinity.

The danger of toxicity from heavy metals is related to the pre-treatment given to the waste water. The activated sludge process removes most of the heavy metals in the sludge and may even result in trace element deficiencies. Where metals are not removed by pre-treatment the levels of zinc, copper and nickel should be monitored. *P. radiata* appears tolerant to high levels of zinc but not to copper.

The use of detergents which contain borax may result in waste waters containing high levels of boron and whilst *P. radiata* appears relatively tolerant, concentrations of this element should also be monitored to guard against boron toxicity.

The operation of a land-based waste water disposal system must be carefully managed to avoid damage to the soil, the crops being grown and the people employed.

The use of non-disinfected waste water on horticultural and agricultural crops involves risks to human health. Pre-treatment and disinfection increases the cost of waste water disposal or reuse. The utilization of waste water on forest crops would enable a lower standard of pretreatment to be practiced without increasing the risk to public health.

In view of the factors outlined, a greater research effort should be mounted in Australia to examine the use of forest areas for the utilization and renovation of waste water. In southern Australia, the use of *P. radiata* plantations is specifically recommended for investigation.

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