# THE POTENTIAL TO INCREASE THE PRODUCTION OF WATER AND WOOD IN THE NORTHERN JARRAH FOREST - A REVIEW OF RELEVANT LITERATURE.

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## 1. Introduction

Due to its proximity to the city of Perth there is a great deal of pressure for the most efficient use of the resources of the northern jarrah forest. Two of the most tangible and highly valued of these resources are quality jarrah timber and fresh water. Both these resources are in high demand but limited supply.

Current research is designed to test the hypothesis that under the peculiar environmental conditions of the northern jarrah forest, a reduction in forest cover will result in higher yields of both fresh water and quality wood. This report studies that possibility.

## 2. Demand and Supply of Water

A number of reports have emphasized the limited nature of potential sources of water for the city of Perth (Metropolitan Water Supply Sewerage and Drainage Board, 1974; Sadler, 1975; Sadler and Field, 1976; Adam, 1977; Public Works Department, 1977). It has been estimated that by the year 2002 50% of the assessed usable resources of the whole of the south west region (see figure 1) will be required, and by 2025 all the fresh and marginal resources will be committed.

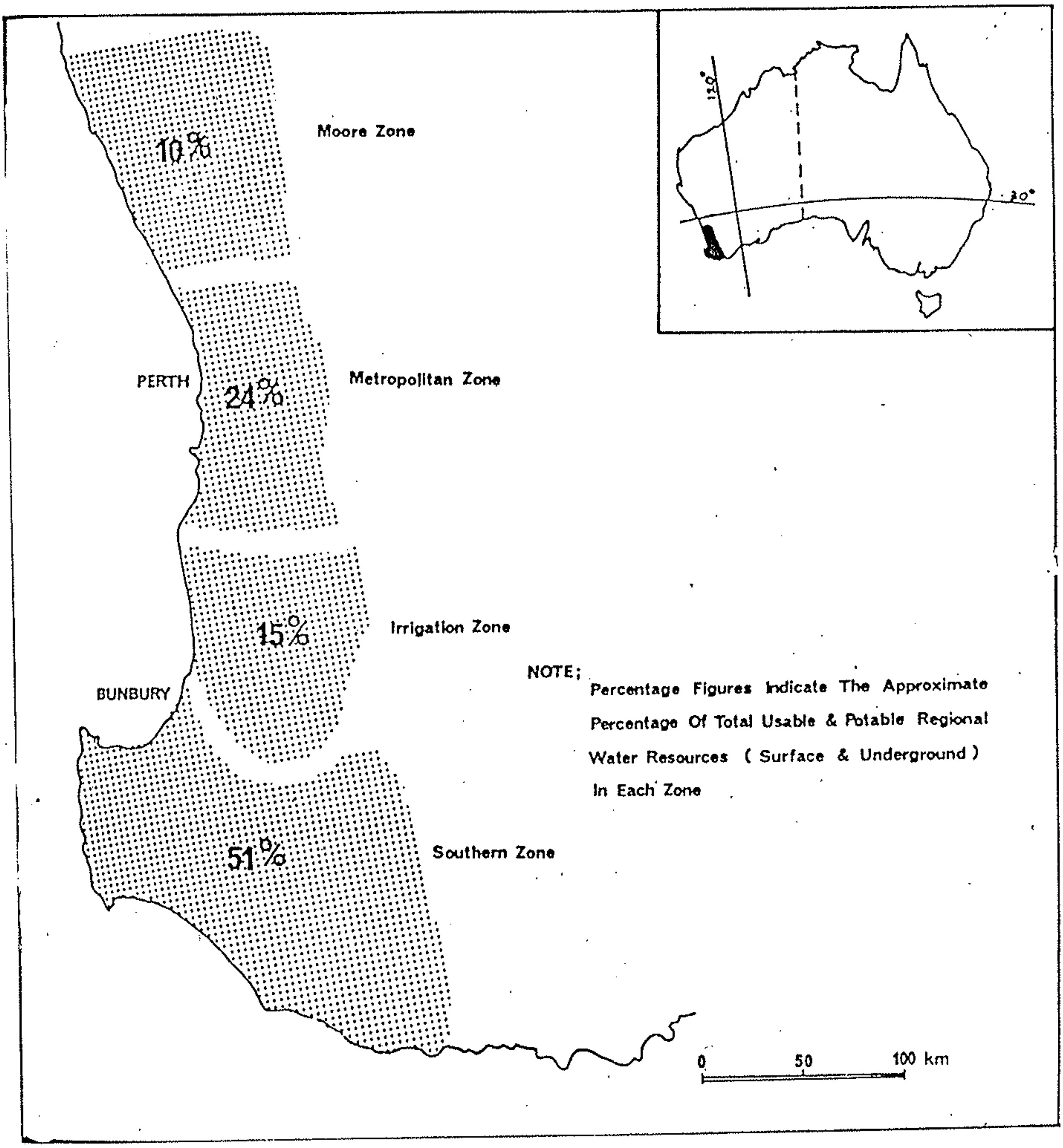


Figure 1: Principal zones of water resources and supply development in the south west region of Western Australia (after Sadler, 1975).

In the Metropolitan Zone the demand for water is expected to exceed supply by 50% by the turn of the century. A number of options are available to overcome this situation (Ritson and Shea, 1979):

(i) decrease per capita consumption,

(ii) desalinate brackish or saline water,

(iii) obtain water from outside present M.W.B. catchments,

or (iv) increase water yield from present catchments.

Options (i) has proved successful in crisis situations. Bans on the use of sprinklers and a 'save water' publicity campaign reduced Perth water consumption by more than 39% in 1977/78 (see figure 2).

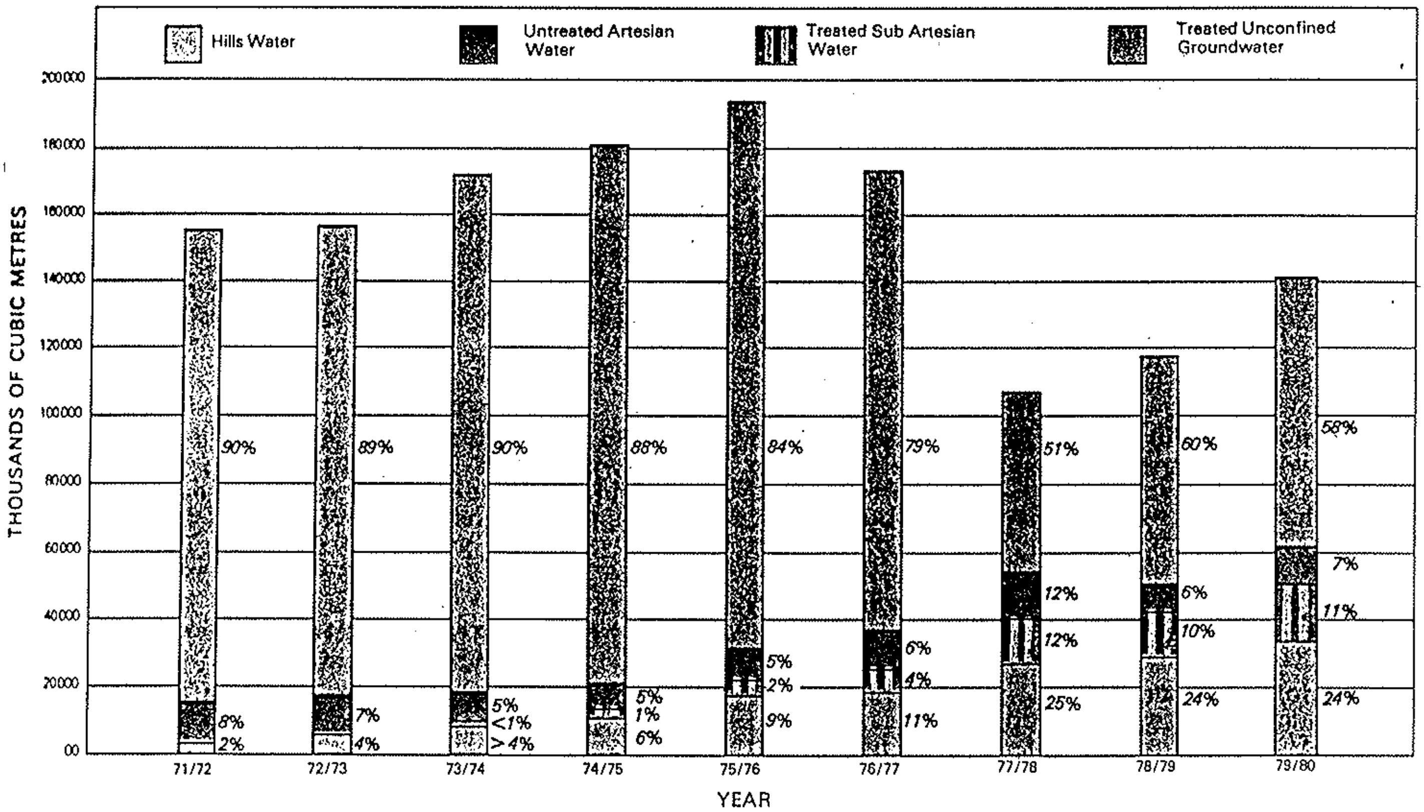


Figure 2: Total annual water consumption (from Metropolitan Water Supply Sewerage and Drainage Board, 1980).

Option (ii) is not yet economically viable because of the prohibitive costs involved in desalination, and this will probably be the case for quite some time.

The costs associated with option (iii) are outlined in table 1.

Option (iv), that of increasing water yield from present catchments is discussed later in this report. The cost of gaining each additional $m^3$ of water by this option has been estimated at less than 10 cents, that is, less expensive than even water from present M.W.B. catchments.

| Source | Cost ($/m$^3$water) |
|---|---|
| Present MWB catchment | 0.16 |
| Harvey River | 0.27 |
| Collie River | 0.31 |
| Murray River | 0.37 |
| Donnelly River | 0.45 |
| Ord River | 6.00 |

Table 1: Costs, before distribution of water delivered to Perth (after M.W.B. 1978). Note that supplies from the Harvey and Collie Rivers are currently used for irrigation and country water supply.

## 3. Demand and Supply of Wood Products

Figure 3 illustrates the predicted total local sawlog supply and demand in Western Australia from 1985 - 2020. The northern jarrah forests contribution to supply although relatively small, is still substantial (in 1985 160,000m$^3$ of a total 900,000 m$^3$). The sawlog resource from this region is expected to consistently diminish, to the year 2020 when the old growth forest will no longer contribute to the supply of sawlogs to the market. The Forests Department (1977a) points out that "the majority of hardwood regrowth forest is not subject to regular tending and therefore bole diameter growth on individual trees in slow. It is likely to continue to yield limited quantities of poles and fencing materials, but it is not expected to contribute to the sawlog resource until well into next century".

If it can be established that demand for the jarrah sawlog resource is sufficient to justify investment in the tending of regrowth stands, such that bole diameter growth on individual trees is markedly increased, then the predicted future supply of sawlogs from the northern jarrah forest would change substantially. Data from thinning trials near Dwellingup need to be analysed to quantify the effect of various thinning intensities on regrowth stands. Of particular importance is the effect of thinning on time required to reach sawlog size.

Jarrah seems to be establishing itself as a high quality timber to be used for specialist and high value end products. It is intended that future usage of jarrah timber should taken greater advantage of its intrinsic properties for joinery, furniture, panelling and veneers (Forests Dept, 1977b). This demand is likely to increase as long as supplies are available. Royalties received for jarrah sawlogs obviously have a major influence on the economics of investment in thinning. If royalties increase as a result of an increased demand for quality jarrah timber, then the prospects of being able to economically justify an investment in thinning will also increase. (Ritson and Shea, 1979). Other values of the forest may also increase following a thinning, particularly water production (which will be discussed later), and this will apply a further impetus on proposals to

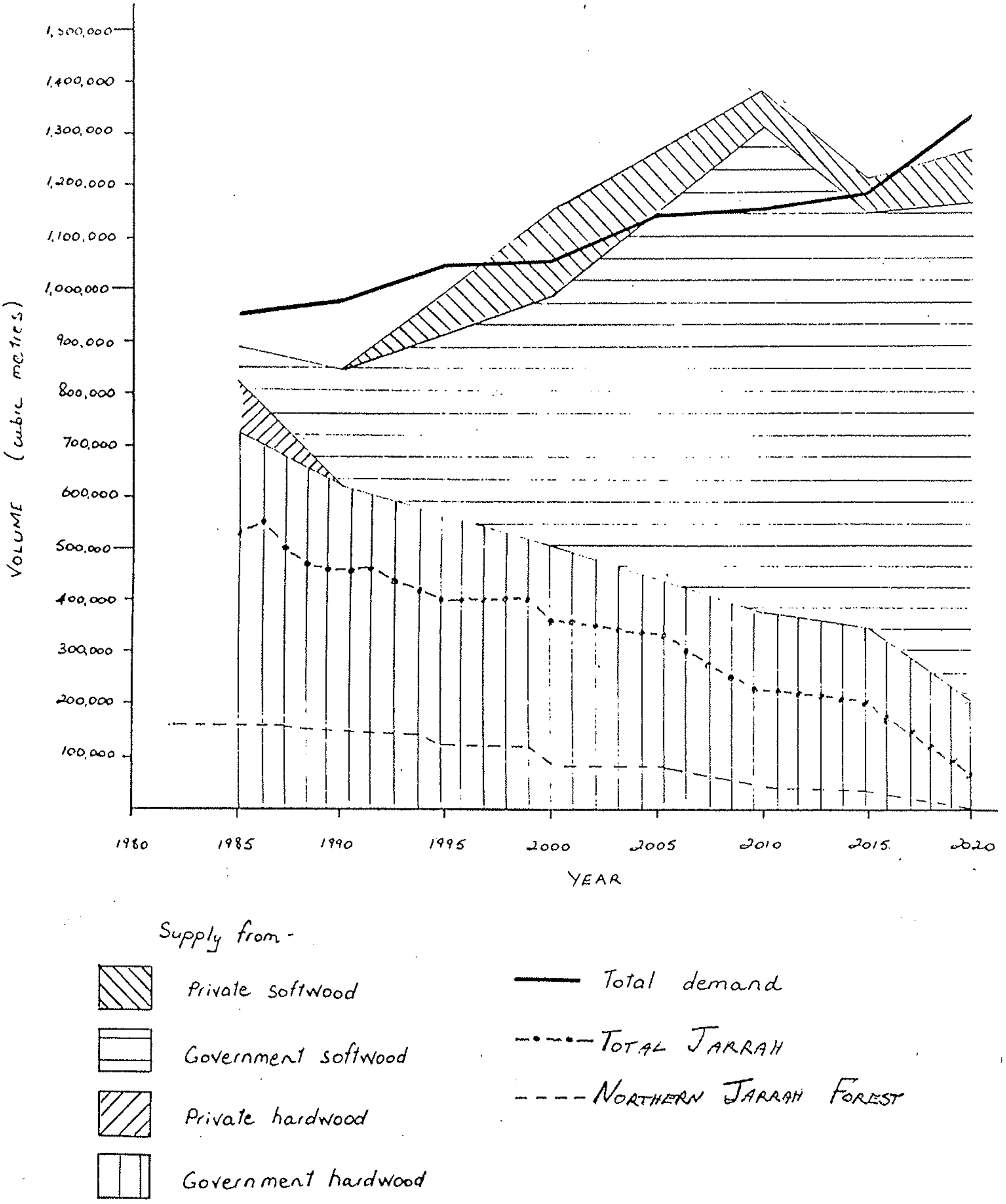


Figure 3: Predicted total local sawlog supply and demand in Western Australia from 1985-2020 (Supplied by Forests Department, Inventory and Planning Branch. Como).

thin appropriate regrowth stands.

As an example of the increasing demand for quality native hardwoods, it should be noted that the Senate Standing Committee on Trade and Commerce's report on Australia's forestry and forest products industries (1981) commented that more of the Commonwealth money that has been spent on establishing pine plantations should be spent on upgrading existing native forests. The report also stated that it would be advisable to grow specialist species that could be managed on an 80 to 100 year rotation. It may well be that jarrah regrowth forest can satisfy this criterion.

Future utilization standards may also have a major impact on the predicted sawlog supply. Currently, sawlogs have a minimum diameter at breast height over bark (d.b.h.o.b.) of 50cm. Over the next five years this minimum is likely to drop to 20 - 30cm d.b.h.o.b., This seems reasonable as many overseas countries which have limited supply but strong demand currently utilize stems of this size for sawlogs.

Increasing demand for other wood products, particularly for fuel , from the northern jarrah forest can also be expected. This, plus possible improvements in harvesting technology (Mulcahy, 1981) will improve the situation with respect to utilization of small size stems that otherwise would be thinned to waste at great expense. Thus the economics of thinning regrowth stands can be expected to improve substantially in the future.

## 4. Effect on Water Yield of a Reduction in Forest Cover.

### 4.1 Overseas Literature

The first controlled catchment experiment described to test the hydrological effects of a reduction in forest cover was at Wagon Wheel Gap, Colorado (Bates and Henry, 1928). Since then numerous studies have been and are continuing to be carried out.

Hibbert (1967) reported the results of 39 studies in the United States, Africa and Japan, on the hydrologic effects of altering forest cover. He came to the conclusion that a reduction in forest cover increases water yield, and in general that the increase is proportional to the reduction in forest cover (see figure 4). However, response to any given treatment was highly variable, and generally, unpredictable. He noted a general pattern of decline with time of the increased water yield following treatments, and that the rate of decline appeared to vary with the rapidity of regrowth.

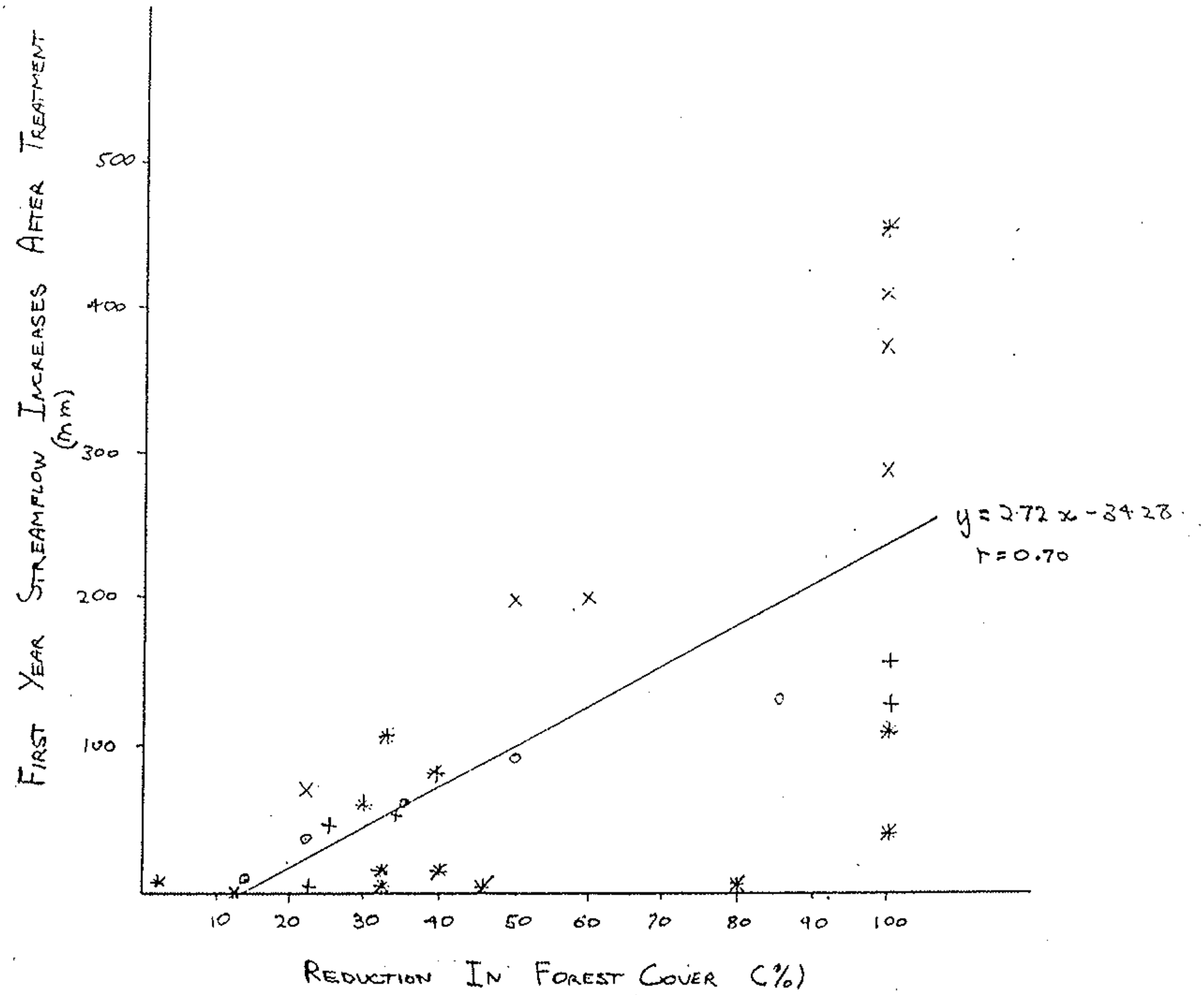


Figure 4: First year streamflow increases following a reduction in forest cover (After Hibbert, ibid.).

Subsequent American studies have not changed these generalisations, but have quantified the effects of particular treatments for particular locations. (Rothacher, 1970; Urie, 1971; Rich, 1972; Douglas and Swank, 1975).

Anderson, Hoover and Reinhart (1976) agree that increases in water yield are proportional to the reduction in forest cover. They and others (Douglas, 1967: Rich, op. cit.) believe that there is a minimum cut which can be expected to produce a significant response. Douglas (1967) estimates this for a humid region at reduction of 20% of basal area of a well stocked stand. It is however, difficult to test this because experimental error is often larger than the expected response to a small partial cutting.

Anderson et al (1976) states that the duration of increased streamflow is dependent on the magnitude of the initial increase, the type and intensity of the cut, and the rapidity of regrowth. They believe selection cuttings and thinnings have only transient influences on water yield because roots and canopies rapidly extend into unoccupied spaces, thus fewer trees will soon be using the same quantity of water over a given area.

However, Chubatyi (1980) (abstracted in Forestry Abstracts, 1981) found that the effects of a partial cut (a two stage shelterwood felling) lasted longer than those of a clearfelling. Australian work reviewed below has also found the hydrological effects of thinning to last longer than those of clearfelling.

4.2 Australian Literature.

Until the 1970's there was little Australian work published on the effects of a reduction in forest cover on streamflow. Gilmore (1971) conducted a study in a north Queensland rainforest which found an increasing trend for streamflow from a logged tropical rainforest as compared to an adjacent area unaffected by logging.

Batini, Black, Byrne and Clifford (1980) in a study in the Wungong Catchment in the south-west of Western Australia found that reductions in forest cover due to the jarrah dieback disease were significantly correlated to changes in water yield.

Kriek and O'Shaughnessy (1974) in treatments to Victorian eucalyptus regnans forest found quite significant changes in streamflow and soil moisture storage after clearfelling. However, a treatment designed to remove 50% of the forest crop was not followed by a significant response to streamflow or soil moisture. These results were only short term though. Langford and O'Shaughnessy (1977a) noted a decline in the increase of streamflow in the clearfallen catchment associated with the rapid regrowth of the forest. After more results had come to hand (Melbourne and Metropolitan Board of Works, 1980) it became apparent that the selective cut had resulted in about a 25% increase in streamflow, and that this was persisting longer than the increase which occurred following the clearfelling. Langford and O'Shaughnessy (1980 a) attributed the observed hydrological changes to changes in stand structure with forest age. They believed canopy leaf area to be of major importance, influencing both interception and transpiration. Bren (1977) agrees that the usually observed increase in streamflow following a thinning is the result of changes in these two parameters.

5. Effect on Water Quality of a Reduction in Forest Cover

5.1 Erosion, turbidity and sediment production

Turbidity problems have resulted following forestry operations in N.S.W., Victoria and the A.C.T.. Boughton (1970) reported that soil type and the amount and type of ground cover were identified as the prime factors in determining turbidity. Soils formed on granodrorite and volcanics are readily dispersible in water and more prone to release turbid water either as surface flow or seepage than soils on other rocks.

In the U.S.A., Anderson (1954) found that the most erosive soils and highest sediment producing soils were developed from intrusive igneous parent rocks, whereas the least erosive soils had developed from aluvium. Wallis and Willen (1963) ranked twelve parent materials in terms of erodibility:

Erodible parent material:
  Granite, quartz diorite, granodiorite
  Cenzou non-marine sediments, schist.
Intermediate:
  diorite, a variety of metamorphic rocks.
Non-erodible:
  Cenzou marine, basalt and gabbro, pre-Cenzou marine sediments, peridotite and serpentimite, and andesite.

Langford and O'Shaughnessy (1977b) report that the relative proportion of an area that is severely disturbed is an important factor determining the potential impact on water quality. Soil compaction along roads, snig tracks and log landing can lead to increased erosion and sedimentation in streams due to reduced infiltration capacity and consequent increased overland flow. Langford and O'Shaughnessy (ibid.) summarise data from Reinhart and Eschner (1962) to produce the following table which highlights the effects that proper prescrptions and planning can have.

| Treatment | Area (ha) | Prescription | % harvested | Max. turbidity observed (mg/l) |
|---|---|---|---|---|
| 1 | 30 | None | 82 | 56,000 |
| 2 | 15 | Bars across snig tracks | 36 | 5,200 |
| 3 | 36 | As above + a ban on stream entry | 22 | 210 |
| 4 | 34 | As above + location of roads away from streams + grass seeding | 14 | 25 |
| 5 | 39 | Control (no logging) | 0 | 5 |

Table 2: Harvesting method and streamflow turbidities at Fernow. (After Langford and O'Shaughnessy, b )

The major differences in turbidity were reported to occur during stormflow. Water quality recovered rapidly after the cessation of operations, and had returned to normal in all areas within two years.

Sopper (1975) stated that most water turbidity and erosion problems are the result of roading. Packer (1967) and Melbourne and Metropolitan Board of Works (op. cit.) agree that roads are the source of most water quality problems. Gilmore (op. cit.) found that poor logging practice caused a marked increased in sediment loads, and that stream crossings were particularly important.

It is generally agreed that careful planning of the roading and logging operation can avoid most problems.

5.2 Stream temperatures

Hart (1974) points out that the composition of aquatic communities depends largely on the temperature characteristics of the environment. Stream temperatures are likely to increase following harvesting of the riparian vegetation. Average maximums have been found to increase by up to 6°c and daily maximums up to 15°c. Removal of the shading overstorey permits direct solar radiation into the stream causing higher water temperatures and greater fluctuations between minimum and maximum temperatures which may have a detrimental effect on native aquatic life. (Sopper, op. cit; Anderson et al., 1976; Swift and Baker, 1973).

Harvesting near the stream zone should therefore be avoided from a conservation point of view.

5.3 Chemical quality

Likens, Bormann, Johnson, Fisher and Pierce (1970) stress the importance of encouraging maximum regrowth to initiate nutrient recycling following forest operations, although it is unlikely that the concentration of any one ion will exceed public health limits. Langford and O'Shaughnessy (1977b) believe that nutrient concentrations , especially N and P, can increase markedly as a result of clearfelling and burning.

The use of herbicides in forest operations has received a great deal of criticism over the last decade. Kimber (1967) reported that little wide scale thinning was attempted in the jarrah forest prior to the introduction of hormone-type herbicides due to difficulties of controlling coppice shoots. He concluded that both picloran and 2, 4, 5 - T were successfully used to control coppice regrowth following the thinning of jarrah regrowth stands. Although a number of studies have found that such herbicides can be used without impairment of water quality if carefully applied at the recommended rate (Lawson, 1976; Reigner, Sopper and Johnson, 1968; Sopper, op. cit), their use is not contemplated as part of the strategy for control of regrowth in experimental catchments.

In south-western Australia stream salinity has been identified as a major water quality problem. (Peck and Bettenay, 1976). Wood (1924) was the first to suggest that removing the native vegetation leads to increased stream salinity. Extensive clearing of native vegetation, particularly for agriculture under dryland farming conditions, has now been shown to have led to increases in soil and stream salinity over a large area. (Malcolm and Stoneman ,1976). The salination of streams and of land, caused by the release of salts stored in the soil profile is now accepted as one of the major water supply and land use planning problems of the south-west.

The Public Works Department (1979) has estimated the rise in average salinity if all private land in a number of river catchments was cleared.

The figures in the table below show that clearing land of native forest can be expected to lead to many unacceptable increases in stream salinity.

| River | *Land Uses In Catchment* | | | *Av. Salinity* | *T.D.S.* |
|---|---|---|---|---|---|
| | *Forest %* | *Private Land %* | | *Present* | *If all private land cleared* |
| | | *Uncleared* | *Cleared* | | |
| *Denmark* | 79 | 5 | 16 | 570 | 850 |
| *Collie* | 65 | 12 | 23 | 750 | 1700 |
| *Warren* | 54 | 14 | 32 | 725 | 1400 |
| *Kent* | 40 | 27 | 33 | 1100 | 2500 |
| *Helena* | 95 | 2.5 | 2.5 | 360 | 700 |

Table 3: Salinity increases predicted following clearing. (After P.W.D., 1979).

Shea, Hatch, Havel and Ritson (1975) reported that selective logging of jarrah had not caused marked increases in stream salinity. However, Ward (1977) found that for the Helena Catchment there was a strong correlation between forest canopy removal and saltflow. Environment factors are very important in the northern jarrah forest and these will be described later.

## 6. The Hydrologic Effects of Fire

Humphreys and Craig (1981) poin out that fire can affect the hydrologic cycle by destroying vegetation covering the soil, and by heating and changing the soil. "The intensity and duration of fire are important in determining the degree to which these two influences occur".

Only fires of very high intensity are likely to affect soil pore space and water transmission properties, and it seems unlikely that the stability of the surface soil structure will be adversely affected by either low or high intensity fires (Humphreys and Craig, ibid.). Fire also has the potential to increase surface runoff and erosion by increasing the water repellence of soils, however, on deep well structured soils the effect can be expected to be small (Langford and O'Shaughnessy, 1977b). Fire can also be expected to affect interception and evapotranspiration, the more intense the fire the greater the reduction in these two factors.

Boughton (op. cit.) points out that the timing and pattern of rainfall following the fire is also of importance "Light showers at regular intervals following an extensive burn can promote rapid regrowth and result in little or no runoff or erosion."

The potential does exist for the timing and pattern of streamflow to be affected. Humphreys and Craig (op. cit.) report that most hydrological studies involving wildfire show substantial increases in both total and peak streamflow in the period soon after the fire.

McArthur (1964) reported increased streamflow following the 1961 Dwellingup wildfire. The results tabled below show that the effect was observed almost immediately.

| Date January | North Dandalup | South Dandalup | Davies Brook |
|---|---|---|---|
| 17 | 0.003 | 0.034 | 0.017 |
| 18 | 0.003 | 0.034 | 0.014 |
| 19 | 0 | 0.034 | 0.010 |
| 20 | 0* | 0.034 | 0.014 |
| 21 | 0.020 | 0.034 | 0.017 |
| 22 | 0.006 | 0.034 | 0.017 |
| 23 | 0.008 | 0.034 | 0.017 |
| 24 | 0.014 | 0.028 * | 0.017* |
| 25 | 0.025 | 0.042 | 0.020 |
| 26 | 0.048 | 0.065 | 0.031 |

Table 4: The effect of fire on streamflow in jarrah forests near Dwellingup, Western Australia, January, 1961. (Streamflow in cumecs)

(After McArthur, 1964).
* The catchment was burnt on this day.

Boughton (op. cit.) believes that it is beyond doubt that intensive fires will result in increased erosion, and possibly increased runoff as well. Prescribed fires of low intensity can be expected to offer a low risk of adverse effects on water resources compared with the uncertain risk of high intensity wildfires if fuel is allowed to accumulate on a catchment. However, the long term effects of such a fire regime may be significant. Shea et al. (1975) point out that the composition and density of both the understorey and overstorey will be affected by the frequency and intensity of fire, and the effect of this on the water balance in a catchment may be pronounced.

## 7. The Northern Jarrah Forest Environment.

### 7.1 Climate

The climate of the area if typically Mediterranean. Annual average rainfall of 1270mm is experienced on the western boundary of the forest, with rainfall dropping rapidly over the next 30 to 40 kilometers to below 600mm on the eastern boundary of State Forest.
Rainfall is strongly seasonal, most falling during the winter months of June, July and August. The ratio of winter (April to October) to summer (November to March ) rainfall is about 6:1. An intense summer drought is experienced, with no rainfall over periods of 3 to 4 months. The south-west of the northern jarrah forest experiences 20 days per annum with temperatures exceeding 32.5$^{o}$C , this ranges to over 40 in the north-east of the area. (Havel 1975 a). Daily potential evaporation rates in excess of 10mm are common in summer. (Shea, Herbert, and Bartle, 1978).

### 7.2 Physiography, geomorphology, geology and soils

Jutson (1950) described the area of the northern jarrah forest as occurring on the western boundary of the ancient and extensively laterized Great Plateau of Western Australia. Rejuvenation of the rivers as a consequence of the uplift and formation of the Darling Scarp has resulted in a sequence of valley types. The western margin is characterized by sharply incised, rapidly draining valleys. This changes to broad, sluggishly drained valleys in the east, a reflection of the degree of valley dissection. (Mulcahy, Churchward, and Dimmock, 1972; McArthur, Churchward, and Hick 1977; Bettenay and McKinnell, 1980).

Lateritic uplands are the dominant soil type. These typically consist of 10 to 20cm of sandy loam in a gravel matrix underlain by concreted laterite and/or unconsolidated laterite to a depth of 2 to 16 metres which is in turn underlain by a deep horizon of pallid zone clay. The lowland soils are formed on truncated laterites or colluvium. (Shea et al. 1975).

## 7.3 Vegetation

Although the forest vegetation superficially appears uniform, Havel (1975a) found that the vegetation and associated environmental factors form a complex multi-dimensional continium.

"Overstorey composition can be used to categorize the forest vegetation broadly. On the lateritic uplands sites the overstorey is primarily jarrah (Eucalyptus marginata Sm.) with scattered Marri (Eucalyptus calophylla R.Br.). Moisture gaining sites in the valleys resulting from partial dissection of the lateritic peneplain where soils have been formed on truncated lateritic profiles or detritus from the uplands, are less favourable for jarrah. Western Australian blackbutt (E.patens - Benth.) Bullich (E.megacarpa F.Muell) and marri form the overstorey in the western valleys but these species are replaced by wandoo (E.wandoo Blakey) and Western Australia flooded gum (E. rudis Endl.) in the eastern forest zone. Where the valleys have dissected the lateritic profile to form younger, more fertile soils jarrah, marri and blackbutt form the overstorey in varying proportions. Banksia species are the predominant understorey trees on both upland and lowland sites. Casuarina frasteriana MIQ. and Persoonia longifolia R.Br. may also be important understorey components on the lateritic uplands. Shrubs are numerous and diverse on all sites.

When placed in the context of the environment in which it grows, the jarrah forest must be recognized as a unique forest ecosystem.
The lateritic soils are infertile and frequently the surface horizon is underlain by lateritic cap rock. The climate is desert-like for one-third of the year and the vegetation is subjected to fires of varying intensity. Despite these unfavourable conditons, standing commercial timber volume in virgin jarrah forest has been recorded at 375 cubic metres per hectare and the height of co-dominant jarrah may exceed 45 metres. The ability of jarrah and other components of the forest to survive and achieve these levels of productivity in an environment which is unfavourable for forest growth is explained by the presence of a high degree of specialization. (Shea and Hopkins, 1973). For example, Kimber (1974) has demonstrated that

jarrah produces vertical roots which penetrate the pallid zone clays of the upland laterites to a depth of 14 meters and proliferate into a fine root system above the water table. This characteristic partially explains why jarrah maintains relatively high transpiration during the summer drought. (Doley, 1967) "(Shea et al, 1975).

7.4 Hydrology

Saltfall vares across a west to east gradient. it has been recorded at 133/kg/ha/annum (North Dandalup, 97 kg/ha/annum (Yarrigal), and 31/kg/ha/annum (Williams in the western, central and eastern forest zones respectively. (Shea et al, 1975). The total amount of salt stored in the soil profile is quite considerable, and may exceed 500,000 kg/ha (Shea et al, 1978). Dimmock, Bettenay and Mulcahy (1974) found that salt storage was related to rainfall, but Batini, Selkirk and Hatch (1976) state that it is also dependent" on the nature of the parent materials (as reflected by the site - vegetation types) and possibly the position and fluctuation of the ground water table".

Peck and Hurle (1972) found that saltfall and saltflow are in approximate equilibrium in forested catchments, but that in farmed catchments saltflow was up to 20 times as much as saltfall. Although saltfall is greater in the western high rainfall zone of the forest, both total salt storage in the soil profile and groundwater salinities increase in a general pattern from west to east. Shea et al. (1978) say that the relatively low salt storage in the soil profiles of the western zone is attributed to rapid drainage and high rainfall flushing the salt out. Stream salinities also increase in a general pattern from west to east. (Shea et al, 1975). West of the 1150mm/annum rainfall isohyet base flow salinity is less than 250 mg/1 TDS. The water can be classified as fresh (PWD, 1979). East of the 1000mm/annum rainfall isohyet base flow salinities are 500 - 1000 mg/1 TDS rising to above 1000 mg/1 TDS a little further east (marginal and brackish respectively). In the intermediate rainfall zone (1150 - 1000mm/annum) the pattern of salt storage in the soil profile, stream salinity and groundwater salinity is complicated. (Ritson, Herbert and Shea, 1981). Conditions in adjacent subcatchments are often very different. Ritson and Shea (1980) have attributed this to variations in geomorphology and soils, or to a reduction of forest cover.

Average annual streamflow yield from forested catchment range from 1% of rainfall in the eastern forest zone to 15% in the western high rainfall zone. (Shea et al, 1978). Havel (1975 a), cited by Shea et al, 1975) found that average yield could be as high as 36% of precipitation if the vegetation on the upland lateritic component of the catchment was denuded or removed.

## 8. The Potential to Increase Water Yield In the Northern Jarrah Forest.

As has already been alluded to, yield of water can increase significantly following a reduction in forest cover by thinning. This has not yet been established for the jarrah forest, however, a strong correlation has been found between percentage canopy cover and percentage water yield (see figure 5). Shea et al (1978) believe that from this correlation it is reasonable to assume that water yield can be increased significantly by a reduction in forest cover in the jarrah forest. O'Shaughnessy, Moran and Flinn (1981) have made a similar assumption for regrowth E.regnans forest in Victoria.

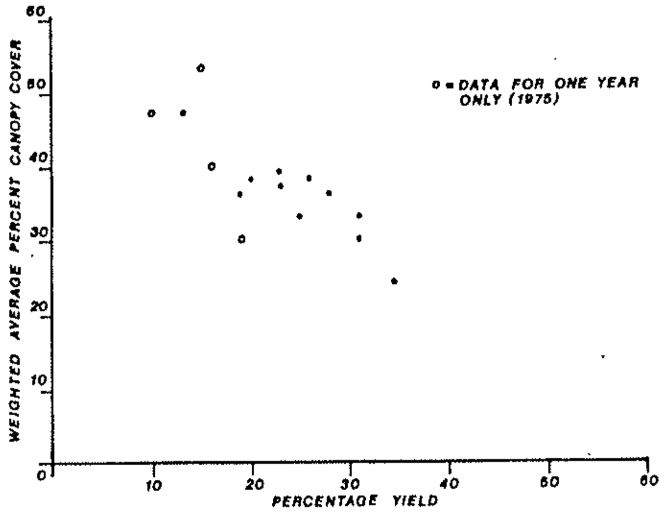


Figure 5: The relationship between weighted average percentage canopy cover and percentage yield for various catchments in the non-saline western zone of the northern jarrah forest. (After Shea et al, 1978).

Anderson et al (1976) believe that thinning will have only a transient influence on water yield because roots and canopies rapidly extend into unoccupied spaces, returning leaf areas and therefore evapotranspiration rates to prethinning levels. However, this may not be the case in the jarrah forest.

Results of crown measurements on thinning plots at Inglehope show that crown area in the heavily thinned plots is still less than in the lightly thinned plots, that is, crowns of trees in the heavily thinned plots have not grown to fill the gaps created in the forest canopy (See figure 6). The effect of thinning in reducing crown cover has persisted for at least 17 years, thus a similar effect on water yield may be expected. Although the crowns have not spread laterally to fill gaps created in the forest canopy, the density of crowns may have changed. Campbell (1966) reported that epicormics developed back along the branches towards the bole following thinning, and that trees in thinned stands had much denser crowns than those in unthinned stands. A measure of leaf area index (Carbon, Bartle, and Murray 1979) in the Inglehope plots would be useful.

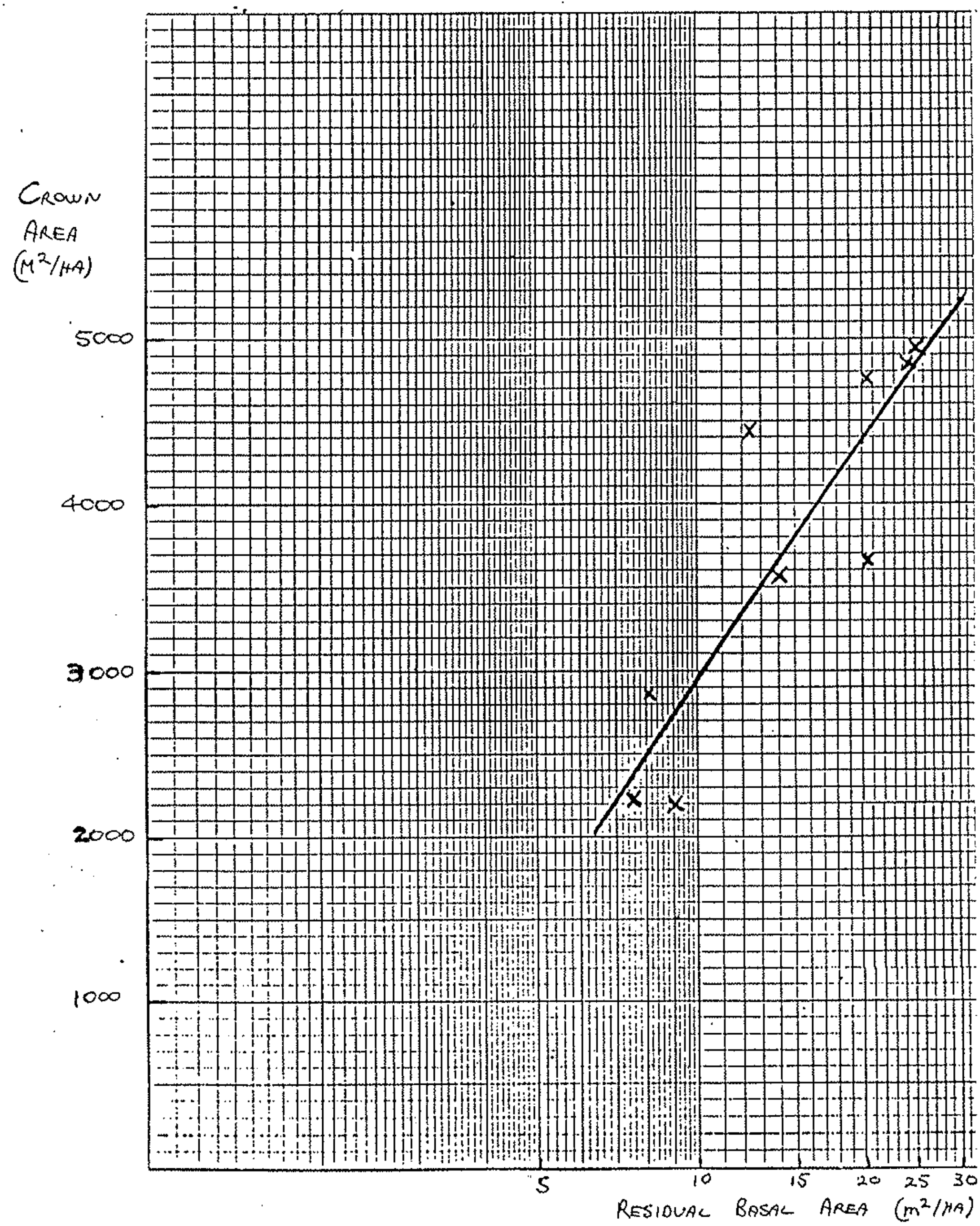


Figure 6: The effect of thinning in reducing crown cover has persisted for at least 17 years, and so indicates that the effect of thinning on increasing water yield would last for at least this long.

## 8.1 Western High Rainfall Zone

Due to the low stream, soil and groundwater salinities and the high rainfall, the western zone of the northern jarrah forest is suitable for manipulation of the vegetation to gain optimum water production. It is quite probable that reduction in forest cover in most catchments will result in significant increases in water yield without major increases in stream salinity. Ritson and Shea (1979) quote a figure of approximately 200,000 ha in which many of the catchments may be suitable for management to increase water yield.

Much of the forest in this western zone is or will be disturbed as a result of bauxite mining and/or jarrah dieback, caused by the Phytophthora cinnamomi fungus (Podger, 1972). Virtually the whole of this area is covered by Alcoa's mineral lease for the purpose of mining bauxite (Beggs, 1972). About 58% of this area is also in the category >20% infected by P.cinnamomi. (Forests Department, 1977c). In non-saline areas affected by dieback it may be better from a water yield point of view not to replant with trees but to allow a sparse woodland to develop. Selection of tree species and planting patterns which minimize water consumption should be possible in areas where rehabilitation is considered necessary. (Ritson and Shea, 1979). In non-saline areas which have been mined for bauxite, reforestation should be aimed at producing higher water yields than the original vegetation, yet avoiding erosion and turbidity of streams (Shea et al, 1978).

## 8.2 Intermediate Rainfall Zone

This area has a complicated pattern of soil, stream and groundwater salinities. Herbert, Shea and Hatch (1978) from a study of the Yarragil catchment in the intermediate zone postulated that a reduction in forest cover on areas where salt accumulation is low could result in an increased yield of high quality water. However, they advised that a reduction of forest cover on areas of high salt accumulation in this zone could result in a rise in stream salinity levels. Ritson and Shea (1980) concluded similarly, stressing that diverse management strategies should be applied to optimize the yield of high quality water and other forest values.

Ritson et al (1981) stressed the importance of analysis of groundwater salinities. Previously, base flow salinity was thought to be a reasonable measure of groundwater salinity, however this has not turned out to be the case. Some catchments have high groundwater salinity (determined from bore holes) yet their streams flow comparatively fresh all year round.

Baseflow salinity data is useful in that it is safe to assume that if the baseflow salinity of a stream draining a catchment is high then that catchment will include groundwater with a high salinity. However, it is not possible to confidently make statements about groundwater salinity if baseflow salinity is low.

## 8.3 Eastern Low Rainfall Zone

A reduction in forest cover in this zone would very likely result in unacceptable increases in stream salinity. The forest should therefore be left undisturbed for catchment protection purposes.

## 8.4 Cost-Benefit Analysis

Shea, Herbert and Edgecombe (1977) and Shea et al (1978) have estimated the costs and resultant benefits of a reduction in forest cover in appropriate areas. Reduction of canopy cover to 30% should result in a 10% increase in water yield. The costs associated with this were (1978) between 80 - $100 per hectare plus $20 per hectare per annum maintenance cost. A 10% increase in water yield in the 1300mm rainfall zone would result in an additional 1300m$^3$ per hectare. At 10 cents per cubic meter (which compares favourably with alternative sources of water for the metropolitan area, ranging from 15 - 50 cents per cubic meter), one hectare would return $130 per annum, thus covering the cost of the initial treatment in the first year. Similarly, in the 1000mm rainfall zone an additional 1000m$^3$ per hectare would result, a return of $100 per hectare per annum, again covering costs after the first year.

Increases in water yield may be near the maximum possible predicted by Hibbert (op. cit.) that is, even more than is assmed above. Analyses of his data shows that the impact of altering forest cover on water yield is greatest where evapotranspiration losses are highest. Jarrah has been shown to transpire actively, even during the summer drought (Grieve, 1956; Doley, op. cit.) and maximum evapotranspiration losses from fully forested catchments of the northern jarrah forest are in excess of 1100mm/year which is high by world standards. It is therefore reasonable to believe that water yield increases due to thinning jarrah forest should be near the maximum possible.

Bren (op. cit.) points out that the value of the additional water produced by such an exercise is not necessarily paid to the authority incurring the costs. Will the Metropolitan Water Board pay the Forests Department for additional water produced as a result of forest cover manipulation, or will the Forests Department need to finance the operation by making it a commercial thinning, or at least a non-commercial thinning which will substantially reduce rotation length?

## 9. The Potential to Increase Wood Yield.

The relationship between stand density and cubic volume production is a most important one, and one that has received a great deal of attention from foresters over the years.

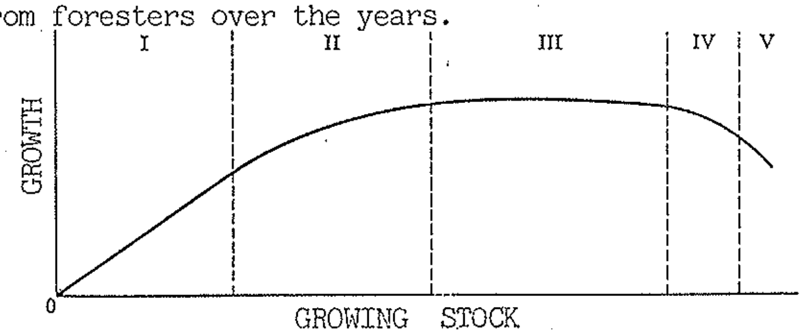


Figure 7: The relationship between density of stocking, measured in cubic volume, and growth in cubic volume. In Density Type I the trees stand so far apart that they do not influence each other and growth is directly proportional to the volume of growing stock. The effect of slight competition in Density Type II is indicated by a declining rate of increase in increment with respect to stand volume. In the broad range of stocking indicated by Density Type III, increment of cubic volume is virtually independent of variations in stocking; the usual objective of thinning is to keep the growing stock somewhere within this optimum range. In Density Types IV and V the effects of extreme competition are reflected in a decline in growth with increasing density. (After Smith, 1962).

Smith (ibid.) has made the following generalization - "The total production of cubic volume by a stand of given age and composition on a given site is, for all practical purpose, constant and optimum for a wide range of density of stocking. It can be decreased, but not increased, by altering the amount of growing stock to levels outside this range."

It would be very useful to know this relationship for a range of ages composition and sites for regrowth jarrah.

Unfortunately this is not the case. However, some work has been done in this direction and this will be reviewed.

Much of the early work concentrated on the effect of thinning on coppice, a problem resulting from the cutting over of virgin jarrah in the early days of sawmilling. Chandler (1939) reported that thinning had after 4 years failed in good quality forest to produce any effect on growth of the residual coppice shoots. In other areas he noted increased girth increment associated with thinning. Loneragan (1961) remeasured these thinning trials and found a response to thinning of up to 5cm diameter at breast height under bark after 23 years. Thinning to one stem per stump was more successful than to 2 stems per stump, and thinning proved to be progressively more effective as stump size increased from 3 - 10cm d.b.h.o.b..

Wallace and Podger (1959) reported that thinning of young saplings had proven to be a failure because of coppice development from thinned stumps quickly returning the stand to a condition of strong competition.

However, they also reported that thinning in stands of 15 - 18 metres (50-60 ft.) codominant height was successful. Coppice did develop from thinned stumps but did not re-enter the level of crown competition. Podger (1959) gives an account of the silvicultural history of the area and the establishment of these thinning plots at Mundlimup, near Jarrahdale. The thinning at age 53 reduced stem numbers from 309 to 175 per hectare, basal area from $20.7m^2$ to $13.1m^2$, and crown cover from 54% to 42%. Twenty eight years later the stands were in the following condition :

| | Age 1956 (years) | Mean Co-dom. Ht. (m) | Total u.b. vol ($m^3$/ha) | B.a.u.b. ($m^2$/ha) | vol u.b. >43.6 cm dbhob ($m^3$/ha) | vol.u.b. >58.2 cm dbhob ($m^3$/ha) | Bole Height (m) | Number of stems per hectare |
|---|---|---|---|---|---|---|---|---|
| Thinned 1928 | 81 | 27.7 | 188.7 | 24.2 | 157.3 | 72.1 | 13.4 | 190 |
| Unthinned | 81 | 27.7 | 213.4 | 30.4 | 80.5 | 30.1 | 14.6 | 464 |

Table 5: Effect of thinning 53 year old poles after 28 years at Mundlimup. (After Wallace and Podger, op. cit).

Wallace and Podger (op. cit.) stress that the differences in merchantable volume production is considerable. They also table figures for diameter growth of 20 codominant crop trees in each plot (See table 6) to which I have also added the mean annual increment for the period before and following thinning. Diameter growth can be seen to have increased substantially.

They concluded that a thinning just before the time of main crown division could produce a favourable distribution of increment without significant loss of volume.

| | Thinned 1928 | Unthinned |
|---|---|---|
| Mean d.b.h.o.b. (cm 1956 | 48.9 | 39.2 |
| M.A.I. before thinning 1875 - 1928 | 0.49 | |
| M.A.I. 1875 - 1956 | 0.61 | 0.49 |
| M.A.I. after thinning 1928 - 1956 | 0.81 | |

Table 6: The effect of thinning at Mundlimup on diameter increment. (After Wallace and Podger, op. cit.).

Hormone herbicides were first tested to control coppicing following thinning by Van Noort in 1960 (Campbell, op. cit.). Kimber improved on these early attempts and by 1964 had produced an efficient and relatively cheap means of killing unwanted trees and controlling unwanted coppice using hormone herbicides (especially 2, 4, 5 - T) (Kimber, 1967).

Campbell (op. cit.) reported that plots established by Sclater in 1962 in thinned and unthinned stands of 15 - 21m (50 - 70 ft) codominant height, were remeasured by Kimber in 1965. The Mean Tree Periodic Annual Increment for 3 years was reported as almost 0.24cm d.b.h.o.b. greater on the thinned than the unthinned plots. In 1964 the thinned plots ranged from a basal area over bark of 17.4 to 24.4$m^2$ per hectare, and the unthinned plots from 26.1 to 45.2$m^2$ per hectare.

Airey (1964), from a stem analysis study, found increased growth rates following the Dwellingup fire in both thinned and unthinned samples. The effect of fire and thinning was cumulative and so he concluded that thinning alone would produce a growth response.

2, 4, 5, T proved successful in thinning coppice areas where previous work by Chandler (op. cit.) had little success. Hewett (1965) reports a diameter growth response of up to 6 times the growth of control coppice plots at Mundaring. Edwards (1965) describes further progress in this area.

Although a number of assumptions on growth rate and stocking were made by Kimber (1965), he came to the conclusion through economic analysis that it was more profitable to thin to waste if no market exists for small pole size material than to delay thinning till the operation could cover its own costs. Kimber (1967) estimated that the return on investment from thinning jarrah pole stands to concentrate growth on selected crop trees was 6% per annum.

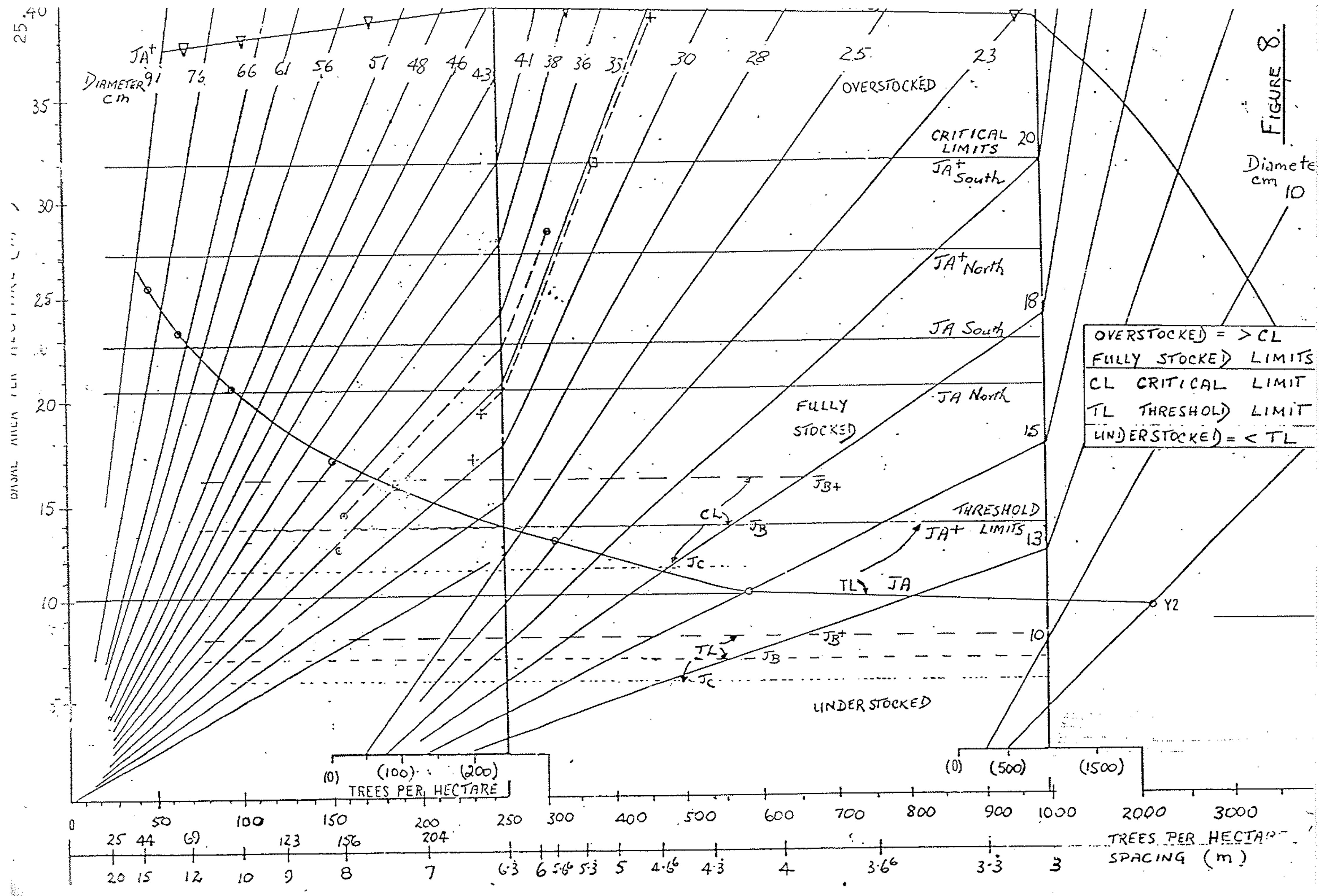
OVERSTOCKED
CRITICAL LIMITS
JA+ South
JA+ North
JA South
JA North
FULLY STOCKED
THRESHOLD LIMITS
JA+
JA
UNDERSTOCKED
Diameter cm
OVERSTOCKED = > CL
FULLY STOCKED LIMITS
CL CRITICAL LIMIT
TL THRESHOLD LIMIT
UNDERSTOCKED = < TL
TREES PER HECTARE
SPACING (m)
Y2

Figure 8.

Whilst at Dwellingup Research Kimber established a number of experiments which could yield valuable information of the type needed if regrowth jarrah forest is to be managed properly for wood production and/or water yield. The most notable of these is local experiment 13 which is designed to give information on thinning intensity and interval. A list of local experiments which may yield valuable information is given in Appendix 1.

Although it is a number of years since these experiments were set up remeasurements would be valuable, as tending operations in the jarrah forest could not realistically be expected to be on a much shorter cycle than the time elapsed between initial measurements and now.

Loneragan (1971) points out that most trees will respond to thinning at any age, but as age increases the response is not so readily obtained. For early thinning he recommends treatment at 7 to 11 years of age, this allows a short period of suppression to operate for selection of well-formed vigorous crop trees. Loneragan (ibid.) has produced a figure (see figure 8) which defines the threshold and critical (as well as other) stocking levels for a range of basal areas, stems sizes and spacings. He recommends maintaining stocking levels between the threshold density and the critically stocked density for maximum growth of saleable timber, although he does point out that Henry (1959) suggests the optimum treatment is one which sacrifices a small part of volume production in favour of increased development of the individual stems (that is, from Smith's (loc. cit.) Density Type III to Density Type II).

Preliminary analysis of data from local experiment 13 indicates the potential for increasing growth on selected crop trees by thinning. Figure 9 shows the relationship between residual basal area and diameter increment of the mean tree per plot over the period 1964-1977. It can be seen that bole diameter growth in high quality regrowth stands can be greatly enhanced by a reduction in stand basal area. Figure 10 indicates that basal area mean annual increment (M.A.I.) of the selected crop trees (assumed to be 285 of the best, well spaced stems per hectare) is also greatly enhanced by a heavy reduction in stand basal area. One of the most important effects of thinning is on time the residual stand takes to reach sawlog size. Figure 11 indicates that high quality 40 year old jarrah pole stands that are thinned to approximately 8m$^2$/ha will reach sawlog size (assumed to be 50cm d.b.h.o.b.) in a further 35 years. Those stands thinned to 26m$^2$/ha would be likely to take 170 further years to reach sawlog size if they keep growing at the same rate as from 1964-1977. The inherent bias associated with the use of mean tree per plot data should be noted. Remeasurement of this thinning trial to give more thorough data is planned for the near future.

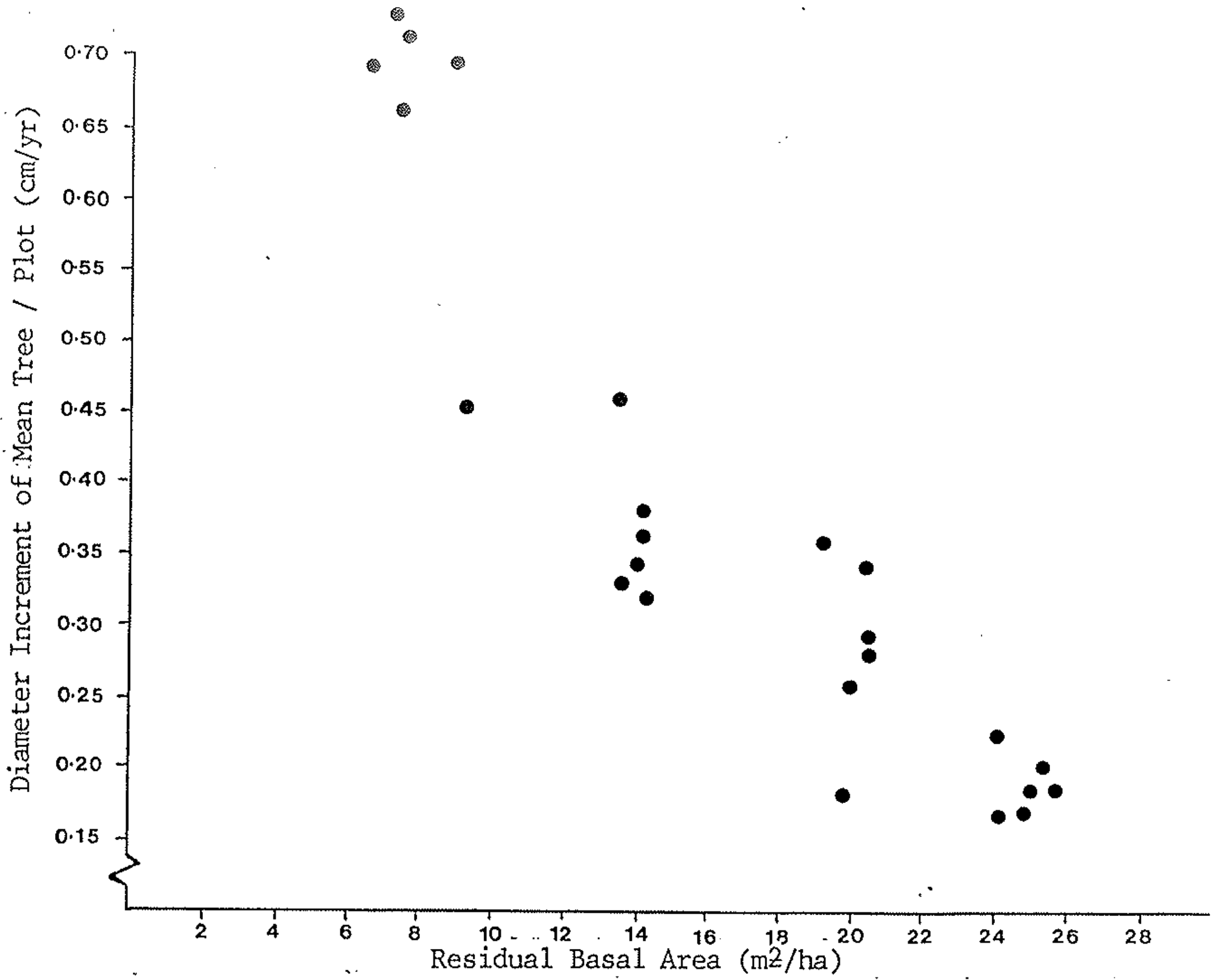


Figure 9: Effect of thinning on diameter increment at breast height.

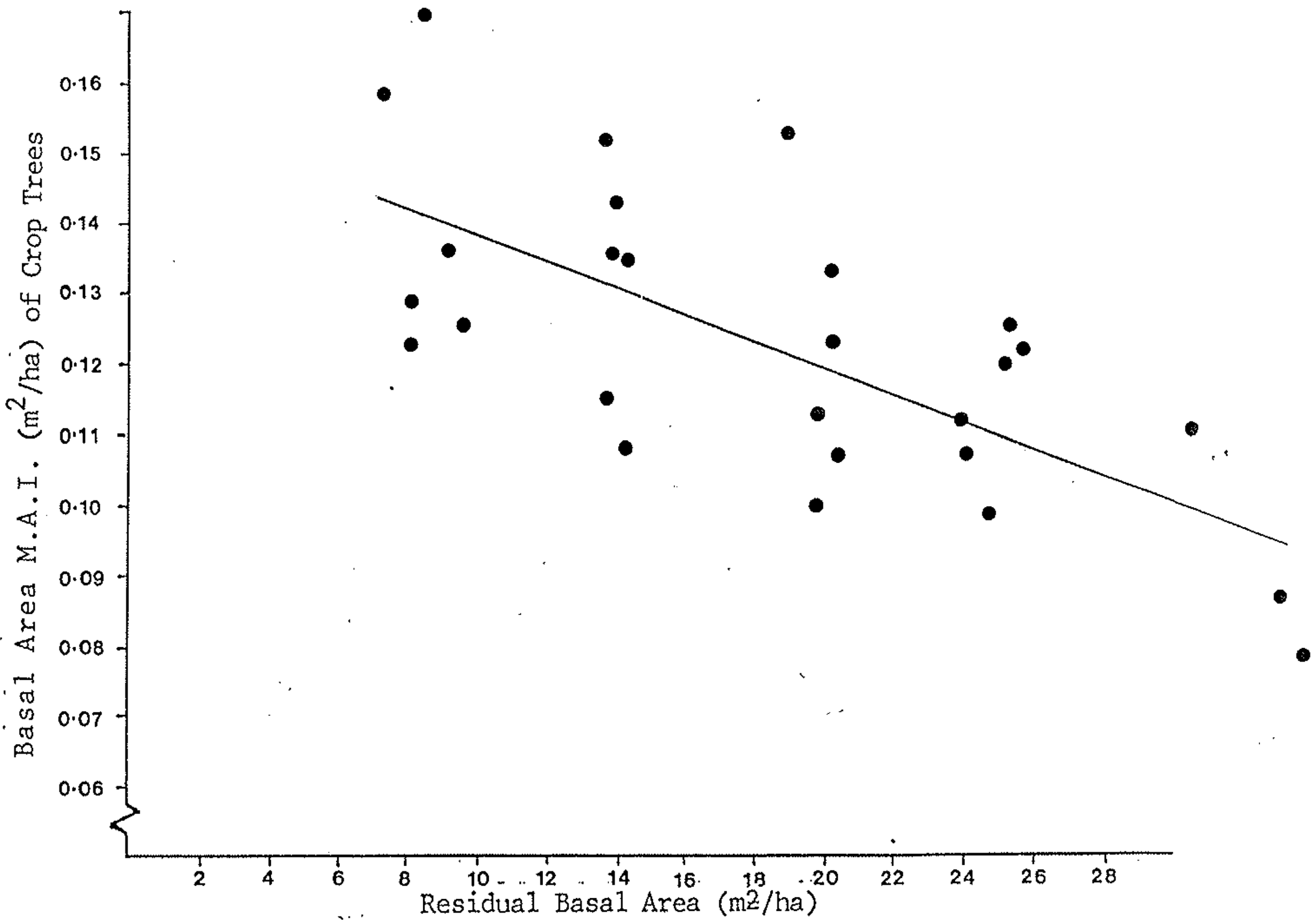


Figure 10: Effect of thinning on growth of crop trees.

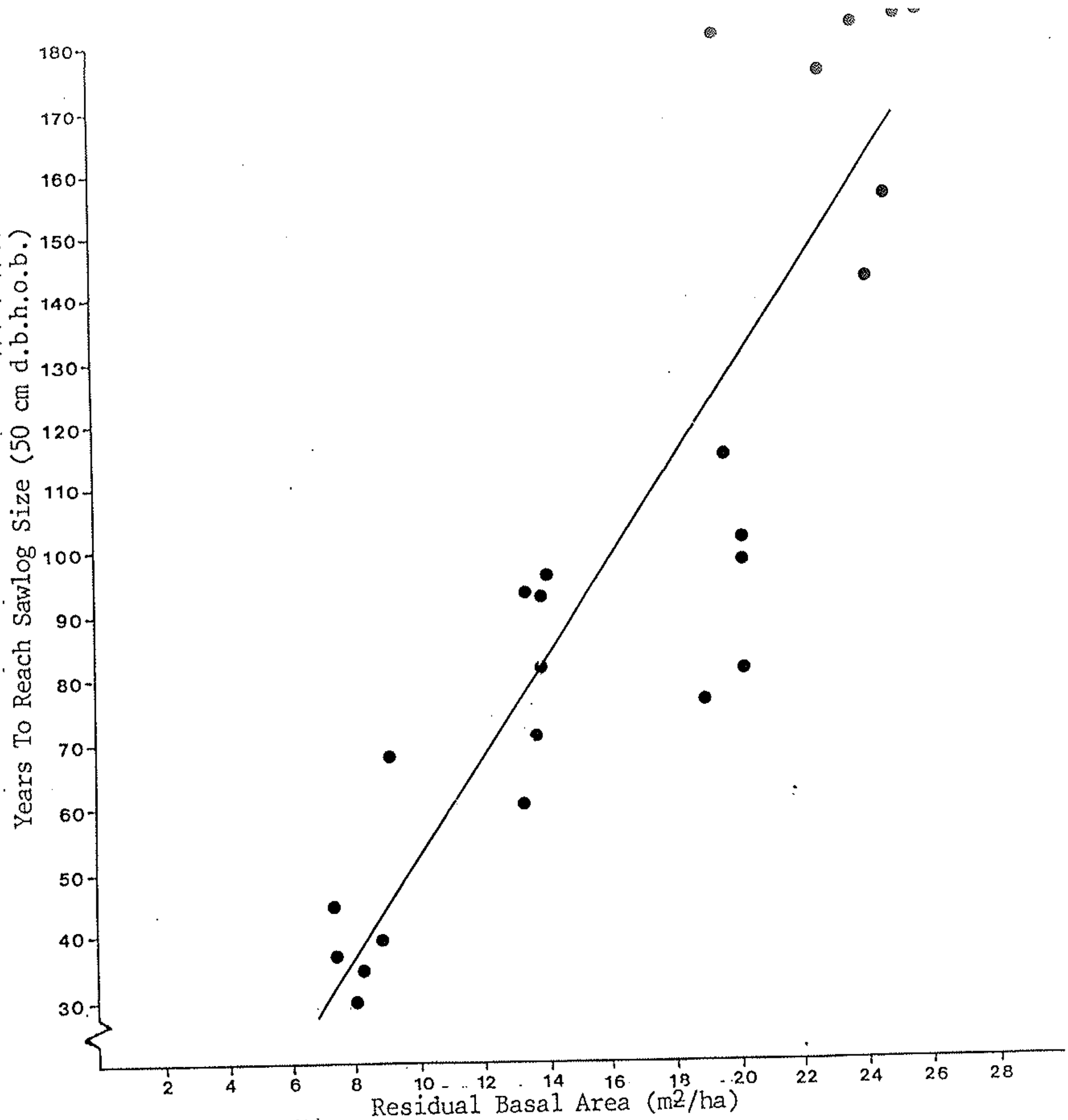


Figure 11: Effect of thinning on time taken to reach sawlog size for a 40 year old jarrah regrowth stand.

It should be emphasized that thinning of regrowth jarrah stands is not contemplated for the whole of the northern jarrah forest. Thinning for wood production purposes is only applicable on high quality sites; the response to thinning on less productive sites would not justify the cost involved in a thinning. Priorities for thinning should initially be on Havel (1975 a) site - vegetation types t ans s, where the response to thinning is likely to be greatest.

The decision of whether to thin or not to thin and when, has so far been discussed only in terms of growth responses. It must be emphasized that many other factors have a major bearing on this type of silvicultural decision. Florence (1978) discusses how factors such as the condition of existing growing stock, ecological factors, environmental factors, technical efficiency, socio-economic factors and resource and market factors may affect the decision. These factors should all be given due consideration before a decision is made.

## 10. Compatibility of Wood and Water Production

Reinhart, Eschner and Trimble (1963) examined the effects of a number of forest practices on both wood and water production. They point out that compromises can be found so that catchments are managed for increased yields of both forest products. Rich (op cit.) agrees, he found that even-aged management of ponderosa pine in the Rocky Mountains, U.S.A., improved wood and water production without harming water quality, wildlife and scenic values. Lawson (1975 abstracted in Dissertation Abstracts International 1975 Vol.36(4) ) also found that wood and water yield could both be increased by treatment of the forest. Cornish and MacKay (1981) also believe that water and timber production are compatible, even though forest operations are likely to increase the possibility of water quality degradation, sediment production and soil erosion. They believe the successful implementation of the correct procedures will overcome these problems.

Whilst water and wood production may be compatible this does not mean that both can be maximized at any one time from a given catchment. Hoffman (1968 abstracted in Forestry Abstracts 1969, Vol. 30 (2), 219) found that maximum water yield is incompatible with maximum timber production (by volume or value), and that maximum streamflow could not be gained by forestry measures.

Forest treatments should not expect to be able to maximize both of these forest products, but in applicable areas it should aim to maximize the overall value of both products. Langford and O'Shaughnessy (1980b) have demonstrated that a compromise is needed to maximize the net benefit from an area managed for both wood and water production. Figure 12 illustrates a hypothetical situation where overall value can be maximized. The water value curve shows that water value increases as stocking density decreases up to a point, but past that point any increases in water yield will be offset by a loss in value due to sedimentation, erosion or water quality degradation. In south-western Australia increasing stream salinity is the most likely parameter to cause this loss in water value following too heavy a reduction in canopy cover. The wood value curve is similar to the curve for wood volume production shown in the last section (from Smith, loc. cit.) except value will peak probably slightly before Density Type III and fall more rapidly.

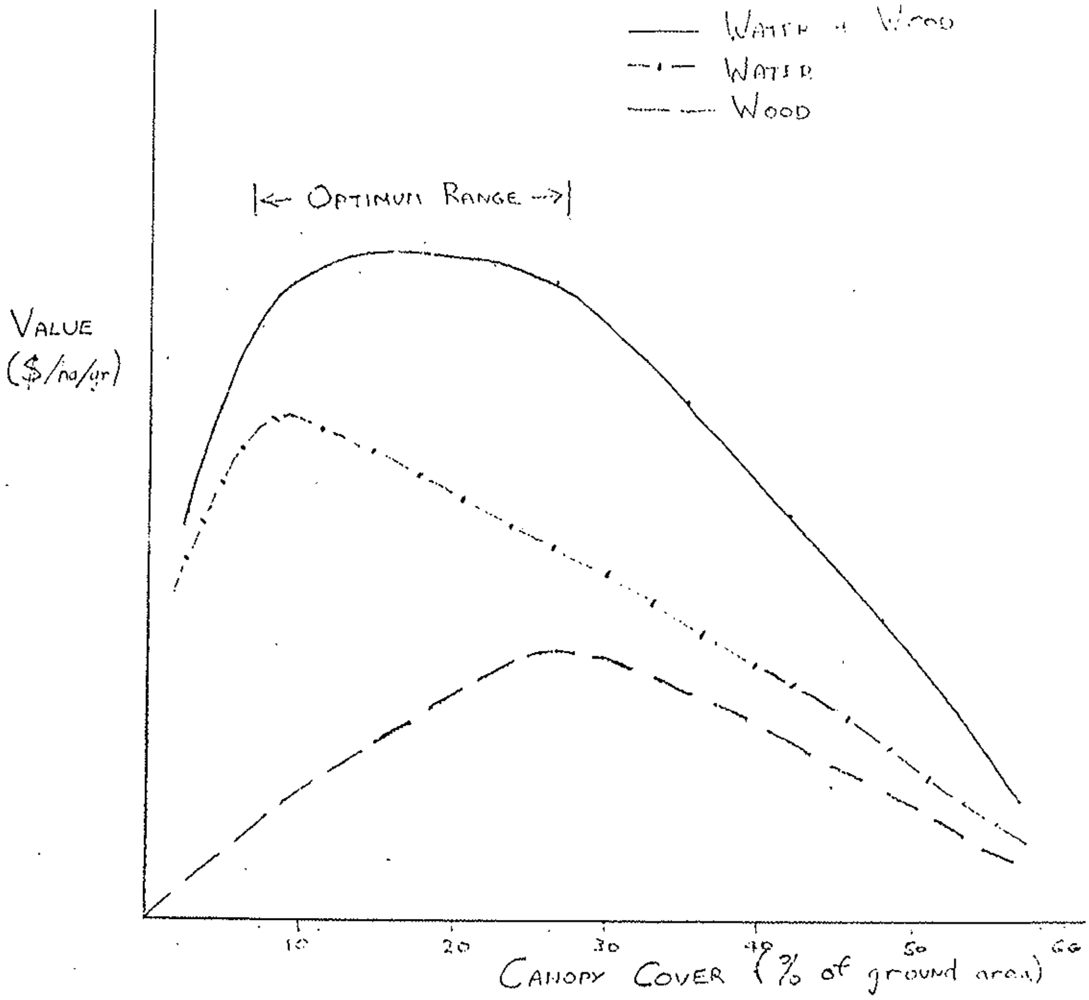


Figure 12: Relationship between wood and water value production and stocking density or crown cover. (After Ritson, unpublished undated report).

Loneragan (1971) believes that a reduction in crown cover for small trees to 20 percent is unlikely to reduce the stand to less than the threshold limit. A reduction in crown cover to 20 percent is what we will be trying to achieve in the 'best bet' treatment of the Yarragil 4L subcatchment, so we can expect wood production to be sacrificed very little in this treatment. The reduction in canopy cover will be achieved not only by thinning of the overstorey, but also by pushing over of the Banksia grandis component of the understorey. This will make conditions less favourable for growth of P.cinnamomi, as will the tops disposal burn encouraging germination of Acacia species which have the capacity to fix atmospheric nitrogen and in some cases are antagonistic to P.cinnamomi (Shea , 1979).

## 11. Future Research

Thinning of the regrowth jarrah forest is dependent upon the movement of machinery for many of the operations involved. The movement of this machinery has been shown in the past to have resulted in the spread of jarrah dieback. The question - Can forest operations be carried out in the jarrah forest without spread of P.cinnamomi ? - has not yet been answered in the positive. It would seem unwise at this stage then to go into those stands that would have the highest priority for thinning, that is the best quality most vigorous of the regrowth stands, whilst the possibility that any benefit that a thinning may do for timber production may be offset by the spread of dieback.

The key to the future success of logging, if dieback is not to be spread, lies in careful planning and intensive supervision by forest officers as McKinnell (1981) has suggested, plus future advances made by research into the disease, and most importantly education of those involved in the field operation.

Analysis of data to be collected from local experiment 13 will allow us to quantify the effects of a range of thinning intensities of wood production of a high quality stand. Data from the Yarragil catchment will quantify the effect of thinning on water production. With these inputs it should be possible to produce a model which incorporates allowances for many variables of site such that when these are put into the model, it will output the desirable stocking so that production of these two forest values is optimized. It may be possible to also include in the model the ability to decide on the economic wisdom of the optimum treatment in each case.

## 12. Summary

The water resources of the Metropolitan Zone available to supply the growing needs of the city of Perth will soon be fully taxed. Alternative sources will need to be utilized, one of these is increasing the water production from present metropolitan catchments. This is feasible over large areas of the northern jarrah forest, where the likelihood of increasing stream salinity by a reduction in forest cover is limited.

The demand for wood from this forest can be expected to increase beyond its capacity to supply. However, there is also scope to increase the production of timber by a reduction in forest cover. In appropriate areas forest management should aim to optimize the overall value of both these forest products.

## 13. Bibliography

Adams, G.M. (1977). Perth Metropolitan water supply

Airey, G.L. (1964). Reports on two research projects 1. A study of operators and of bark gauges in measuring jarrah bark thickness. 2. Response to thinning and treatment of jarrah poles. Thesis submitted for the Degree of B.Sc. (Forestry) University of Western Australia.

Anderson, H.W. (1954). Suspended sediment discharge as related to streamflow, topography, soil and land-use. Amer. Geophys. Union Trans. 35, 687-699.

Anderson, H.W. Hoover, M.D. and Reinhart, K.G. (1976). Forests and water: effect of forest management on floods, sedimentation and water supply. USDA Forest Service General Technical Report PSW - 18/1976.

Bates, C.G. and Henry, A.J. (1928). Forest and streamflow experiment at Wagon Wheel Gap, Colo. USDA Weather Bureau Monthly Weather Review, Supplement No. 30. 79pp.

Batini, F.E., Selkirk, A.B. and Hatch, A.B. (1976). Salt content of soil profiles in the Helena catchment, Western Australia. Forests Department of Western Australia Research Paper No. 23.

Batini, F.E., Black, R.E., Byrne, J. and Clifford, P.J. (1980). An examination of the effects of changes in catchment conditions on water yield in the Wungong Catchment, Western Australia. Aust. For. Res., 10, 29 - 38.

Beggs, B.J. (1972). Forestry and water catchments in relation to mining activities. "Conservation and Mining" Australian Conservation Foundation. Special publication No. 8, 41-48.

Bettenay, E. and McKinnell, F.H. (1980). The physical and biological environment of the Darling Range. UNESCO MAB program. Exploratory workshop on land use and stream salinity management in south-west of Western Australia. 6 - 28.

Boughton, W.C. (1970). Effects of land management on quantity and quality of available water: a review. Australian Water Resources Council Research Project 68/2, Report No. 120.

Bren, L.J. (1977). Water use in forests. Victoria's Resources, 11-18.

Campbell, F.J. (1966). The development of thinning in jarrah regrowth forest. Report submitted to the University of Western Australia to complete the requirements for the Degree of Science in Forestry.

Carbon, B.A., Bartle, G.A. and Murray, A.M. (1979). A method for visual estimation of leaf area. Forest Science, Vol. 25 (1), 53-58.

Chandler, W.G. (1939). Thinning experiments in jarrah coppice. (Eucalyptus marginata). Australian Forestry, Vol. 4(2), 69-78.

Chubatyi, O.V. (1980). [The effect of forest, and of felling it, on the water balance of catchments, as exemplified by the Carpothians]. Lesnovedenic 2, 59-67. Abstracted in Forestry Abstracts (1981) 42(4) No. 1463.

Cornish, P. and MacKay, S. (1981). The production of water and timber- are they compatible ? Australian Forest Industries Journal, April 1981, 26 - 29.

Dimmock, G.M., Bettenay, E. and Mulcahy, M.J. (1974). Salt content of lateritic profiles in the Darling Range, Western Australia. Australian Journal of Soil Res., 12, 63 - 69.

Doley, D. (1967). Water relations of Eucalyptus marginata Sm. under natural conditions. Ecology 55: 597-614.

Douglas, J.E. (1967). Effect of species and arrangement of forests on evapotranspiration. "Internation Symposium on Forest Hydrology" eds. Sopper W.E. and Lull H.W. Pergamon Press. 451-460.

Douglas, J.E. and Swank, W.T. (1975). Effects of management practices on water quality and quantity. USDA Forest Service General Technical Report NE - 13.

Edwards, C.J. (1965). Thinning jarrah coppice pole stands - Mundaring, and Coppice emergence study Mundaring. Report submitted to complete the requirements for a Degree of Bachelor of Science (Forestry) University of W.A.

Florence, R.G. (1978). The silvicultural decision. Forest Ecology and Management, 1, 293-306.

Forests Department (1977 a) General Working plan No 86 of 1977. Part 1.

Forests Department (1977b). Submission to industries assistance commission.

Forests Department. (1977 c). A perspective for multiple use planning in the northern jarrah forest. Forests Department of Western Australia, Perth. 55pp.

Forests Department Western Australia (1980). Land use management plan. Northern jarrah forest management priority areas.

Gilmore, D.A. (1971). The effects of logging on streamflow and sedimentation in a North Queensland rainforest catchment. Comm. For. Rev. 50, 38-48.

Grieve, B.J. (1955). Studies in the water relations of plants. I- Transpiration of Western Australia (Swan Polain) Sclerophylls. Journal of the Royal Society of Western Australia, Vol. 40, 15 - 30.

Hart, B.T. (1974). A compilation of Australian water quality criteria. Australian Water Resources Council Technical Paper No. 7.

Havel, J.J. (1975 a). Site - vegetation mapping in the northern jarrah forest (Darling Range) 1. Definition of site - vegetation types. Forests Department of Western Australia Bulletin 86.

Havel, J.J. (1975 b). The effects of water supply for the city of Perth, Western Australia, on other forms of land use. Landscape Planning, 2, 75-132.

Henry, W.B. (1959). The effect of silvicultural treatment on the production from native forests. Qld. For. Ser. Res. Report Aust. For. Conference.

Herbert, E.J. Shea, S.R. and Hatch, A.B. (1978). Salt content of lateritic profiles in the Yarragil catchment, Western Australia. For. Dept. W. Australia. Res. Pap. 32.

Hewett, P.N. (1965). Pole thinning in northern jarrah forest. Forest Notes, Vol. 3 (3), p 20.

Hibbert, A.R. (1967) . Forest treatment effects on water yield. "International Symposium on Forest Hydrology" (eds.) Sopper, W.E. and Lull, Pergamon Press. 527-544.

Hoffman, D. (1968). [The water regime of forest soils - can water yield be influenced ?] Forst - u. Holzur. Vol 23 (18), 370-3. Abstracted in Forestry Abstracts 1969, Vol. 30(2). 219, 1794

Humphreys, F.R. and Craig, F.G. (1981). Effects of fire on soil chemical, structural and hydrological properties. In "Fire and the Australia biota" Gill, A.M., Groves, R.H. and Noble, I.R. (Eds). Australian Academy of Science, Canberra.

Jutsen, J.T. (1950). The physiography of Western Australia 3rd Ed. Bull. Geol. Surv. West. Aust. 95.

Kimber, P.C. (1965). The economics of thinning jarrah pole stands. Forest Notes, Vol. 3 (1), 16 - 20.

Kimber, P.C. (1967). Thinning jarrah with hormone herbicides. Aust. Forestry. Vol. 31(2). 128-136.

Kimber, P.C. (1974). The root system of Jarrah (Eucalyptus marginata Sm) Forests Department of Western Australia Research Paper 10 .

Kriek, P.N. and O'Shaughnessy, P.J. (1974). Some initial effects on water quantity and quality of an experimental roading and timber harvesting operation in a Victorian mountain catchment. Report No MMBW-W-0002.

Langford, K.J. and O'Shaughnessy, P.J. (1977a) (Eds) First progress report - North Maroondah. Report No. MMBW - W -0005.

Langford, K.J. and O'Shaughnessy, P.J. (1977b). Some effects of forest change on water values. Aust. For. Vol. 40 (3). 192-218.

Langford, K.J. and O'Shaughnessy, P.J. (Eds) (1980a) Second progress report - Coranderk. Report No. MMBW - W - 0010.

Langford, K.J. and O'Shaughnessy, P.J. (Eds.) (1980b). A case study of Maroondah catchment. Melbourne and Metropolitan Board of Works Report No MMBW _ W - 0011.

Lawson, E.R. (1975). Effects of partial and complete vegetation removal on soil water, runoff and tree growth in the Ouachita Mountains of Arkansas. Ph.D. Thesis Colorado State University. Abstracted in Dessertation Abstracts International 36(4), 1528-B.

Lawson, E.R. (1976). 2,4,5,T residues in storm runoff from small watersheds. Journal of Soil and Water Conservation. 31(5). 217-219.

Likens, G.E., Bormann, F.H. Johnson, N.M., Fisher, D.W. and Pierce, R.S. (1970) Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed ecosystem. Ecol. Monographs, Vol. 40, 23 .

Loneragan, O.W. (1961). Jarrah (Eucalyptus marginata) and Karri (Eucalyptus diversicolor) regeneration in south-west Western Australia. Thesis submitted to the University of Western Australia as part of requirements for the Degree of Master of Science in Forestry.

Loneragan, O.W. (1971). Second growth jarrah (Eucalyptus marginata Sm). Forests Department of Western Australia.

Malcolm, C.V. and Stoneman, T.C. (1976). Salt encroachment - the 1974 saltland survey. W.A. Journal of Agriculture. June 1976.

McArthur , A.G. (1964). Streamflow characteristics of forested catchments. Aust. Forestry, 28 (2). 106-118.

McArthur, W.M. Churchward, H.M. and Hick, P.T. (1977). Landforms and soils of the Murray River catchment area of Western Australia. CSIRO Division of Land Resources Management. Land Resources Management Series No. 3.

Melbourne and Metropolitan Board of Works (1980). Summary of technical conclusion to 1979. Report No. MMBW - W -0012.

Metropolitan Water Board (1978). Harvesting underground water. Metropolitan Water Supply, Sewerage and Drainage Board, Perth 55pp.

Metropolitan Water Supply Sewerage and Drainage Board (1974) Future Water Resources. Perth, Western Australia.

Metropolitan Water Supply Sewerage and Drainage Board (1980). Annual report. Perth, Western Australia.

McKinnell, F.H. (1981). Review of the dieback disease situation 1981. Forests Department of Western Australia Technical Paper No. 21.

Mulcahy, M.J. (1981). Soil resources and land use in south-western Australia. Journal of the Royal Society of Western Australia, Vol. 64 (3), 69-77.

Mulcahy, M.J., Churchward, H.M. and Dimmock, G.M. (1972). Landforms and soils on an uplifted peneplain in the Darling Range, Western Australia. Australian Journal of Soil Research, 10, 1-14.

O'Shaughnessy, P.J., Moran, R.J. and Flinn, D.W. (Eds). (1981). The Crotty Creek project: The effects of strip thinning Eucalyptus regnans on water yield. First progress Report - Pre-treatment Phase. Melbourne and Metropolitan Board of Works Report No. MMBW-W - 0013. Forests Commission Victoria Miscellaneous Publication No. 9.

Packer, P.E. (1967). Forest treatment effects on water quality. "International Symposium on Forest Hydrology" (eds.) Sopper W.E. and Lull, H.W.. Pergamon Press. 687-700.

Peck, A.J. and Hurle , D.H. (1972). Chloride balance of some farmed and forested catchments in South - western Australia. Water resources research 9: 648-657.

Peck, A.J. and Bettenay, E. (1976). Hydrologic and geomorphic background to problems of land management and water quality in the Darling Range. "Land Management and Water Quality" Department of Conservation and Environment.

Podger, F.D. (1959). Thinning in cut-over jarrah stands. With particular reference to a study of the effect of past thinning. Submitted as part of the requirements for the Degree B.Sc (For) in the University of Western Australia.

Podger, F.D. (1972). Phytophthora cinnamomi a cause of lethal disease in indigenous plant communities in Western Australia. Phytopath. 62 (9), 972-81.

Public Works Department W.A. (1977). Water resources in system 6. Submitted to the System 6 Committee May 1977.

Public Works Department Western Australia (1979). Clearing and stream salinity in the south-west of Western Australia. Document No. MDS 1/79.

Reigner, I.C., Sopper, W.E. and Johnson, R.R. (1968). Will the use of 2, 4, 5, T to control streamside vegetation contaminate public water supplies? Journal of Forestry, 66, 914-918.

Reinhart, K.G., and Eschner, A.R. (1962). Effects on streamflow of four different forest practices in the Allegheny mountains. J. Geophys. Res. 67, 2433-2445.

Reinhart, K.G. Eschner, A.R. and Trimble, G.R. (1963). Effect on streamflow of four forest practices in the mountains of West Virginia: U.S. Forest Service Research Paper NE-1.

Ritson, P. and Shea, S.R. (1979). Increasing water yield. "Water Resources and Land Management Issues in the Darling Range" September 1979. 2.1

Ritson, P. and Shea, S.R. (1980). Water and salt cycles across a forested catchment. "Land and Stream Salinity Seminar" Western Australia, November, 1980, 21.2 - 21.4

Ritson, P., Herbert, E.J. and Shea, S.R. (1981). Groundwater Hydrology Studies in the Yarragil Catchment, Western Australia. Forests Department of Western Australia Research Paper 66.

Rich, L.R. (1972). Managing a ponderosa pine forest to increase water yield. Water Resources Research. 8, 422-428.

Rothacher, J. (1970). Increases in water yield following clear-cut logging in the Pacific North-West. Water Resources Research 6, 653.

Sadler, B.S. (1975). Water supply resources and demands in the south-west region. Paper presented at "Water requirements for agriculture, industry and urban supply for a metrpolis of two million in the south-west of W.A.". Proceeding of the symposium jointly organzed by the Aust Inst. of Agric. Science, W.A. Branch and the Inst. of Engineers of Australia (W.A. Chapter) Hydrology Branch, Perth, W.A., 2-10

Sadler, B.S. and Field C.A.R. (1976). Population and water needs. In "Groundwater resources of the Swan Coastal Plain" Carbon (ed). 37-60.

Senate Standing Committee on Trade and Commerce: (1981) Australia's Forestry and Forest Products Industries. Aust. Government Publishing Service. Canberra. 132pp

Shea, S.R. (1979). Forest management and Phytophthora cinnamomi in Aust. From "Phytophthora and Forest Management in Aust" Old, K.M. (Ed) 73-100.

Shea, S.R. and Hopkins, E.R. (1973). Environmental factors in relation to distribution, intensity and control of Jarrah Dieback. A paper presented to the 45th ANZAAS congress , August, 1973.

Shea, S.R., Hatch, A.B., Havel, J.J. and Ritson, P. (1975). The effect of changes in forest structure and composition on water quality and yield from the northern jarrah forest. "Managing Terrestrial Ecosystems" eds. Kikkawa, J. and Nix, H.A. Proc. Ecol. Soc. Aust. 9, 58-73.

Shea, S.R. Herbert, E.J. and Edgecombe, W.B. (1977). Potential to increase water yield in the northern jarrah forest of Western Australia. Australian Salinity Newsletter, No. 5, 80-81.

Shea, S.R. Herbert, E.J. and Bartle, J.R. (1978). An ecological approach to the active management of jarrah forest catchments in the south-west of Western Australia. Proceedings Hydrology Symposium, Canberra 1978, The Inst. of Engineers, Australia. 155-162.

Smith, D.M. (1962). The practice of silviculture Seventh Edition. John Wiley and Sons. 578 pp.

Sopper W.E. (1975). Effects of timber harvesting and related management practices on water quality in forested watersheds. J. Environ. Management Vol. 4(1), 24-29.

Swift, L.W. and Baker, S.E. (1973). Lower water temperatures within a streamside buffer strip. USDA Forest Servide Res. Note. S.E. - 193.

Urie, D.H. (1971). Estimated ground water yield following strip cutting in pine plantations. Water Resources Res., Vol. 7(6). 1497-1510.

Wallace, W.R. and Podger, F.D. (1959). Thinning in second growth jarrah stands. Paper delivered to section K, A.N.Z.A.A.S. Congress, Perth, 1959.

Wallis, J.R. and Willen D.W. (1963). Variation in dispersion ratio, surface aggregation ratio, and texture of some California surface soils as related to soil - forming factors. Intern. Assoc. Sci. Hydrol. 8(4), 48-58.

Ward, D. (1977). Tree removal and salinity in Helena catchment, Western Australia. For. Dept. West. Aust. Res. Pap. 29 .

Wood, W.E. (1924). Increase of salt in soil and streams following the destruction of the native vegetation. Journal of the oyal Society of Western Australia, 10, 35-47.

Appendix 1.

| Local Experiment No | Research Working Plan | TITLE |
|---|---|---|
| 13 | 12/65 | 40 year old jarrah pole thinning Inglehope. |
| 72 | 15/66 | Thinning 12 year old jarrah poles |
| 61 | 57/65 & 58/65 | Jarrah pole growth rates-thinned and unthinned stands |
| 12 | | Thinning jarrah poles- Curara |
| 65 | 49/65 | Pile growth rates and even-aged stocking |
| 53 | 17/65 | Jarrah silvicultural system trials |
| 126 | | Pile growth rates |
| 91 | | Relating stocking to jarrah increment |
| 20 | 12/64 & 49/66 | Thinning 3 year old jarrah coppice |

Dwellingup Research Local Experiments which may yield valuable silvicultural information.