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THE GREENHOUSE EFFECT AND WESTERN AUSTRALIAN FORESTS

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Introduction

There are two general environmental parameters that have a major bearing on patterns of distribution and growth in the forests of south-western Australia: climate and soils. Even small changes in these parameters can have a marked effect on forest ecology (e.g. Havel 1975a,b). In view of this, and considering the economic importance of these forests, it is important that the implications of any possible climate change associated with the so called greenhouse effect be thoroughly evaluated.

This paper was prepared specifically to identify areas of research that should be addressed so that future planning and management of forested lands can keep pace with any possible changes in climate. To develop this perspective, we first review information on the greenhouse effect and likely climate change scenarios for the forest region. We then examine the implications of these changes on the major tree species and highlight uncertainties leading to recommendations for future work.

The Greenhouse effect

Many natural phenomena influence the Earth's climate and cause it to change. Many of the changes are cyclical at periods ranging from a few years to about 260 million years and can be correlated with patterns of movement within the solar system (Harrington 1987, Frakes 1988, Chappell 1988). For example, there have been major periods of glaciation in the past 600 million years that can be related to the Milankovitch effect, the variations in orbital geometry.

Figure 1 shows reconstructions of rainfall/evaporation regimes for Australia at two periods of glacial activity in the past compared with present day patterns. Eighteen thousand years ago there was a period of maximum aridity which was associated with the last major glaciation. Prior to that, the Mungo maximum lacustral phase occurred when temperatures were warmer and the ice caps were of intermediate size (Bowler 1982, Broecker 1987).

Insert Figure 1 here

Although the magnitude of change during past episodes of climate change has been considerable, the rate of change, at least during the last 10,000 years (see Broecker 1987), has generally been slow. For example, mean temperatures in north eastern Queensland have declined by something in the order of 2°C since the hypsithermal period about 6,500-3,600 years ago (De Deckker et al. 1988). The global mean temperature has declined by about 1°C over the same period (Pittock 1990, pers. comm.). This represents a change at the rate of 1°C per 2-4,000 years. In human historical terms this change has been virtually imperceptible. Thus, much present-day human activity is based on an assumption that, while climatic variables oscillate around a mean value, the mean values will remain the same and the variability will be broadly predictable.

The overwhelming body of opinion among climatologists now is that the above assumption is no longer valid (Bolin et al. 1986). The changes predicted to occur as a result of anthropogenic greenhouse warming are virtually unprecedented in their rapidity, at least for the period of recorded human history. In the next fifty years, the mean ambient temperature on land is expected to increase by about 2.5°C; that is 1°C in twenty years (see later).

The changes in the Earth's climate may not occur in a smooth and gradual way. Evidence from recent investigations of arctic ice cores and Atlantic deep sea sediments suggests strongly that there have been in the past large reorganizations and jumps in atmospheric/oceanic systems which are apparently a result of climatic forcing (Figure 2). The timing and magnitude of these changes could not have been predicted on the basis of present understanding. Such events might include the reversal of one or more major oceanic currents, with immediate regional changes in temperature by as much as 6°C, and similarly abrupt changes to regional rainfall patterns (Broecker 1987).

Insert Figure 2 here

Figure 2 illustrates the dramatic switching that occurred around 10,000 years ago (the Younger Dryas) when, over a period of less than 1,000 years, the temperature in the North Atlantic plummeted by about 8°C and then rose again by approximately the same amount. Broecker (1987) argues that the possibility cannot be dismissed that the present rapid accumulation of greenhouse gases could act as a trigger for just such dramatic changes.

Hansen _et_ _al_. (1988) point out that changes to the frequency and intensity of extreme climatic events may pose greater threats to human societies and biological systems than simple changes in average temperature. They also argue that the temperature changes themselves, especially the increasing occurrence of extreme warm events, are likely to be large enough within the next thirty or so years to have major impacts on human societies and on the environment.

Climate is more than ambient temperature, but it is a useful generalization that patterns of weather and climate are driven by thermal gradients. Changes to the thermal gradients will have profound effects on all aspects of weather and climate including rainfall (seasonality, intensity and amount) because of changes to the patterns of movement of atmospheric pressure cells and ocean currents.

The theory behind the predictions of increases in ambient temperature is well established and is not in dispute (Bolin et al. 1986, Schneider 1989). The Earth's surface receives energy from the sun. Some of this solar radiation is reflected but much is absorbed at the surface causing warming. The warmed Earth's surface then emits energy as long wave radiation. Water vapour, CO_2 and other trace gases within the Earth's atmosphere are relatively opaque to this low energy radiation reflected or radiated from the Earth's surface; some of the energy is trapped and causes a warming of the lower atmosphere and so increases the temperature at which the Earth is held at equilibrium. This is the greenhouse effect.

This effect has long been recognized as a major reason for differences in temperature between various planets of the solar system (Schnieder 1988, Dickinson and Cicerone 1986). Without an atmosphere of radiation absorbing gases the Earth would be approximately 33°C colder than it is (Houghton 1977).

What has been in dispute until a few years ago was whether human activities, such as the clearing of forests and burning of fossil fuels, could so alter the levels of atmospheric carbon dioxide as to significantly increase the opacity of the atmosphere to low energy radiation and thus cause a significant additional warming of the Earth. Much of the dispute originates from uncertainty about the nature and extent of feedback effects, especially those involving the uptake by the ocean and living plants of carbon dioxide and heat energy, and the potential changes in incoming solar radiation and outgoing long-wavelength radiation resulting from increased cloudiness (Dickinson 1986, Lashof 1989, Schnieder 1989, Mitchell et al. 1989, Raval and Ramanathan 1989).

Research published in the last four years on the analysis of fossil air trapped in Greenland and Antarctic ice has provided clear evidence that the concentration of atmospheric CO_2 has increased from 285 ppmv or less in pre-industrial times to the present 350 ppmv (Figure 3) (Barnola et al. 1987, Friedli et al. 1986, Pearman et al. 1986).

Insert Figure 3 here

Further, there are now thirty years of data resulting from precise measurements of CO_2 in air over Antarctica and Hawaii. Similarly precise measurements conducted in Australia over the last eighteen years have confirmed the global picture that the concentration of carbon dioxide in the atmosphere is increasing at about 0.4% per year (Pearman 1988) (e.g. Figure 4).

Insert Figure 4 here.

The measurements of fossil air and the continuous monitoring of atmospheric gases have also established that, in addition to CO_2, a number of other trace gases capable of trapping infra-red radiation are accumulating in the atmosphere (Table 1) (Pearman 1988, Dickinson and Cicerone 1986). The more significant other greenhouse gases are methane (CH_4), tropospheric ozone, nitrous oxide (N_2O) and various chlorofluorocarbons (CFCs). Between them they are thought to provide about the same amount of capacity to trap heat as the predicted concentrations of CO_2, effectively doubling the potential for greenhouse warming created by the additional CO_2 alone (Ramanathan et al. 1985).

Insert Table 1 here

Some of the other trace gases, especially the CFCs, are particularly significant because they capture infra-red radiation at a wavelength that neither CO_2 nor water vapour do. That is, these minor greenhouse gases are acting to make more opaque the thermal window through which a large proportion of the earth's radiated heat escapes to space (Dickinson and Cicerone 1986, Schnieder 1989). Molecule for molecule these gases are more effective at trapping heat radiation than CO_2 (Bouma and Pearman 1989).

An increase in global mean temperatures in the range of 1.5 to 5.5°C within 50 to 100 years is widely accepted as a realistic prediction of the global response to the anticipated approximate doubling of the atmospheric concentration of greenhouse gasses. The prediction is based on physical and thermodynamic principles, not on observed changes (Bolin _et_ _al_. 1986).

Changes to the temperature regimes around the globe have been reported. However, there is still controversy as to the interpretation of actual measurements of temperature around the world over the last one hundred or so years.

In recent years various workers have shown that the Earth's global average temperature has increased by about 0.5°C in the last 134 years (Figure 5). This warming trend is shown by land based air temperatures, sea surface temperatures and night time marine air temperatures (Jones _et_ _al_. 1982, Jones, Raper and Wigley 1986; Jones, Wigley and Wright 1986, Folland _et_ _al_. 1984, Vort _et_ _al_. 1987). Although there is no evidence as to whether or not these observations are a consequence of the increased concentrations of greenhouse gases, they are in the direction and within the range predicted by many theoretical models (Jones, Wigley and Wright 1986).

Insert Figure 5 here

Further, measurements of atmospheric temperatures from 1950 to 1985 indicate a warming trend in the troposphere of 0.1 to 0.5°C per decade, with a trend of 0.2 to 0.8°C for the last twenty years of that period (Angell 1986, Karoly 1988; Flohn and Kapala 1989). These two authors have also shown that increases in tropospheric temperatures have been accompanied by decreases in temperature in the lower stratosphere. This pattern is consistent with predictions generated by most of the current general circulation models (GCMs) (e.g. Wetherald and Manabe 1986).

On the other hand, there is clear evidence that in some parts of the Northern Hemisphere annual mean temperatures decreased significantly at least between 1940 and 1965 (Wigley _et al_. 1986). Most climatologists interpret this as a transient regional effect (Schneider and Thomson 1981, Hansen _et al_. 1988) such as a large uptake of heat in the deep North Atlantic Ocean (Levitus 1989). Hansen _et al_. (1981) showed that the temperature decline was also compatible with increased levels of stratospheric dust resulting from recent volcanic activity in the Northern Hemisphere. Workers such as Jones and Hansen and their colleagues point to an apparent increase in Northern Hemisphere temperatures as a whole from 1965 to the present (Wigley _et al_. 1986, Jones 1988).

However, Watt (1987) suggests that the chilling of the Northern Hemisphere is still continuing (at least to 1983) and that much of the evidence for increasing temperatures in the Northern Hemisphere is biased by the inclusion of data from large towns and cities which exhibit a heat-island effect. Very recently, Jones, 1988; Jones _et al_. (in press) and Karl _et al_. (1988) have shown that, even after correcting for the heat-island effect, a global warming over land of about 0.4°C is still apparent over the last 100 years and that a downward trend in overall Northern Hemisphere temperatures is not continuing (although it is in some specific regions (Jones, 1988). These conclusions, based on measurements over land, are supported by temperature records taken from oceanic sites (e.g. Folland et al. 1984).

Temperatures in the tropics and Southern Hemisphere regions appear to have sustained a steady increase over the last century (Flohn and Kapala 1989; Jones 1985, Jones, Wigley and Wright 1986; Rupa Kumar et al. 1987), although again there are regions which have gone against the overall trend (Jones, 1988). Seven of the eight warmest years in the Southern Hemisphere since 1900 have occurred during the 1980s (Jones et al. 1988).

Jones et al. (1988) and Hansen et al. (1988) predict that a significant signal showing the global warming due to increasing greenhouse gases will be discernible within a few years. Hansen et al. (1988) further expect that during the 1990s a noticeable increase in the local frequency of warm events will be discernable to the general public in many parts of the world. One important signal has been identified by Flohn and Kapala (1989): increases in sea surface temperatures in tropical waters around the globe appear to be leading to the intensification of convective circulation patterns which positively reinforces the effects of the temperature increases themselves.

In summary, and despite some uncertainties resulting from regional variations in temperature, considerable agreement now exists among atmospheric scientists on the following major points:

(i) that, by about the year 2030, greenhouse gases are likely to have effectively doubled in atmospheric concentration when compared with pre-industrial levels;

(ii) that the prediction on theoretical grounds of resulting higher global temperatures is unlikely to be invalidated by feedback effects (although temperature rises may be buffered to some degree by feedback mechanisms and uptake of heat by the oceans);

(iii) that evidence of various changes to world temperature in the last one hundred, and more specifically, the last thirty, years is largely consistent with changes predicted on theoretical grounds from the build-up of greenhouse gases although the evidence does not yet constitute proof of those predictions; and

(iv) that, for all realistic scenarios of world economic and energy policies, concentrations of greenhouse gases are likely to continue increasing long past the middle of next century, and with them the Earth's temperature is likely to continue to increase.

There is also general agreement that a continuing increase in global average temperature within the anticipated range will have significant effects upon global and regional climatic patterns. However it is not yet possible to predict with confidence the nature of these effects, particularly those at the regional level. Other than temperature, rainfall is the factor most likely to be affected: the amount, seasonality and intensity. Wind patterns and ocean currents are also likely to change, as well as the distribution, frequency and severity of tropical cyclones. A general expectation is that extreme events will occur more frequently and be more intense in the same direction as any general change. Such changes in extreme events are likely to be of great significance to ecosystems, often acting as reset mechanisms and changing the whole direction of ecosystem development (e.g. Moore 1988 cf. Weatherhead 1986)

Despite the uncertainties of secondary changes resulting from greenhouse warming, the following global trends, based on physical and dynamical theory, are seen as being highly likely.

(i) The changes in temperature will not be uniform around the world. For an increase in global average temperature of 2.5°C, the increase at the equator may be as small as 1°C while at higher latitudes it could be 5° or 6°C or more (Pittock and Salinger, 1982).

(ii) Global mean precipitation is likely to increase. The range of estimates of this increase are between about 3% and 11% (Schlesinger and Mitchell 1987).

(iii) Increases in precipitation are likely to be more marked in tropical areas and in summer, with monsoonal weather patterns becoming more intense and possibly more widespread.

(iv) Some areas of the world in mid latitudes are likely to receive less winter rainfall due to changes in position of high pressure cells.

(v) Sea level around the world is likely to rise as a consequence of thermal expansion of the ocean water bodies.

Forests and CO_2

Before the evolution of life on Earth, the atmosphere was high in CO_2 (perhaps about 1%) and lacking in free oxygen. As photosynthetic plants evolved and became larger and more abundant, more and more CO_2 was removed from the atmosphere and the carbon stored in the living tissue of plants (and eventually animals) and in detritus, sediments and fossil fuels. In this process oxygen was released by vegetation so that it now represents 21% by volume of the atmosphere, while CO_2 has declined to 0.03%.

Table 2 illustrates the vast amount of carbon which has been extracted from the atmosphere by plants over evolutionary time, and stored away as sedimentary rocks or fossil fuels. Currently the amount of carbon stored in living terrestrial vegetation is thought to be about the same as the total mass of carbon in atmospheric CO_2 (Barson and Gifford 1989).

Carbon storage in standing forests is also significant, even though mature forests generally are in approximate balance in terms of CO_2 and O_2 use and release. The amount of CO_2 fixed is balanced in the long-term by respiration, decomposition and fire. Human use of timber from forests harvested on a sustainable yield basis should not change this long-term balance provided that the total carbon content of the regrowth forest at the end of each subsequent rotation is equal to that of the original forest and that a high proportion of the harvested timber goes into long-term storage i.e. wood used in structures and in furniture. Where the final yield (i.e. other than thinnings) is used for products that have a short half life such as paper pulp, packaging or pallets and posts then conversion of mature forests to regrowth forests will result in a nett loss of carbon into the atmosphere (Harman <u>et al</u>. 1990).

The long-term balance between CO_2 fixed and released by forests can, of course, be significantly changed by permanent removal of forests or by their expansion. Removal by clearing and burning releases CO_2 to the atmosphere as does the burning of fossil fuels. Pittock (personal communication 1989) has pointed out that the permanent clearing of about two thirds of Australia's tall forests is likely to have contributed at least as much CO_2 to the atmosphere since European settlement as the burning of fossil fuels over that time.

At a global level, deforestation over the last century is also thought to have contributed approximately the same cumulative total of CO_2 to the atmosphere as has the burning of fossil fuels (Gifford 1988a). Currently, the annual output of CO_2 from deforestation, thought to be between 1.0 and 2.6 x 10^{15} g of carbon, represents approximately 20-25% of that generated each year from the burning of fossil fuels (Houghton et al. 1987). However, Tans et al. (1990) note that the global carbon cycle is not well understood and, in particular, the amount of CO_2 released by changes in land use remains uncertain, as does the response of terrestrial ecosystems to higher CO_2 levels. In fact, their calculations suggest that terrestrial ecosystems represent an important link for CO_2, perhaps absorbing as much as one third to one half of the approximately 5.3 gigatonnes of CO_2 generated by the burning of fossil fuels each year.

Gifford (1988a) suggests that the CO_2 fertilizing effect of higher ambient concentrations of CO_2 will result in a more rapid uptake of CO_2 by living plants and that this will more or less balance the output from deforestation. This claim is contentious (e.g. Houghton et al. 1987; Woodwell et al. 1983), but in broad terms it is clear that deforestation contributes less than or about one quarter of the annual increase of atmospheric CO_2 currently, and that its long-term contribution to the greenhouse effect, while potentially very significant, is limited compared to that of the use of fossil fuels (Table 2).

On the other hand, the retention or expansion of forests could well play a part in slowing down the greenhouse effect (Woodwell et al. 1983), although even a massive global expansion of forests will only sequester CO_2 from the atmosphere for a long as the trees remain standing, or for as long as their products are stored (Barson and Gifford 1989, Harman et al.). Gifford (1988a) is pessimistic as to the effectiveness of vegetation management in ameliorating the greenhouse effect pointing out, correctly, that an eventual equilibrium is reached in old growth forests between new growth and decomposition. Nevertheless any increase in the area or productivity of the world's forests will store additional CO_2 and would cause that equilibrium to be established at a new (lower) level of atmospheric CO_2 than it would otherwise be. Such extra storage of CO_2 will help to "buy time", during which more permanent solutions, such as reducing the usage of fossil fuels, can be developed.

Australian Scenarios for Climate

Given the difficulties in establishing secondary effects, even at the global level, which might result from increased global temperature, and the immense natural variability in regional climatic factors, prediction of regional changes are bound to be tentative. Pittock and Salinger (1982) have used four separate forms of analyses in an attempt to provide a first assessment for Australia and New Zealand. The four methods involve (i) computer modelling of climate patterns using sophisticated general circulation models (GCMs), (ii) comparing subsets of historical climate data and looking for correlations between the various parameters, (iii) analysing palaeoclimate records to elucidate apparent links between temperature and other climatic parameters and (iv) developing arguments based on dynamic principles.

Although each one of the four approaches has serious limitations, it is of considerable interest that they all point in the same broad direction for changes in the Australian region. The following climate scenario for Australia to the year 2030 was developed by CSIRO ,Division of Atmospheric Physics prior to the Greenhouse 87 Conference (CSIRO 1988) and subsequently modified as more recent information has come to light (CSIRO 1990, IPCC 1990, Pittock, personal communication 1990). It represents an integration of results from all four approaches given above. The scenario should be regarded as indicative only of the likely changes to Australian climate patterns as a whole; there are still very considerable uncertainties attached to the process of predicting climate even at this scale (Pittock 1988a).

Temperature

A rise of 2 to 4°C in the annual mean temperature is predicted with the greatest warming in inland regions and in the dry season. Some regional variations in this general picture might be expected due to changes in cloudiness, air-sea temperature differences, etc. Oceanic temperatures might be expected to lag behind atmospheric temperatures by about 10-20 years (although this does not seem to be borne out by recent temperature trends which show greater warming at various mid-latitude coastal stations; Pittock, personal communication 1990).

Rainfall

Higher spring, summer and autumn rainfall by up to 50% in those regions deriving such rain from the southward penetration of tropical/subtropical air during the Australian monsoon season is expected. This change will be a maximum at the southern limits of the summer rainfall regime. Winters may in general be drier by 20% or more in those areas deriving such rain from the eastward passage of midlatitude high and low pressure systems and associated frontal storms with the possible exception of Tasmania and southern Victoria.

Sea level

An average rate of global mean sea level use of about 6 cm per decade (uncertainty range 3-10 cm per decade) over the next century is expected. This is due mainly to thermal expansion of oceans and melting of some land ice, to which must be added or subtracted any local tendency due to subsidence, uplift, etc. The predicted rise is about 20 cm on global mean sea level by 2030.

Tropical cyclones

There is great uncertainty about the response of tropical cyclones, especially at the regional level. However, the southern limit of tropical cyclones (determined by sea-surface temperatures >27°C) might shift some 200-400 km further south and the maximum intensity may increase. The frequency of occurrence of tropical cyclones in the Australian region is affected by the behaviour of the El Nino - Southern Oscillation system (ENSO), which is uncertain under enhanced greenhouse conditions (Holland et al. 1988).

Snow line

The snow line would on average rise by about 100m per 1°C warming; however, local variations related to changes in storm frequency and cloudiness may be significant.

Wind speeds

Wind speeds could decrease by 20% north of about 35°S, but might increase south of 35°S due to changing north-south temperature gradients.

Evapotranspiration

Evapotranspiration could decrease due to higher stomatal resistance at higher ambient CO_2 concentrations but generally greater leaf area may partially compensate.

To this scenario it is necessary to add that extreme events, especially of high temperature and high rainfall, are likely to become more frequent and to be of greater magnitude (Pittock, 1988a, 1989).

A Regional Scenario for South Western Australia

Much of the climate modelling work for Australia thus far has been focussed on the eastern part of the continent and the Pacific region. This is at least partly a reflection of the concentration of populations along Australia's east coast and consequent socio-political pressures. It also reflects a preoccupation with the ENSO system as the major driving force of climate patterns virtually Australia wide.

A third consideration when it comes to developing reliable predictions of likely climate changes in the south-west of Western Australia is the absence of scientific data on oceanic circulation patterns, particularly in the Indian Ocean region. As a consequence, climate modellers have tended to use a simple model of circulation patterns in this part of the world and regional predictions for the south-west cannot be regarded as highly reliable. For instance, it is known that the Leeuwin Current has an important influence on winter rainfall patterns in the region. If changes in circulation patterns in the Indian Ocean cause changes to the Leeuwin Current, winter rainfall in the south-west could decline by as much as 20% over and above any effect created by ENSO changes or by the southwards movement of high pressure cells (B. Hatcher personal communication 1988).

Notwithstanding the inadequacies of the present models in predicting changes to climate at a regional scale, some attempts have been made. Hille (1988) produced two scenarios for temperature and sea level for 2040 which could be described as probable (Scenario 1) and the upper limit (Scenario 2). Details of the two scenarios as they relate to the south-west are as follows:

Temperature

Under Scenario 1, mean summer temperature would increase by 1.2 to 1.5°C and mean winter temperature would increase by 1.8 to 2.1°C. Under Scenario 2, temperature increases would be 3.2 to 4.0°C for summer and 4.8 to 5.6°C for winter.

Sea level

Expected sea level rises to 2040 are 30 cm (Scenario 1) and 140 cm (Scenario 2).

Hille's two scenarios for temperature are in reasonable agreement with the range of possible outcomes for these parameters envisaged by the CSIRO (1988) scenario as subsequently modified (CSIRO 1990). However, Hill's scenario and sea level rises now appear too high (cf. CSIRO 1990, IPCC 1990).

Hille (1988) and CSIRO (1988, 1990) are in broad agreement as regards the following points.

Tropical cyclones

The predicted change is as already given above for Australia as a whole, namely that the southern limit of these cyclones could shift some 200-400 km further south.

Wind speeds

In the southern half of the State there is likely to be less wind in winter but more in summer associated with more constant easterly winds.

Extreme events

It is likely that the predicted climatic changes would result in an increasing incidence of extremes such as floods, droughts, maximum wind gusts and severe storms etc. Increased frequency of extreme rainfall events is likely to lead to flash flooding, crop damage and soil erosion.

Rainfall

Hille (1988) also presented two possible scenarios for precipitation in Western Australia in 2040 based on two quite different climatological models. The first of these assumes intensification of summer monsoon rainfall and a poleward shift of the westerlies and the winter rainfall belt. Hille's prediction under this scenario, of an increase in summer rainfall by up to 40% and a decrease in winter rainfall in the lower south-west by up to 20%, agrees closely with that made by CSIRO (1988) (see also CSIRO 1990).

Hille's second scenario for rainfall, which assumed an increase in the number of "cut off" lows reaching the south-west, predicted a small increase in winter rainfall in the south-west and an increase in summer rainfall by up to 40%. It also suggests a lower number of tropical cyclones, in contrast to his first scenario and CSIRO (1988) under both of which tropical cyclones would be expected to increase.

Neither of Hille's scenarios incorporates the likelihood of changes to oceanic circulation patterns and the impact of this on rainfall. Hille (personal communication, 1988) believes that the predicting of regional rainfall under greenhouse warming is highly uncertain and that his two rainfall scenarios are equally possible.

The above regional scenarios, like the global ones, are based on well established theoretical principles rather than on actual observations of change. It may be another decade before changes due to the greenhouse effect become marked enough to be unambiguously distinguished from normal climatic variability at a regional level. However, analysis of historical rainfall records by Pittock (1983) has shown a 10 - 20% reduction in winter rainfall in the south-west of W.A. for the period 1946 to 1978, compared with the period from 1913 to 1945. This observation is consistent with, but does not constitute evidence for, the prediction of the CSIRO scenario that rain-bearing winter fronts will reach and cross the coast into south-west W.A. less frequently. Broadridge (1988) presents data to support this view, but also points out that there are places within the south west (such as Busselton) which have gone against the trend, and that it is still too early to say that the present trend is any more than part of a normal climatic cycle.

For the purposes of discussing potential impacts of the greenhouse effect on the forests, we have chosen to use the Hille's rainfall Scenario 1, suggesting dryer conditions on the south west. This is closest to recent modelling results (e.g. CSIRO 1990). It is the worst case scenario but one that requires earliest attention from planning and managers.

Possible Implications of Climate Change for Western Australian Forests

Making reliable predictions of the effects of global change on local ecosystems is complicated by two major factors. Firstly, as noted previously, the predictions of climate change at the local and regional scale are themselves surrounded with considerable uncertainty. Secondly, knowledge of the likely responses of ecosystems to the types of change projected is very limited. It has been possible to test experimentally the short-term effects of changing some environmental parameters on individual organisms e.g. increased [CO_2] on crop plants (Gifford 1988b). However, there are real problems in scaling up results from this kind of experiment from the laboratory to the field and to the ecosystem level, validating them and also in dealing with interactions between the various parameters.

None of the studies on effects of changes in climate parameters undertaken so far has ever involved the species or groups of species to be found in the forested regions of Western Australia. In order for us to make any judgement about the implications of the greenhouse effect for these forests, it is necessary for us to draw on indirect evidence. Our findings must, therefore, be regarded as speculative despite the fact that they are based on the best information available at present.

Increased CO_2 concentration

Table 1 indicates that the concentration of atmospheric CO_2 is expected to increase by around 50% in the next 30-50 years. In vascular plants with the C_3 photosynthetic pathway (which, as far as is known, includes all species in the forest region) an increased CO_2 concentration is likely to lead to increased photosynthesis where other factors are non-limiting (Bazzaz 1990). This fast, short-term response relationship is not linear and varies from species to species and between genotypes. Leaves of various Eucalyptus species have shown an increase in photosynthesis of 50% with a doubling of CO_2; these results have been confirmed on trees up to 10 m tall (Wong et al. 1978, Wong and Dunin pers. comm. in Pittock 1987). The increased growth rate resulting from this so-called CO_2 fertilizer effect would theoretically result in a commensurate increase in dark (true) respiration; this has been found for several arctic tundra species (Oechel and Strain 1985). However, empirical data on crop plants show the reverse effect and there is some evidence to suggest that this is the likely response at the ecosystem or global level (Gifford 1988b). As well as the fast, biochemical responses, plants are also expected to exhibit morphological changes in response to increases in CO_2 levels. Leaf areas may increase and therefore add to productivity and, at the same time, root to shoot ratios may change with greater allocation to roots, especially when nutrients and/or water are limiting (see Bazzaz 1990, cf. Gifford 1988b).

A further effect of elevated CO_2 concentrations is that efficiency of water use increases: stomatal apertures are reduced and thus diffusion conductance increases. In the short-term, a doubling of CO_2 concentration around a leaf leads to an approximately 40% reduction in stomatal conductance (Morison 1985). In Eucalyptus, transpiration rates decreased by 50% under these conditions (Wong et al. 1978, Wong and Dunin pers comm. in Pittock 1987). This improvement in water use efficiency may not be maintained in the longer-term however since an increase in leaf area may compensate (Gifford 1988b).

Integrating these three responses appears to provide a contradictory result in that the increases in overall productivity are much less than would be expected. The response in yield of 13 C_3 crops to a doubling of CO_2 levels averaged 26% (Gifford 1988b). Pinus radiata seedlings also showed a similar (30%) increase in total dry weight after 22 weeks when grown under optimum conditions (Conroy et al. 1986).

At this point it is only possible to speculate that while increased $[CO_2]$ alone may theoretically increase growth in the forests, other factors, such as available nutrients and water, are most likely to remain limiting.

Increased Temperature - Direct Effects on Main Species

Temperature is a major determinant in many biochemical reactions and thus it can be expected that the predicted increases in ambient temperature will have significant repercussions. Two types of effects could be seen: the first where reactions will be speeded up and the second where a threshold temperature is crossed and so something may cease to occur or may occur prematurely.

Leith (1972) has derived an empirical relationship between annual productivity in natural ecosystems and temperature which shows an increase in productivity with increasing mean annual temperature but only within a range of temperatures. The increased productivity effects will be greatest at high latitudes which are coolest to begin with and where temperature increases are expected to be greatest. For Manjimup with a mean annual temperature of 15.2°C the calculated increase in productivity with a 1.8°C rise in temperature is 7.3%.

Kauppi and Posch (1987) estimated a poleward shift (at equalibrium) of several hundred kilometres by the boreal forests of the northern hemisphere as a result of the temperature changes associated with a doubling of [CO_2] (see also Roberts (1989) for a summary of changes anticipated in North America). However they noted that such a distributional change would take hundreds of years if normal plant successional processes were the dominant mechanism (see also Huntley and Webb 1989, Sauer 1988); in the meantime many of the existing forested areas including those in eastern Canada, Finland and the USSR would increase in productivity by up to 50% as a result of the increase in temperature.

Specht (1988), on the other hand, has highlighted the effect on plant respiration of increased temperature that would lead to a reduction in the amount of photosynthate available for structural growth and storage. He has identified the tall open forests of southern Australia as ecosystems most likely to be adversely affected by temperature rises. It is not possible at this juncture to account for the discrepancy between Specht's findings and those of Leith (1972) and Kauppi and Posch (1987) except to point out that each author has used a different modelling procedure. The forests being modelled by Specht (1988) occur in temperate regions where higher temperatures may have been limiting, whereas Kauppe and Posch (1987) are dealing with Boreal forests which are limited in their growth at present by low temperatures.

However, a consideration of temperature alone has serious limitations. In a number of Australian ecosystem/community types, the period of optimal temperature for shoot growth now coincides with the period of available moisture to give a "climatic temperature window" in which shoot growth occurs (Specht 1988). A change in ambient temperature by as little as 1 or 2°C may be sufficient to disrupt this coincidence. It seems equally probable that there will be situations where the windows are enlarged by the warming or a shift in rainfall distribution.

Inions' (1990) has classified the karri forest environment using a broad range of physical parameters including climatic variables. He then related his groupings of sites to observations of tree productivity. The temperature gradient throughout the study area is not pronounced and, perhaps as a consequence, temperature does not appear to be an important factor in discriminating between groups of sites. However it is noticeable that the warmest sites (in Inions' Homoclimes 1 and 2) are generally more productive than sites that experience coldest winters (Homoclime 3a particularly) although these temperature differences are not evidenced from the table of statistics used in the analysis.

In a grouping of virtually the same set of karri forest sites based on floristic attributes, Inions' et al. (1990) identified a similar relationship: groups of sites experiencing cold temperatures (Community Groups 1 and 2) are, in general, less productive than groups which are warmer (Community Group 5 particularly). Again the contribution of temperature to the discrimination of the floristic groups is not obvious in the table of univariate statistics produced although it is significant at the $p>0.0001$ level.

The role of temperature alone, as opposed to its interaction with other factors such as rainfall (e.g. to give co-efficient of evaporation, see later), in the patterns of growth in the jarrah forest is no more clear. The appropriate analyses have yet to be done. However, seasonal patterns of growth of the canopy (e.g. Gentilli 1989), the stem (Nicholls 1974, Mazanec 1989) and the fine root system

(Dell and Wallace 1983) clearly have a temperature component (cf. Abbott and Loneragan 1986). Therefore it is to be expected that an increase in temperature of one or two degrees may increase growth rates, reducing the late-winter dormant period, provided other factors are not limiting.

Increased Temperature - Effects on Other Forest Organisms

A large range of organisms are known to affect forests and trees and therefore the impacts of global change on these and the consequences for timber production should be considered. Symbionts involved in nutrient cycling, particularly in nitrogen fixation, display seasonal patterns of activity (e.g. Grove and Malajczuk 1981, O'Connell and Grove 1986). Similarly, invertebrates of the soil and litter layers which contribute to forest processes are seasonal in abundance e.g. springtails and ants (Majer and Abbott 1989). An increase in winter temperature will favour insect species which emerge early and will speed up their lifecycles; thus species that are not currently considered pests may become so. For example *Uraba lugens*, the gum leaf skeletonizer, may have three life cycles per year. Jarrah leaf miner *Perthida glyphopa* on the other hand, may decline slightly since oviposition is optimal at moderate temperatures (15-20°C, see Mazanec 1989).

The jarrah dieback fungus *Phytophthora cinnamomi* is known to be favoured by periods of high soil moisture at temperatures above 15° and below 31°C with an optimum at approximately 22-27°C (Shea 1975, Zentmyer 1980). The increased winter temperature projected as a consequence of the greenhouse effect will therefore increase the period of activity of *P. cinnamomi* and may well also increase its geographic range of virulence.

Several other species of *Phytophthora* are also known from south-western Australia. It is possible that one or more of these could become more active under warmer conditions and thus impact on forest communities.

A final consideration of the consequences of temperature changes in the forest region relates to temperature thresholds. An example, given above, is that egg laying in Perthida glyphopa is temperature limited: laying ceases over 22°C. A similar phenomenon can be observed in plants; for example many species have a cold requirement (stratification) for seed germination (e.g. Roberts 1979 for Umbelliferae in Britain). Equivalent information for plant species of south-western Australia is scanty and is generally based on horticultural experience rather than scientific experiment. It is known, for instance, that many species in the Proteaceae germinate under conditions of falling temperatures. There is the potential, therefore, for floristic changes in the forests when temperatures change.

The present distribution limits of some plant species is set by occurrence of frosts (e.g. Davidson and Reid 1985); thus any reduction in the incidence of frost as a consequence of global warming is likely to enhance regeneration of those frost-sensitive species and may, therefore, enable them to expand their ranges.

Changes in Rainfall Regime

Seasonal distribution of rainfall is an important factor determining site productivity. In mediterranean climate regions, summer rainfall generally contributes less than 20% of the overall rainfall total and often a smaller proportion to available soil moisture.

The anticipated 20% decline in winter rainfall in south-western Australia will have a greater impact on total rainfall than the anticipated 40% increase in summer rainfall (Hille's Scenario 1). For Manjimup, with a mean annual rainfall of 1035 mm, for example, the nett result of these changes would be to reduce total rainfall to 952 mm p.a. Notwithstanding this, the likely increase in summer rainfall is not inconsequential, particularly since it will ameliorate the extreme summer water stress; this aspect will be discussed later.

Large changes in the relative abundances and distributions of the major tree species in geological time have been reported by Churchill (1968); these are attributed to changes in rainfall associated with phases of glacial activity (cf. Fig. 1). The relative importances of the various species in the fossil pollen sequence and the presence of outlying populations of Eucalyptus marginata (Fig. 6) was taken as indicating a higher rainfall in the early to mid Holocene in south-western Australia. Churchill (1968) calculated that an increase of 76 mm in mean annual rainfall would allow the present main area of jarrah to link up with the outlying populations (see Gentilli 1989 Fig. 4 for data on karri outliers).

It is reasonable, therefore, to suggest that there would be a contraction of the major production forest types commensurate with any decline in rainfall. Arnold (1988) has mapped the likely distribution of the jarrah forest in the year 2040 solely on the basis of a 20% decrease in winter rainfall (Fig. 6). This shows a westward contraction of the eastern (dry) boundary and a southern expansion into the area presently dominated by karri, presumably reflecting a contraction of that forest type. However, the real impact of the rainfall changes will be more complex at least because of the ameliorating effect of the increment in summer rainfall (cf. Churchill 1968). Furthermore, the forest boundaries are unlikely to alter at the rate implied by the figure - typical migration rates for forest boundaries are of the order of 50-2000m p.a. (Huntley and Birks 1983; Huntley and Webb 1989; Roberts 1989). As rainfall declines, the trees on the dry margins will be subjected to increasing water stress. Productivity will decline and mortality will increase, thus the forests will become more open (woodlands) and less tall. Plants may be more vulnerable to the attacks by insect pests and pathogens during the period of stress and transition to a new structure.

The ultimate distribution of each tree species will be influenced by a range of factors but it is more likely to reflect the extent of drought periods rather than changes to mean rainfall.

Insert Figure 6 here.

In the karri forest climatic classification of Inions (1990), discussed previously in relation to temperature, rainfall (amount and distribution) clearly contributes to the discrimination of the groups identified. Homoclime 1 sites are the wettest with highest winter rainfall whereas Homoclime 3 sites have highest summer rainfall. However the correlation between rainfall and site productivity is not direct, probably because all sites have relatively light rainfall. The floristic classification of karri sites (Inions <u>et</u> <u>al</u>. 1990) also fails to show a clear relationship between precipitation and productivity although the wettest sites have very high productivity (e.g. Community Groups 4, 5 and Community Type Beggs, Community Type Lane-Poole with high summer rainfall).

The change in amount and seasonality of rainfall will also affect the range of other organisms which contribute to the vitality of forest ecosystems. Biological activity in the litter layer of the jarrah forest, a measure of nutrient cycling, is generally greatest when moisture conditions are highest (O'Connell and Grove 1986). Peaks in abundance of soil and litter invertebrates, particularly the latter, at a number of forest sites could be related to favourable moisture conditions (Majer and Abbott 1989). Indigenous species of earthworms, a major component of the soil-animal biomass of the jarrah forest, are present in the upper soil horizon from May to November when surface soils are moist (Abbott 1985). The increased summer rainfall will extend this period of favourable conditions. Sporulation of many species of fungi of the jarrah forest, presumably including some of the mycorrhizal species, is also correlated with patterns of soil moisture availability (Hilton _et al_. 1989).

The likely increased impact of a range of plant pests and diseases on forests suffering drought stress has already been mentioned. However, more needs to be said about the changes to the pattern of rainfall on _Phytophthora cinnamomi_. On the one hand, lower total rainfall would reduce the virulence of the fungus (Shea 1975) and potential dispersal, whether by human transport of diseased soil or by zoospore movement. On the other hand, increased summer rain would increase the period of time over which _Phytophthora_ is active.

Finally, it is known that jarrah seedlings are very sensitive to waterlogging (Davidson and Tay 1985). The effects on other forest species are not documented. Clearly there is potential for interaction between waterlogging and _Phytophthora_ (eg Davidson and Tay 1986). The soils and landforms of the forest region predispose some forest sites to waterlogging (Churchward and Dimmock 1989). Thus, any reduction in winter rainfall could result in a decrease in waterlogging and improved conditions of jarrah in these sites.

Interactive Effects - Temperature and Rainfall

Much of the discussion so far has focussed on effects of changes of various physical climate parameters considered in isolation from each other. In view of the complexities of the greenhouse effect, this is a reasonable starting point. But it is also necessary to examine in concert changes in combinations of parameters where reliable methods exist to do so. Factors most often considered together are temperature and rainfall.

Pittock and Nix (1986) have estimated changes in nett primary productivity of natural vegetation for the Australian continent as a consequence of expected climate changes resulting from a doubling of [CO_2]: a 0.1°C increase in mean annual temperature for every 1° latitude south i.e. a 3.2°C increase for Perth, a 40% increase in summer rainfall and a 20% decrease in winter rainfall. These rainfall regime changes are consistent with some of the present predictions but the increase in temperature is about twice that for the most likely scenario for south-western Australia (Hille's Scenario 1, see earlier). Pittock and Nix (1986) calculated productivity using the empirically derived Miami Model of Leith (1975) which uses both rainfall and temperature data. Under this climate scenario, the part of Australia predicted to show a decrease in productivity is the south-west coast of Western Australia from Carnarvon through to about Denmark. The decrease is less than 5% within that broad coastal strip; to the east there is a small increase in productivity of about the same order of magnitude.

A similar approach was used by Graetz _et_ _al_. (1988) who modelled potential productivity of the vegetation as a function of Plant Available Moisture (integrating precipitation, temperature and soil type) and Available Nutrients. Graetz _et_ _al_. confined their attention to the arid parts of the continent, thus the south-west was not considered. However the results do show a decline in tree cover in the Kalgoorlie region and an increase east of Geraldton.

The climatic classification of the forest, developed by Gentilli (1989) could be used to develop a clearer picture of the likely geographic changes in forest types to result from the greenhouse effect. Gentilli has plotted median yearly rainfall against total summer evaporation using the latter as an index of water stress. Changes in the rainfall and evaporation coefficients could be estimated using the chosen climate scenario.

The projected future distribution of the karri forest community types of Inions et al. (1990) could be modelled using the Bioclim analysis technique of Busby (1988) at some stage; however at present there are insufficient data points to give useful results. A superficial examination suggests that the Stoate community group, containing yellow tingle, Eucalyptus guilfoylei and the Stewart community group are particularly vulnerable to the warming and drying that is anticipated.

Indirect Effects of Climate Change on Forests

Thus far we have concentrated on the direct effects of changed climate parameters on the organisms of the forests, paying some attention to the interactions between organisms. However, secondary or indirect influences could have equally profound effects on the extent, composition and structure of forest vegetation. The two most important of these influences are fire and land-use or socio-economic changes. Here we examine aspects of the former; the latter is beyond the scope of the present paper.

Fire is a major management consideration in the forests (and beyond) of south-western Australia. This is largely a reflection of two factors: the mediterranean fire bioclimate (sensu Naveh 1974) with long, hot, dry summers and the very flammable nature of the largely sclerophyllous vegetation. There exists the potential for widespread and intense wildfires. A strategy of pre-emptive, fuel reduction burning has been developed to militate against the threat that such wildfires pose to property values (e.g. Underwood et al. 1985). At the same time it is recognised that fire has an important role in many ecosystem processes, triggering regeneration and contributing to nutrient cycling for example. Thus the fire regimes that prevail throughout the forest areas are critical for a variety of reasons and can have major consequences for a range of forest values.

As a generalization, fire regimes (intensity, seasonality, frequency and spatial factors, (Gill 1975, Hopkins 1985) are a function of climate, vegetation and fuels and availability of sources of ignition. All these factors could be modified by changes associated with the greenhouse effect. Thus, the present regimes of natural and imposed fire may change, or may need to be altered, in response to the greenhouse effect.

On the other side of the issue, fire has short term potential feedback effect into the greenhouse effect. N. Burrows (pers comm.) has calculated that the present fuel reduction burning program throughout State forests produces annually about 46,000 tonnes of particulate matter and 4.14 m tonnes of CO_2. Ozone and nitrous oxides are also produced. Any alternative burning regime, including one based around occasional hot wildfires, would probably contribute similar quantities of pollutants in the long-term. Decomposition eventually produces similar outputs of CO_2.

Increases in temperature in summer and winter will lead to increases in the length of the fire season and in the intensity of individual fires. A diminution of winter rainfall would also lead to an increase in the length of the fire season. Some of these effects will be militated against by the increases in summer rainfall. If there is a decrease in forest productivity there will be a corresponding reduction in rates of fuel accumulation in the longer term; in the shorter term the death of drought stressed trees may balance this.

Higher wind speeds in summer (predominantly easterly winds) would promote curing of fuels, increase rates of spread and lower the fuel threshold values below which fires will not propagate. As well the unstable weather patterns associated with the southward migration of the belt of anticyclonic depressions may give rise to increases in thunderstorm activity and consequently in lightning caused ignition.

It would be possible to model changes to fire patterns, for example along the lines of the work of Beer et al. (1988) but that may better await the development of more detailed regional climate scenarios. Those authors examined changes to the McArthur Forest Fire Danger Index values under a range of scenarios for three eastern Australian locations. In all cases there was a small increase in the Fire Danger Index. Examination of predictions for Sale (Victoria) revealed that higher Index values were expected for all months principally because of the increases in temperature; the altered patterns of rainfall do not have a marked effect. It is worth noting that the elevated values for Fire Danger Index under greenhouse conditions are still much lower than those calculated for the peak fire season of 1982/83 when there were extensive and major bushfires through south-eastern Australia. Beer et al. (1988) highlighted the need for precise information on relative humidity values in order to project future bushfire incidence.

Inions (pers. comm.) has found that karri forest sites experiencing highest temperatures and lowest rainfall overall generally support the greatest numbers of vascular plant taxa and particularly species which resprout after fire. The suggestion is that these sites, being most vulnerable to fire, have indeed been burnt most often; the recurrent disturbance has promoted the maintenance of high species richness perhaps with some selection against obligate seed regenerating species. A further suggestion is that fire has probably had an important controlling influence on the distribution of karri forest in the past.

Effects of Ozone Depletion

Pittock (1987) in reviewing the likely effects of predicted atmospheric changes on Australian forestry over the next several decades included the possible adverse effects of increased ultra violet radiation (UV.) resulting from the depletion of stratospheric ozone as a factor to consider in forestry planning. While this review has confined itself to climatic change resulting from greenhouse warming we present the following brief summary of points regarding present knowledge of the implications of increased UV. levels.

(i) Globally, a decrease in ozone of about 3% since 1970 has been confirmed (Rowland 1988).

(ii) Despite increasingly stringent international actions to reduce the use of ozone depleting CFCs, continued loss of ozone will occur for many decades because of the long atmospheric life of CFCs.

(iii) The percentage increase in biologically significant UV. is about twice the percentage decrease in stratospheric ozone.

(iv) Evidence exists that UV. radiation adversely effects the health and growth of a wide range of plants (e.g. Teramura 1983 and 1986 in Pittock 1987).

Thus, it will be important that the effects of a possible increase in UV. radiation are considered in developing plans for management of and research on Western Australian forests.

Implications of the Greenhouse Effect for Forest Management

It is clear from the discussion in the early part of this chapter that the changes to the climate anticipated as a result of the greenhouse warming are diverse and not at all clearly understood. The effects of these changes on complex forest ecosystems are even more difficult to predict with certainty. The effects are dependant to a degree on the level of management that can be undertaken in any forest. Where there is moderated to intensive management as is the case in forests used for production then composition and structure can be manipulated to minimise any adverse consequences of climate change or to take advantage of any beneficial changes. At the other end of the spectrum, forest areas set aside for nature conservation purposes where natural processes are to prevail, the impacts of climate change may be very conspicuous. It will be necessary to consider intensification of management of nature conservation forests if this occurs.

Having reviewed the available information we are left with a series of key questions, questions of importance in considering future forest management and thus questions requiring further attention.

1. What are the effects of the predicted changes on levels of productivity of the forests? While a decrease in total annual rainfall might be expected to reduce overall vigour and productivity, this effect could be substantially alleviated by an increase in summer rainfall. Where moisture is a limiting factor at present, the outcome of these two factors is unknown. Should there be a nett loss in productivity this will be reflected in the short term by increased mortality until a new equilibrium is achieved. Active management of the forest (by reducing tree density) could be used to compensate for this drought stress and to maintain productivity.

2. Are current contractual commitments for forest products appropriate? Current commitments, which are for a maximum of 15 years, are not dependent to any significant degree on intervening growth but are based on resources which already exist. If future trends suggest that reductions in total growth are occurring then alterations to future allowable levels of cutting will need to be made. At the same time there will be a need to maintain the utilization capacity should it be required for salvage operations or increased thinning activity in the shorter term.

3. What will be the effects on different tree species? Changes in the relative growth rates and capacity to regenerate may occur and lead to alterations to the natural distribution of species, tending to favour those species able to cope with drier conditions and perhaps having greater fire resistance. Climatic extremes that result in droughts and changes in fire conditions will be more critical than changes to average conditions. Sites which are already difficult to regenerate because of moisture limitations would be most affected.

   Present distribution patterns are a function not only of soils and climate but also of ability to regenerate, particularly under fire regimes that have existed over a long period of time. These fire regimes have already been influenced by human activity.

   In forests used for production, intervention in regeneration processes makes it possible to reduce the impact of greenhouse changes and to postpone shifts in distribution. Changes in relative growth rate of species may occur and eventually cause changes in relative dominance but this would be very difficult to detect.

In general, young, regrowth forests will be more resilient to changes than will stands of older trees.

4. What will be the impact of pests and pathogens on the forest? The effect of pests and pathogens on the forests represents a third level of interaction and the effects are even more difficult to predict. Conditions however are likely to favour an intensification of the effects of Phytophthora where it exists but conditions for dispersal may be reduced.

   Relatively minor climatic changes could dramatically affect the life cycles and survival of insect pests. The interactions are extremely complex and it would be speculative at this stage to suggest what the overall effect might be. Any increase in drought stress in the short term would, however make the forests more susceptible to attack.

5. What aspects of the current fire management program will need to be modified to take into account greenhouse effects? There could be a minor increase in the overall fire danger with possibly a more substantial increase in intensity and rates of spread of individual fires. In the longer term, levels of fuel accumulation may decline. More frequent occurrence of extreme fire weather conditions will make it necessary to maintain emphasis on prevention and strategic protection.

Forest management practices are subject to regular review. Changes to the forest resulting from predicted climate changes will occur gradually; therefore modifications to operational procedures to deal with those changes can also be introduced gradually when trends are more evident. The opportunity exists with more intensively managed forests to alter management practices and to manipulate species composition and stand densities in order to avoid many of the less desirable consequences of climate change. In the case of forests set aside for nature conservation, decisions will be required on whether there should be management intervention and on the extent of that intervention.

Research Requirements

We have identified eight areas requiring research input in the coming years and that are directly linked to the subject of this review.

1. Environmental factors that are limiting forest growth and regeneration at present need to be more clearly identified for all forest types so that areas most at risk from climatic change can be mapped and managed.

2. Once limiting factors have been identified it will be necessary to establish a series of inventory and monitoring plots throughout the forest estate in order to collect background information with which to assess future changes. A framework for a monitoring program has been developed (Hopkins in press) so that much of what will be required will merely involve better co-ordination of existing projects under this umbrella.

3. Gentilli (1989) has drawn attention to the inadequacies of existing climate data throughout the jarrah forest region, including the drier margins, and the southern forest. The climatological station at Dwellingup is an important asset but more data points are required. At least a few should be equipped to record free-pan evaporation.

   An improved network of reliable climate recording stations is a fundamental requirement for studies of greenhouse effect. The data will also provide a basis for ongoing planning and management of the forests (e.g. bushfire predictions, Beer et al. 1988). Therefore we strongly support Gentilli's plea for the establishment of additional stations throughout the forest.

4. The climatic changes associated with the greenhouse effect will happen very quickly on a biological time scale. It is possible that the rate of change will exceed the ability of the biota to cope by several orders of magnitude. The process of natural selection will be effective to a limited degree only and plant migration is unlikely to keep pace with geographic changes in climate zones (cf. Sauer 1988). Therefore, if the productivity of the forests is to be maintained, some genetic management may be required. Ideally, this should commence with genetic resource mapping throughout the forests using sites where productivity and ecological site data are also obtained. The proposed system of inventory and monitoring sites outlined above could form the basis for this study.

   A preliminary study of karri genetics has recently been completed (Coates and Sokolowski 1989). It will be necessary to extend this work to other forest tree species and to attempt to relate the genetic data to detailed site observations.

5. The Western Australian Government is currently providing financial support for a CSIRO modelling study aimed at developing detailed regional climate scenarios. This support should continue because it is fundamental to any future planning to respond to climate change.

6. Forest growth models will need to be adapted to incorporate climatic variables, and response to [CO_2] and UV-B and then run under a variety of climatic

scenarios as part of the process of planning for climate change.

7. In the course of ongoing research on pathogens and insect pests in the forest regions, attention should be given to developing predictive models which are responsive to the likely changes in [CO_2], UV-B and climatic parameters. Results from modelling procedures can then be linked with forest growth models to provide insight into likely production trends.

8. There are still significant gaps in knowledge about physiological responses of eucalypts, particularly the local species, to the likely changes in [CO_2], UV-B and climatic parameters. Much of the current research is being done in institutions in eastern Australia. Western Australia should encourage further research which also looks at <u>Eucalyptus</u> <u>marginata</u> and <u>E. diversicolor</u>.

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TABLE 1

Present and Predicted Levels of CO_2 and Other Greenhouse Gases to the year 2050 with estimates of likely consequential surface temperature rises to 2050

Gas	Pre-industrial Concentration	Current Concentration	Predicted Concentration	**Predicted Minimum Warming Effect to Year 2030 °C**
Carbon dioxide	275 ppm	350 ppm	400-600 ppm	0.71
Methane	0.7 ppm	1.7 ppm	2.1-4.0 ppm	0.41
Tropospheric ozone (Northern Hemisphere only)	0-25% less than present	10-100 ppb	+15-50%	0.06
Nitrous oxide	285 ppb	310 ppb	350-450 ppb	0.10
Chlorofluorocarbons				
CFC11	0.00 ppb	0.25 ppb	0.7-3.0 ppb*	
CFC12	0.00 ppb	0.45 ppb	2.0-4.8 ppb*	0.44
TOTAL				1.45

Based on Bouma and Pearman (1989), Pearman (1988) and Dickinson and Cicerone (1986). Predictions (to 2030) of surface temperatures are from Ramanathan et al. (1985) and are based on estimates of future changes for each greenhouse gas which are similar to those of Dickinson and Cicerone (1986).

*ignoring effects of probable decline in use as a consequence of the Montreal Protocol.

TABLE 2

The pools of stored carbon that have been created over aeons by the biosphere acting as a pump pulling carbon out of the atmosphere. Units are "atmosphere units" being the amount of CO_2 in the global atmosphere just before industrialization last century (1 a.u. = 590 x 10^9t C) (From Gifford 1988).

	Atmosphere Units
Pre-industrial atmosphere (1860 AD)	1.0
Modern atmosphere (1987)	1.3
Biosphere:	
above-ground	0.9
soil-organic matter	2.8
living in the ocean	<0.01
dead in the ocean	1.8
Carbonates in sedimentary rocks (limestone, chalk)	67 000
Fossilized organic matter:	
total in sedimentary rocks	27 000
potential "fossil fuel"	14

Figure 1. Reconstructions of climatic patterns of Australia at 18,000 years Before Present and 30-35,000 years BP compared with present day patterns. Prescotts climatic index $I = P/E^{0.7}$ where P = precipitation and E = potential evaporation is used to depict the climatic patterns. (Redrawn from Bowler 1982).

Figure 2. Indicators of climatic change in the Northern Hemisphere over the past 35,000 years: (a) the ratio of ^{18}O to ^{16}O in Foraminifera shells in deep sea sediments can be correlated with amount of ice in the ice cap because the snow which builds the ice caps is depleted in ^{18}O and (b) the record of the planktonic Foraminifera *Pachyderma* (left coiling) in the North Atlantic. Figure 2(b) shows an abrupt warming 15,000 years ago and two brief but intense epochs of renewed cold since then. The pollen record from bogs in northern Europe for the second of these epochs shows that the forests which revegetated that area with the retreat of the last great ice sheet were destroyed by a brief but intensely cold interval of several hundred years duration. The species of trees were replaced with shrub species of glacial time (redrawn from Broecker 1987).

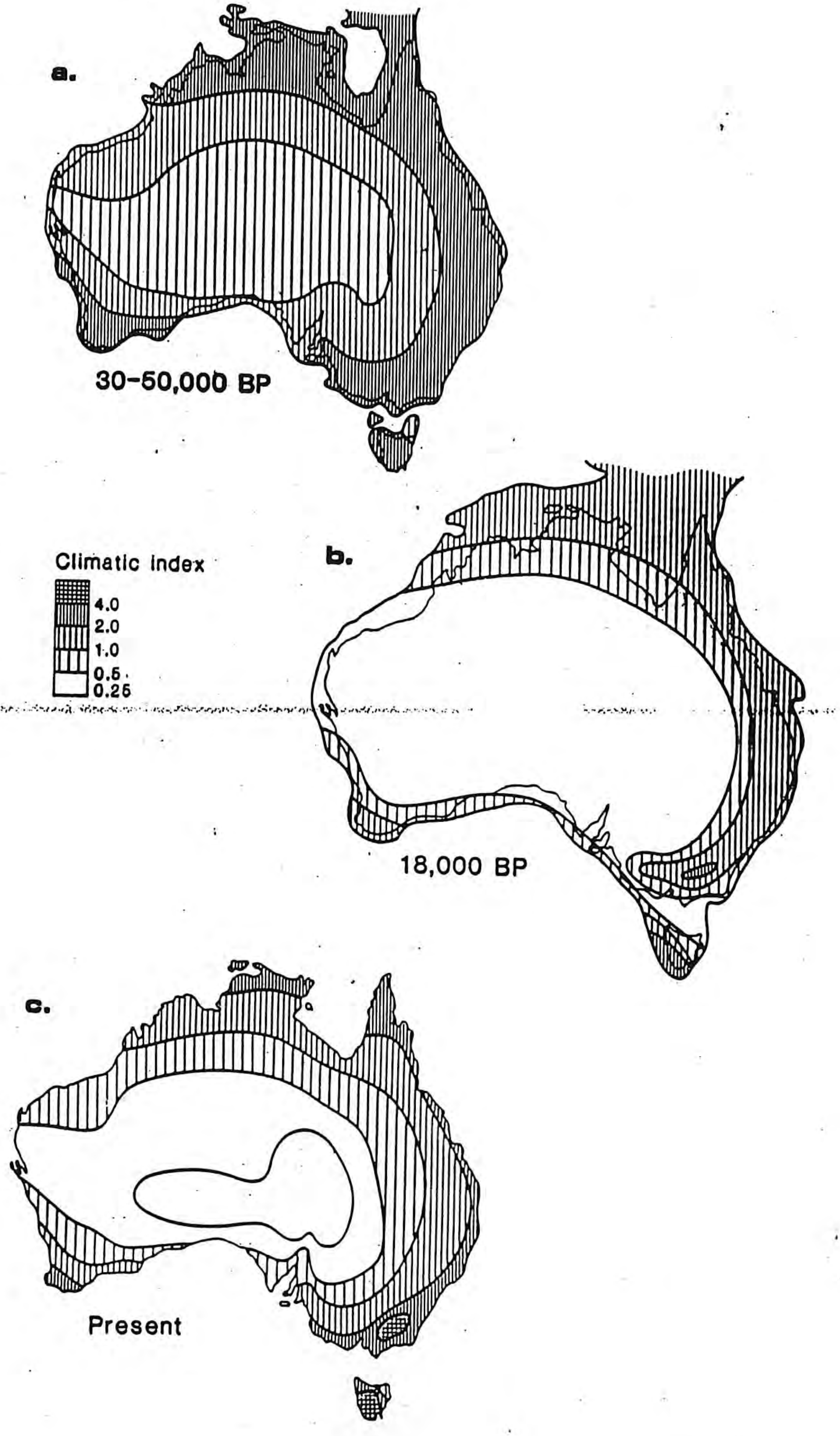
Figure 3. Changes in concentration of atmospheric CO_2 for the past few centuries as revealed in air extracted from Antarctic ice (redrawn from Pearman 1988).

Figure 4. Concentrations of atmospheric CO_2 measured in the mid troposphere over southeastern Australia (redrawn from Pearman 1988).

Figure 5. Annual mean temperature variations since 1861 for Northern Hemisphere (a), Southern Hemisphere (b) and the globe (c). Figures are redrawn from Jones, Wigley and Wright (1986) which gives details of methods of estimating values.

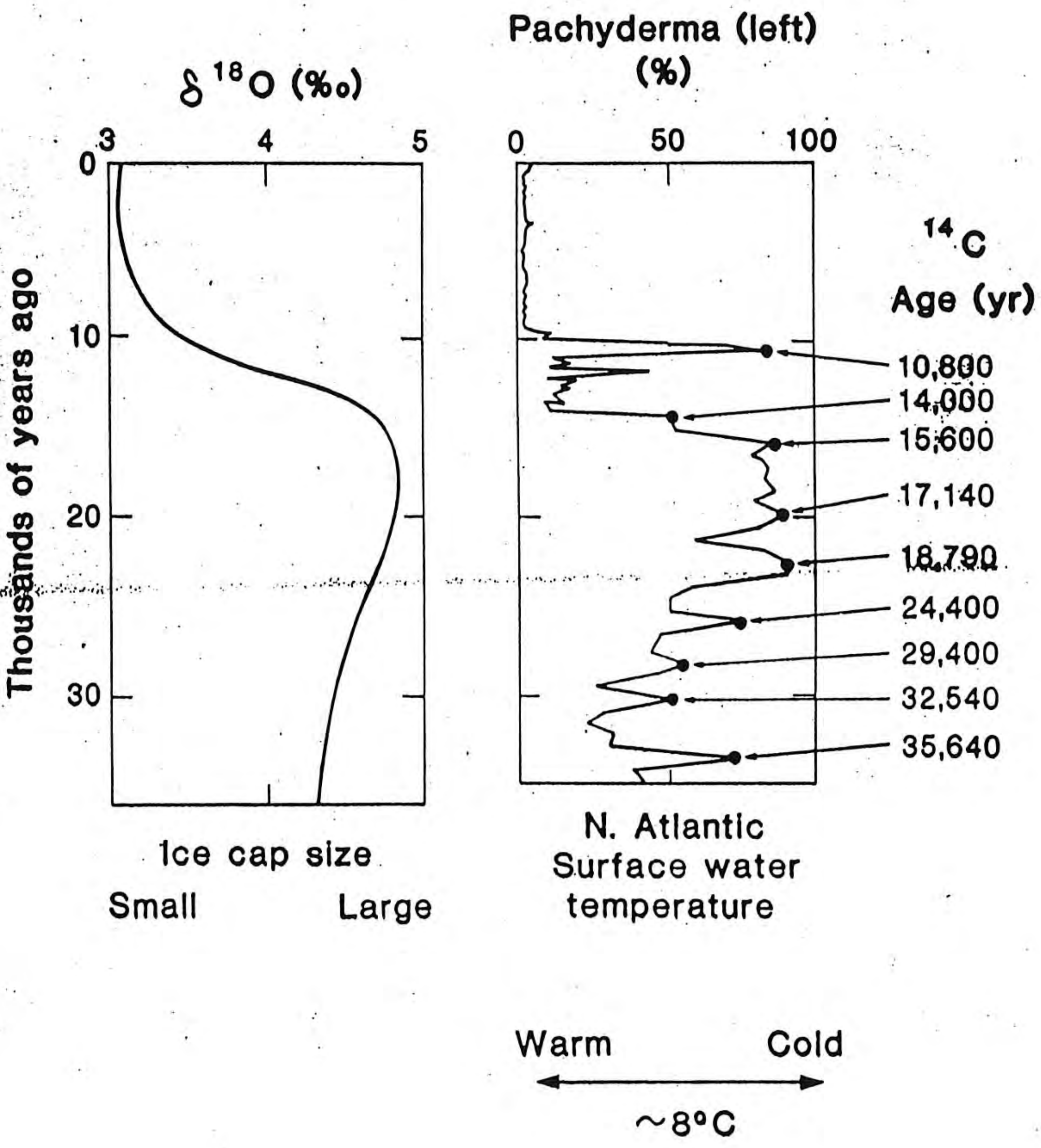
Figure 6. Postulated (after Arnold 1988) likely extent of sustainable jarrah forest by the year 2040 compared with its present extent (from Beard 1980). The present distribution of Eucalyptus marginata is also shown (from Havel 1989).

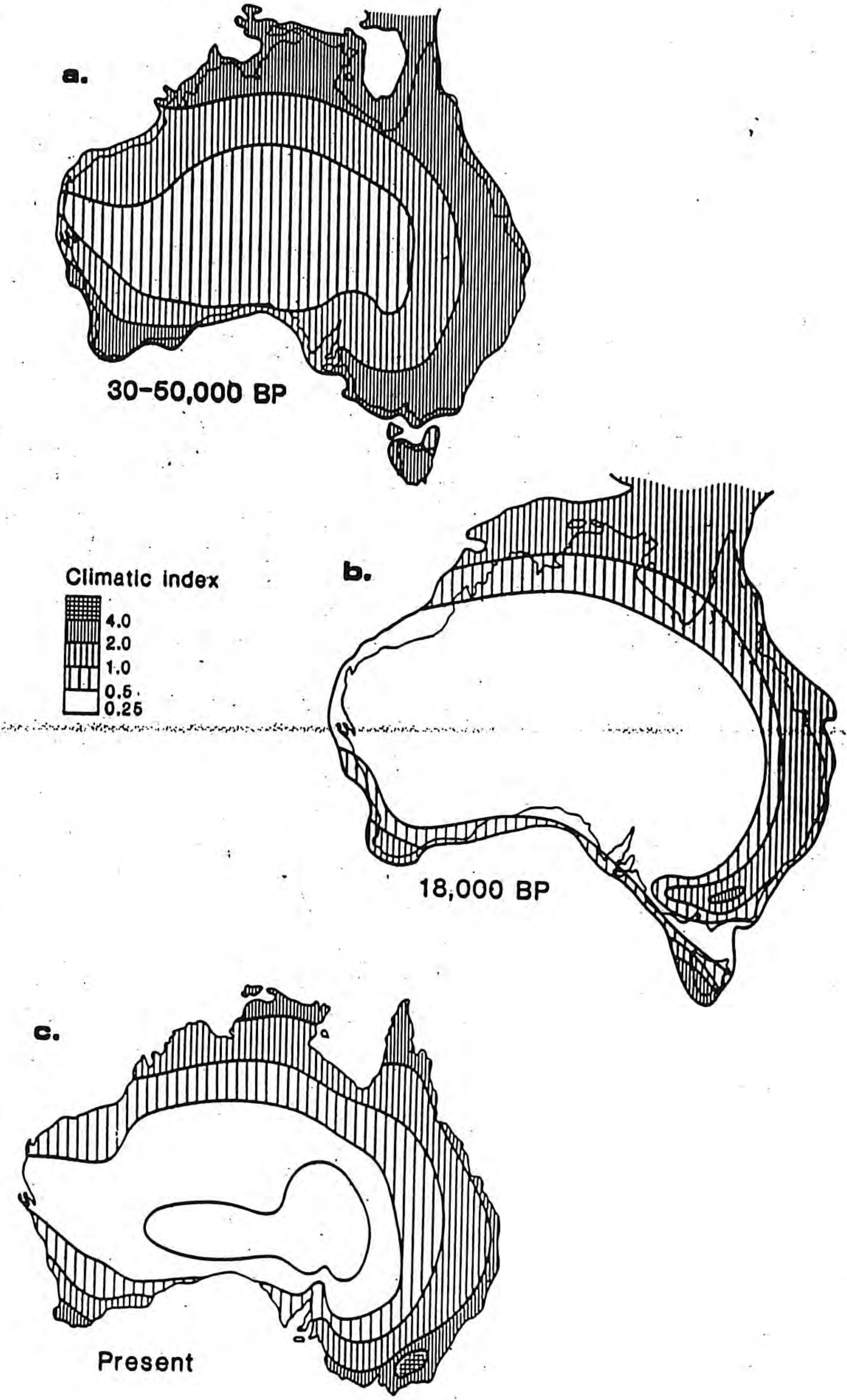
Figure 7. Postulated distribution of climate stations and associated forest types in relation to rainfall and total summer evaporation expected under the CSIRO climatic scenario for 2040.


a.
30–50,000 BP
Climatic index
4.0
2.0
1.0
0.5
0.25
b.
18,000 BP
c.
Present

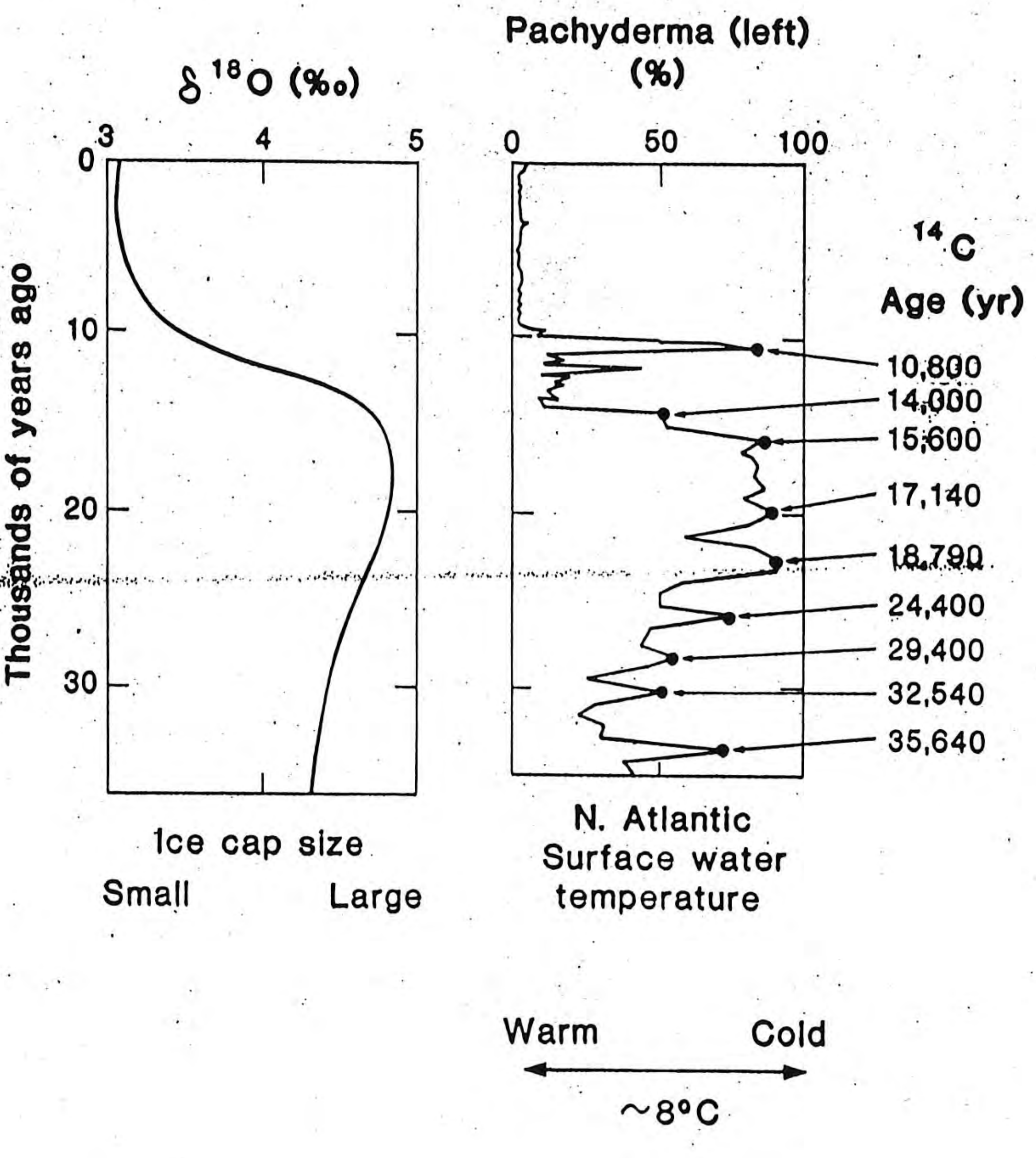
Remove
(left)

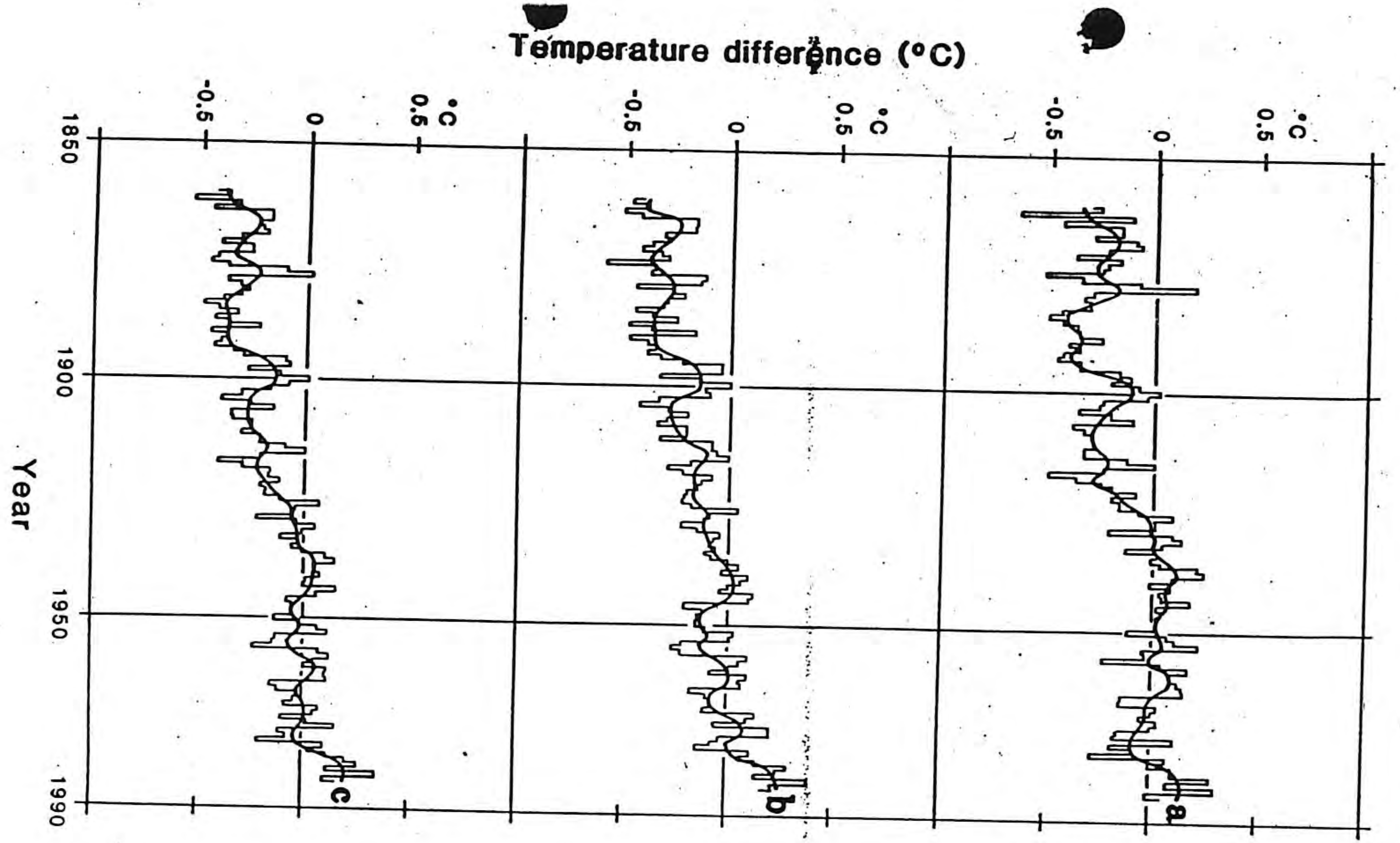
↓


δ 18O (‰)
3
4
5
0
10
20
30
Thousands of years ago
Ice cap size
Small
Large
Pachyderma (left)
(%)
0
50
100
14C
Age (yr)
10,800
14,000
15,600
17,140
18,790
24,400
29,400
32,540
35,640
N. Atlantic
Surface water
temperature
Warm
Cold
~8°C


a.
30-50,000 BP
Climatic index
4.0
2.0
1.0
0.5
0.25
b.
18,000 BP
c.
Present

Remove
(left)


Pachyderma (left)
(%)
δ ¹⁸O (‰)
3
4
5
0
50
100
0
10
20
30
Thousands of years ago
¹⁴C
Age (yr)
10,800
14,000
15,600
17,140
18,790
24,400
29,400
32,540
35,640
Ice cap size
Small
Large
N. Atlantic
Surface water
temperature
Warm
Cold
~8°C


Temperature difference (°C)
°C
0.5
0
-0.5
a
b
c
1850
1900
1950
1990
Year

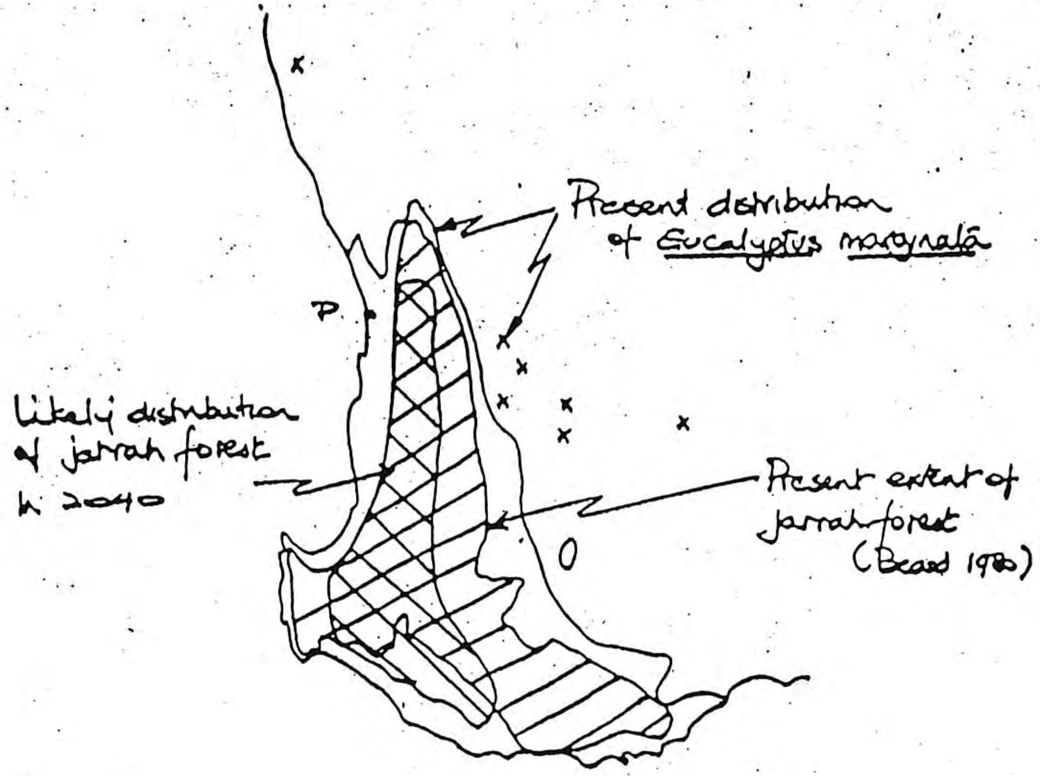

Present distribution of Eucalyptus marginata
P.
Likely distribution of jarrah forest in 2040
Present extent of jarrah forest (Beard 1980)
O

Fig 6