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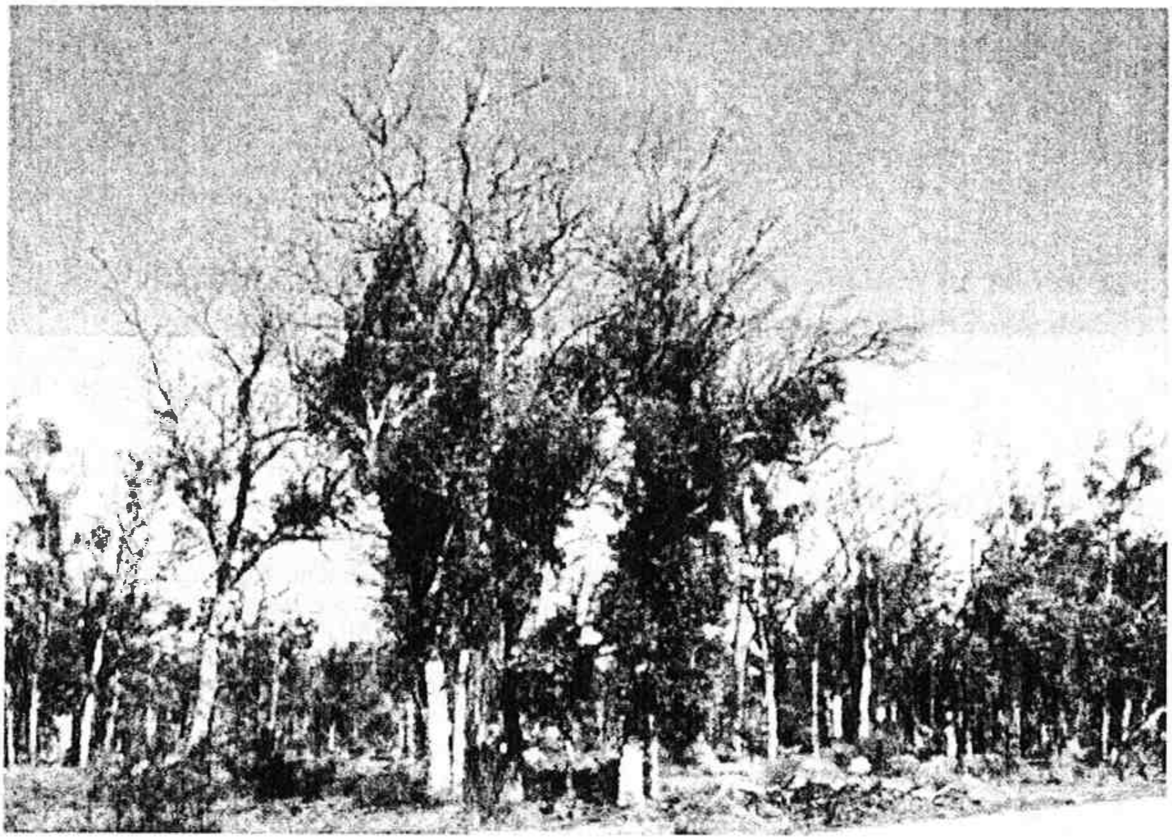

Final Report

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May, 2003

Survey of *Eucalyptus wandoo* decline

Jack Mercer

A report on wandoo decline in the Western Australian wheatbelt on behalf of the Department of Conservation and Land Management

ACKNOWLEDGEMENTS

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1. SUMMARY

Over the last decade or so wandoo (*Eucalyptus wandoo* Blakely), has experienced a period of rapid decline across its range in the south-west of Western Australia. The present decline is the latest in a series of events which several reports have documented over the last 40 years. Although several factors have been implicated over this time, no definitive cause or set of causes has been isolated to satisfactorily explain these episodic declines. This survey was designed to examine several parameters in order to establish the extent of this decline and clarify the role of various potential causes that could be further studied.

Insect damage and, specifically, lerp insect damage may be implicated but these were more likely to be contributory, rather than primary, causal factors. Insects may also be acting as a vector for fungal infection of wandoo trees. The longer a site was without intense fire, the healthier the tree crowns were, suggesting that fire brought disturbance that allowed decline patterns to develop. This was exemplified by the strong relationship between two recent intense fire events in the Stirling Ranges and the acceleration of the present decline pattern. Crown health improved at higher positions in the landscape. Some steeper slopes also exhibited some of the higher crown health ratings. This is inconsistent with the theory that rainfall deficits were responsible for wandoo decline. The higher elevations, however, have not been cleared or affected by rising watertables and deeper root systems of wandoo may not have been compromised, allowing the utilisation of soil moisture from deeper soil profiles during drought. It was also likely that adaptation to less available moisture at higher elevations, such as deeper root systems, has protected these trees from recent rainfall deficits. Small private remnants and road reserves typically exhibited higher crown ratings than National Parks and Nature Reserves and other reserved bushland. This suggested that generally higher stem densities and competition from understorey at these sites were predisposing wandoo to water deficits in a low rainfall period. A reliable indicator of healthier wandoo was a higher percentage of trees with minimal or no impact, where epicorms were not present or very old, and the increasing abundance of fruit and buds.

Both temporal and spatial trends in decline were apparent in this study. Separate decline events had occurred, or were occurring, that may be distinct from one another, that is, discrete events over different time frames that may overlap. Long term cyclical dieback was possibly occurring over several decades. It was not related to or did not display symptoms typical of the present decline. Salinity-related dieback was the most recognisable and was a long term, recent and ongoing decline pattern. The present decline pattern, witnessed over the last decade, was characterised by cyclic decline and recovery, over an intermediate time frame of between 3 and 10 years. Rapid crown defoliation following extreme summer temperatures in 1991 may also be considered a separate pattern but was not witnessed in this survey.

Along the transects from east to west, the increased severity of decline coincided with increased occurrence of wandoo. On the southern and central transects, decreasing crown health also coincided with increasing average annual rainfall between 400 - 450 mm and 600 - 650 mm but improved west of the 650 mm rainfall isohyet. Along the northern transect a similar trend occurred, the exception being that there was no definitive improvement of crown health in the higher rainfall zones.

Rainfall deficits over the last 25 years, and particularly over the last decade, may be implicated in wandoo decline. Zones of marked crown decline roughly coincided with areas where marked rainfall deficits have been recorded. Sites assessed for wandoo decline in 1991 and again in 2002 showed little structural change after 11 years, with old decline symptoms generally remaining much the same. With regard to the older decline patterns, sites were classed as healthy,

intermediate and degraded in 1991. With the present decline in 2002, these sites showed no impact, minimal impact and advanced symptoms in that order, implicating previous site condition as predisposing wandoo to greater impacts from a new decline.

Understanding wandoo decline would benefit from further studies into rainfall history, fire history, the role of insects and fungi, position in the landscape and slope gradient where the species is present. Prevailing site conditions that predispose trees to degrees of further decline need to be addressed in any future studies. Ultimately, there is a need to address wandoo decline in the perspective of recent and rapid changes inflicted on a long-lived and apparently successful species, which were beyond the scope of this survey. These changes included land clearing, some subsequent agricultural practices, climate change, rainfall deficits, fire regimes, salinity and waterlogging.

2. TAXONOMY AND DISTRIBUTION OF WANDOO

The subject of this survey, *Eucalyptus wandoo* subsp. *wandoo* (southern wandoo), is endemic to the south-west corner of Western Australia. In general, wandoo distribution is bounded by Mt. Barker in the south, Corrigin in the east, and the jarrah forests in the west. However, wandoo grew on parts of the Pinjarra Plain before European settlement (Capill 1984). In the north, its distribution is bounded by Bencubbin and Moora with outlying enclaves near Three Springs and south of Eneabba in the Gardiner and Herschel Ranges (Capill 1984; Brown et *al.* 1990), and near Denmark on the Hay River and near Narembeen (Brooker et *al.* 2002). Wandoo is mainly restricted to elevations between 210 and 340 m above mean sea level which places it below the main topographical distribution of *E. accedens*, *E. marginata* and *E. calophylla* (Campbell 1956). Its general distribution falls within the isohyets of 350 mm and 1000 mm mean annual rainfall (Capill 1984).

It is classified as a dry savannah open woodland (Beard 1990) with the upper strata having less than 40 per cent cover (Hewitt and Underwood 1963). It originally occupied most of the extra dry and western part of the dry Mediterranean climate zones (Beard 1990). Other characteristics influencing the distribution of wandoo are soil types and topography. Exposed parent rock (granite, gneisses and dolerite) of the Yilgarn block has weathered to produce red-brown clayey loams (Capill 1984). It is in these areas that wandoo mostly grows, among a non-uniform woodland (Campbell 1956) by preferring the sandy loams, loamy sands and sometimes soils of higher clay content that are found in the upper, middle and lower valleys (Capill 1984). The species predominated on the more gentle slopes before clearing.

To the east of its range, wandoo has a loose association with the mallets, *E. falcata* (silver mallee), *E. gardneri* (blue mallet) and *E. astringens* (brown mallet), that usually radiate downslope from lateritic outcrops (Campbell 1956). In the eastern wheatbelt region wandoo grades into *E. capillosa* (wheatbelt wandoo). Although often confused with wandoo, seedlings and juvenile leaves of *E. capillosa* are hairy scabrid whereas those of wandoo are glabrous (Brown et *al.* 1990, Brooker et *al.* 2002). *E. capillosa* has more orange than yellow in its bark, has green rather than blue-green leaves, glaucous branchlets and has a more spreading mallee appearance. The two species are associated in a belt from Kellerberrin south to Corrigin. Other related species are *E. livida* (mallee wandoo), located east of *E. capillosa*, and *E. nigrifunda* (desert wandoo), located east of Kalgoorlie (Brooker and Kleinig 1990). North of Gingin, *E. wandoo* subsp. *wandoo* has been graded into *E. wandoo* subsp. *pulverea* by Brooker and Hopper (Brown et *al.* 1990). The latter differs only slightly from the former by having a degree of powdery bark, glaucous branchlets and less consistent yellow bark. It occurs on the alluvial silty loams of the Moore and Hill River valleys. *E. loxophleba* (York gum) also has a loose association with wandoo over its range (Campbell 1956). Further south, so do *E. occidentalis* (flat-topped yate) and *E. cornuta* (swamp yate). In the lower gullies and creek beds, *E. rudis* (flooded gum) is predominant and marks the lower topographical limits of wandoo. In its northern distribution, wandoo has been graded into two subspecies. In the west, wandoo is associated with poorer forms of *E. marginata* (jarrah) and *E. calophylla* (marri) but more generally occupies the deep valleys that penetrate westward into the Darling Scarp (Capill 1984). Wandoo may be associated with *E. accedens* (powderbark wandoo) further upslope with the latter assuming dominance as elevation increases. *E. accedens* is not of the same taxonomic group as *E. wandoo* subsp. *wandoo*, *E. wandoo* subsp. *pulverea*, *E. capillosa*, *E. nigrifunda* and *E. livida*. (Brooker et *al.* 2002).

3. APPROACH TO 2002 SURVEY OF WANDOO DECLINE

The approach taken for the 2002 survey was a rapid or reconnaissance style survey that covered the main geographical extent of wandoo, excluding outlying populations north and east of Julimar. Three transects were established within the Western Australian wheatbelt and multiple sites along these transects were assessed for several semi-quantitive and descriptive parameters. It was assumed that the set of parameters used would identify those factors that warranted further investigation. The parameters were also comprehensive enough to give a reasonable profile of site history and change over several years. Thus the general trends observed along the transects and some comparisons of 1991 and 2002 data from three sites are also presented.

3.1. Hypotheses

The central hypothesis tested in this study was that environmental disturbance had caused wandoo decline on a wheatbelt-wide scale over the last decade, evidenced by crown defoliation, loss of twigs, branchlets and branches and ultimately some deaths of trees. Factors potentially causing this decline, and tested in this study, were: (i) rainfall deficits, that may incite decline higher in the landscape and on steeper slopes, and where high stem density may result in tree water deficits; (ii) fire history, where optimum fire frequencies and intensities may not be occurring; (iii) connectivity in the landscape, with land clearing and consequent fragmentation predisposing wandoo to decline; (iv) changes in land use; (v) secondary salinity; (vi) insect damage; and (vii) changes in understorey and litter structure.

3.2. Methods

3.2.1. Establishment of transects and site selections

Three transects comprising a total of 129 sites were assessed. Transects were oriented in an east-west direction, with most sites having relatively easy access for future observations, if required. The extent and approximate latitudes of the transects were:

- the southern transect extending from Chillinup to just west of Manjimup along the 34th parallel;
- the central transect extending from just east of Kulin to Collie along the 32nd and part of the 33rd parallel; and
- the northern transect extending from just east of Kwolyn to Helena Valley along the 31st parallel, with some additional sites included further north in Julimar.

3.2.2. Establishment of quadrats

Usually one but up to three quadrats were assessed at each site, depending on the variability of the landscape, and sites were sometimes clustered in an attempt to encompass landscape variability. Quadrats were 2500 m^2 (50 m by 50 m) and, where possible, were oriented with a GPS ground position reading (easting and northing) on the north-west corner of the quadrats with the first 50 metres paced in an east to west compass direction and the quadrat positioned south of this line.

3.2.3. Semi-quantitive assessment

Semi-quantitive parameters, except for crown assessment, insect damage and salinity, were assessed on a common scale as: (1) none present; (2) low (1-25%); (3) moderate (26-50%); (4) high (51-75%); and (5) very high (76-100%). Parameters assessed were as follows:

- Crown condition. Crown condition as a measurement of tree health was assessed using a method adapted by Abbott (1992). It involved rating the leaf density (0-9), incidence of dead branches (0-9) and contribution of epicormics to foliage (0-6), giving a maximum aggregate of 24 for undamaged crowns. In this survey, this method was used to establish average crown rating of the stand within each quadrat rather than that of individual trees (see Appendix 1).
- Percentage of dead trees due to present decline. The proportion of dead trees was estimated within each quadrat. Trees that appeared to have been dead a long time were omitted, since the survey aimed to assess the present decline pattern.
- Percentage of trees unaffected by or showing minimal impact from, the present decline. The proportion of trees unaffected by or showing minimal impact from the present decline was estimated within each quadrat.
- Insect damage to leaves. Insect damage to leaves was assessed for each quadrat from 2 or 3 random "grabs" of 10 to 15 leaves from tree canopies within reach. Approximately 50% of leaves assessed were young and the other 50% were older leaves. Damage was allocated into three main groups as a percentage of leaf area that (i) was chewed or missing, (ii) was browned, mined or scarred and (iii) had lerp builders attached. Abnormal levels of other damage types were noted, in particular the presence of borers. Insect leaf damage groups were: (1) none or very little (0-5%); (2) low (6-10%); (3) moderate (11-25%); (4) high (26-50%); and (5) very high (>50%).
- Vegetative cover under tree canopies. For each quadrat, vegetative cover under tree canopies was estimated as a percentage covering the ground (using projected foliage cover for plants present). Three categories were recorded: (i) native woody vegetation; (ii) native grasses and sedges; and (iii) exotic weeds.
- Litter layer cover. Cover of the litter layer for each quadrat was estimated as the percentage of ground covered by litter.
- Soil salinity. Soil salinity (as mSm^{-1}) was measured using an EM-38 salinity meter at 50 cm and 100 cm soil depths in the approximate centre of each quadrat. Salinity groups relative to south-west woodlands were: (1) none or very little (0-50 mSm^{-1}); (2) low (50-100 mSm^{-1}); (3) moderate (100-150 mSm^{-1}); (4) high (150-500 mSm^{-1}); (5) very high (500-1000 mSm^{-1}); and extreme (>1000 mSm^{-1}) (Agriculture WA 2002).

3.2.4. Descriptive assessment

Descriptive parameters assessed were as follows:

- Age of epicormics. Age of epicormic growth was an estimate of how many years since epicormic response had occurred, with the dominant age group recorded and other age groups noted. There were 6 groups: (1) no epicormics present; (2) <1 yr; (3) 2-3 yr; (4) 3-4 yr; (5) 4-5 yr; and (6) >5 yr old.
- Land use. Land use was allocated to one of 6 groups: (1) paddock; (2) parkland cleared; (3) private remnant; (4) road reserve; (5) State forest; and (6) National Park or Nature Reserve.
- Soil types. Soil types included a general description of soil depth of the A-horizon and percentage composition of gravel, if relevant. Groups were: (1) sandy loam or loamy sands; (2) duplex soils (>50 cm over clay); (3) duplex soils (<50 cm over clay); (4) stony duplex; (5) shallow soils over laterite/granite; or (6) other soil type.
- Position in landscape. These categories were: (1) valley floor; (2) low to mid slope; (3) mid to higher slope; (4) ridge; and (5) outcrop.
- Connectivity to reserve or remnant. Connectivity to a reserve or remnant was classed as: (1) isolated; (2) adjacent/close by; (3) adjoining; and (4) inside.
- Tree density for each quadrat. Density of stems per quadrat was used to estimate tree density of all age groups of wandoo. Other tree species were included in the estimate, if present. Groups were; (1) <10; (2) 11-20; (3) 21-30; (4) 31-40; (5) 41-50; and (6) >50 stems/quadrat.
- Average tree diameter at breast height over bark. Average diameter of wandoo trees in each quadrat was approximated from a quick sampling of 6 to 10 trees at breast height over bark (DBHOB). Groups were: (1) 5-10; (2) 11-20; (3) 21-30; (4) 31-40; and (5) >40 cm.
- Fire history. Fire history for each site was assigned to categories of: (1) <5 yr; (2) 5-10 yr; (3) 10-20 yr; (4) 20-30 yr; and (5) >30 yr. The date of the last fire was recorded, if known. Recorded fires were those that were intense enough to scorch tree crowns.
- Slope type, aspect and gradient. Slope type was described as uniform, convex or concave. Slope aspect was approximated as direction of fall relative to magnetic north. Slope gradient was estimated as from: (1) 0-2; (2) 2-4; (3) 4-6; (4) 6-8; (5) 8-10; and (6) >10 degrees fall.
- Phenology. Phenology was estimated using a similar method to that of Mercer (1991): binoculars were used to observe the presence of fruit, buds, new leaves and flowers and their density and uniformity within the stand. The categories were: (0) none present; (1) few present; (2) sparse and uneven; (3) sparse and even; (4) moderate and uneven; (5) moderate and even; (6) dense and uneven; and (7) dense and even.
- Type and nature of tree decline. Type and nature of tree decline was a short description for each stand based on whether crown symptoms were typical of the present decline pattern, including: whether this decline event was recent, with characteristic fresh mosaic patterns of leaf deaths in the crowns or in the epicorms; whether there was evidence of old decline events; or whether decline was not typical.
- Average annual rainfall. Annual rainfall for each site was interpolated from isohyets generated from rainfall data using Weaver (1997).
- Broader observations. Additional observations for each quadrat were: associated vegetation communities, including nearby farmland as a defined association; dominant understorey

species; and the presence of any notable features within or around each quadrat. These observations were not included in data analysis.

3.2.5. Recording of general trends and mapping

General trends of crown decline along the transects were recorded to present a wider profile of the wandoo decline patterns. A thematic grid map (Map 1) was produced using "ER Mapper" (Earth Resources) to illustrate the spatial pattern of wandoo decline. Crown ratings, interpreted as colours for each site, were mapped using standard triangulation techniques to generate interpolated values. Average crown rating values for each site were grouped into five colour categories. Navy blue indicated the highest ratings for crown health progressing in an order of declining crown health through light blue, green, yellow, orange and finally red which represented the lower ratings for crown health. Data from assessed sites were extrapolated over the areas outside the transects. Areas were labelled where insufficient data was captured. Average annual rainfall isohyets were from Weaver (1997) and illustrate the spatial representation of wandoo stand health over the south-west of Western Australia from data gathered over 129 sites along the southern, central and northern transects.

3.2.6. Comparison of 1991 and 2002 data on wandoo decline

Comparison of 1991 and 2002 data was undertaken at three sites (Boyagin, Noombling and Popanyinning on the central transect) used by Mercer (1991) to assess wandoo decline in the central wheatbelt. Sites were re-visited to assess the impact of the present decline and its relationship to the past decline. From similar reference points, sites photographed in 1991 were again photographed in 2002 for the present survey. Both the 1991 and 2002 photographs for each site were more representative of the quadrats used 11 years later, rather than the original transects based on random selection of specific age classes of trees along a given compass point. Data collected in 1991 were gathered from these selected trees. Specific DBHOB groups were chosen to represent 4 age classes (5-10, 11-20, 21-30 and >30 cm). Analysis was more precise, including several field excursions to collect samples for laboratory analysis.

3.2.7. Data collection and analysis

Within each quadrat, several semi-quantitive and descriptive parameters (independent variables) were assessed. Average crown health rating was tested against this set of independent variables using an initial univariate approach. A multivariate model based on those variables identified as being significantly ($p<0.05$) or marginally significantly ($p<0.15$) related to crown health was then developed using a step-wise linear regression model and the model building strategy of Hosmer and Lemeshow (1989).

For all sites, parameters showing significance against average crown condition were divided into those related to potential causes of decline and those related to site location and history. Variables likely to be related to potential causes were average annual rainfall, time since last fire, overall insect damage and lerp insect damage in particular, and time since last fire. Parameters also possibly related to decline were litter layer, land use, position in the landscape, connectivity and slope gradient. Factors related to site history were longitude, proportion of trees with no or minimal impact, presence of fruit, presence of buds and age of epicorms. The extent of crown decline was related to the set of potential predictor variables (Table 1) using stepwise multiple linear regression analysis and standard criteria (p-value for entry and removal = 0.15, Hosmer and Lemeshow 1981). To ensure that the assumptions underlying each technique were met, the standard diagnostic tools (stem-leaf plots, normal-normal plots, Shapiro-Wilk normality tests and plots of residuals against fitted values) were used.

Table 1. The set of potential predictor variables for crown decline. Variables with a non-ordinal pattern (such as "Land use") or where it was judged that the response may not be linear (such as "Fire history") were reduced to a set of dummy variables (hence LUSE1-LUSE6, FIRE0-FIRE5) as indicated.

Variable Name	**Description**
DEAD	Proportion of trees dead due to present decline (%)
INSECT	Insect damage group 0 = None or very little (0 – 5 %) 1 = Low (6 – 10 %) 2 = Moderate (11 – 25 %) 3 = High (26 – 50 %) 4 = Very high (> 50 %)
CHEW	Leaf area chewed or missing (%)
MINE	Leaf area browned, mined or scarred (%)
LERP	Leaf area with lerp builders attached (%)
WOODY	Cover of native woody vegetation (%)
GRASS	Cover of native grass and sedges (%)
WEEDS	Cover of exotic weeds (%)
LITTER	Cover of litter layer (%)
SALT	Soil salinity (mSm^{-1})
LUSE 1 – 6	Land use 1 = paddock 2 = parkland cleared 3 = private remnant 4 = road verge 5 = State Forest 6 = National Park or Nature Reserve
SOIL 1 – 5	Soil type 1 = Sandy loam or loamy sand 2 = Duplex soil (< 50 cm over clay) 3 = Duplex soil (> 50 cm over clay) 4 = Stony duplex 5 = Shallow over laterite or granite
LAND 1 – 5	Position in landscape 1 = Valley floor 2 = Low to mid slope 3 = Mid to higher slope 4 = Ridge 5 = Outcrop
CONNECT 1 – 4	Connectivity to reserve or remnant, 1 = Isolated 2 = Adjacent or close by 3 = Adjoining 4 = Inside

Variable Name	**Description**
DENSITY	Tree density for each quadrat
DBOH	Average tree diameter over bark at breast height
FIRE 0 – 5	Fire history 0 = Unknown 1 = < 5 years 2 = 5 – 10 years 3 = 10 – 20 years 4 = 20 – 30 years 5 = > 30 years
GRADIENT	Slope gradient (degrees)
SLOPE 1 – 3	Slope type 1 = Uniform Slope type 2 = Convex Slope type 3 = Concave
ASPECT 1 - 4	Slope aspect 1 = 0 – 90 degrees Slope aspect 2 = 90 – 180 degrees Slope aspect 3 = 180 – 270 degrees Slope aspect 4 = 270 – 360 degrees

4. RESULTS OF 2002 SURVEY

4.1. Specific factor effects

4.1.1. Parameters correlated with crown decline

In relation to wandoo crown rating, average annual rainfall and longitude were marginally significant and significant ($p<0.15$ and $p<0.05$ respectively). Overall insect damage was significant and showed an inverse relationship, with increasing damage with decreasing crown ratings. Lerp insect damage was also significant, but no correlation was evident to suggest that this parameter was clearly related to crown health trends (Figs. 1, 2).

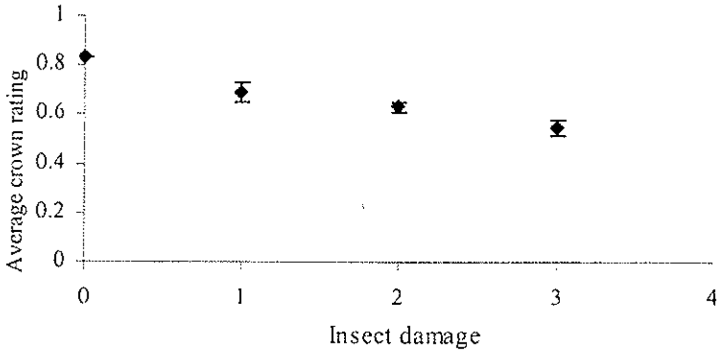


Figure 1: % Overall insect damage and Average crown rating

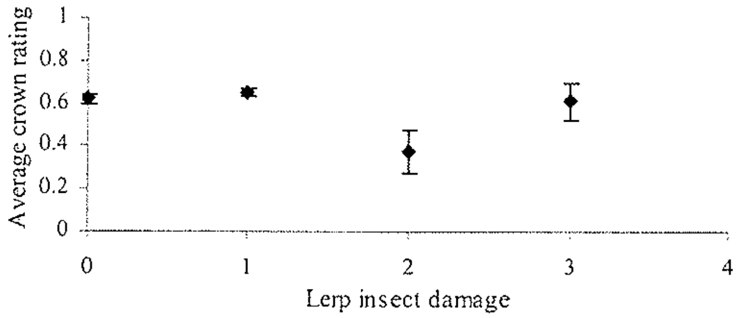


Figure 2: % Lerp insect damage and Average crown rating

Fire history was significant with increasing crown ratings directly correlating with increasing years since the last intense fire (Fig. 3). Position in the landscape ($p<0.15$), also showed a distinctive trend where crown ratings increased with higher position in the landscape (Fig. 4). Land use ($p<0.05$) had no discernible trend, although highest crown ratings were in private remnants and road reserves (Fig. 5). Sites within National Parks and Nature Reserves had the lowest average crown ratings.

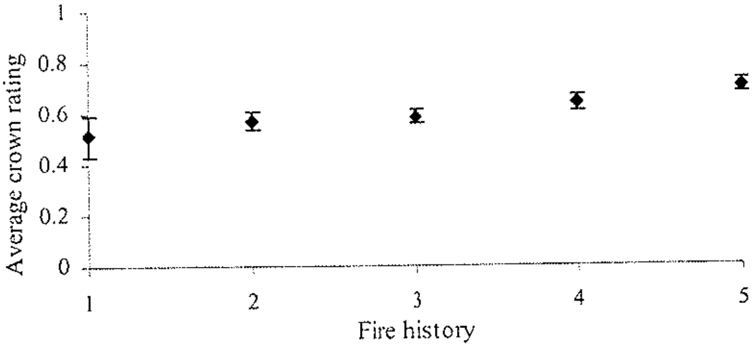


Figure 3: Fire history and Average crown rating

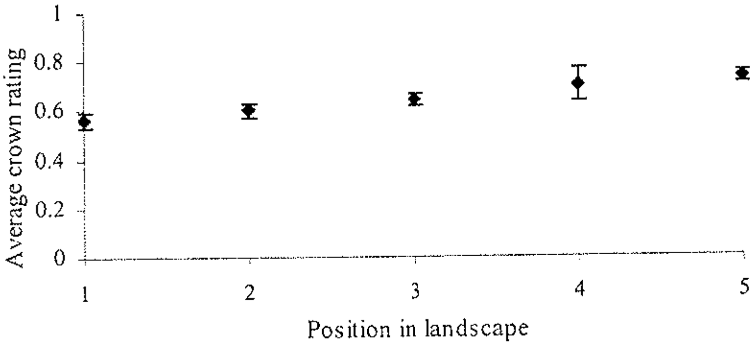


Figure 4: Position in the landscape and Average crown rating

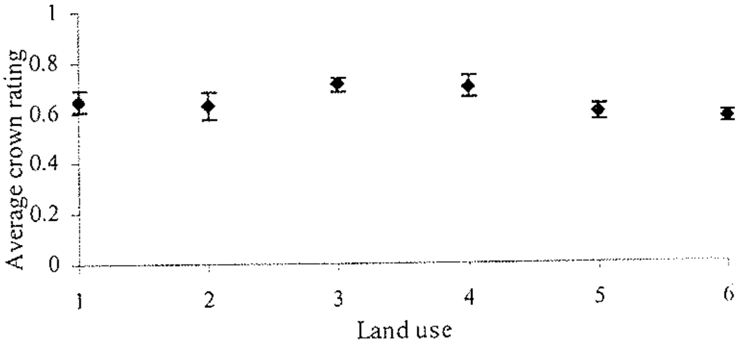


Figure 5: Land use and Average crown rating

Isolated sites or those adjoining bushland typically exhibited high crown ratings, with the lower ratings being inside and adjacent to/close by bushland ($p<0.05$, Fig. 6). Gradient slope ($p<0.05$) also showed no distinctive trend, with slopes of 4-6 degrees having the highest average crown ratings (Fig. 7).

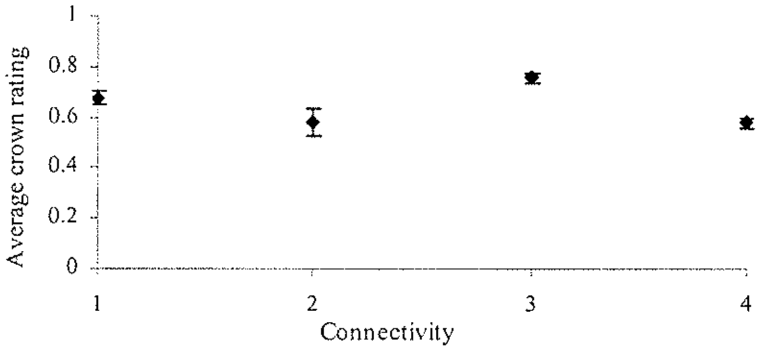


Figure 6: Connectivity and Average crown rating

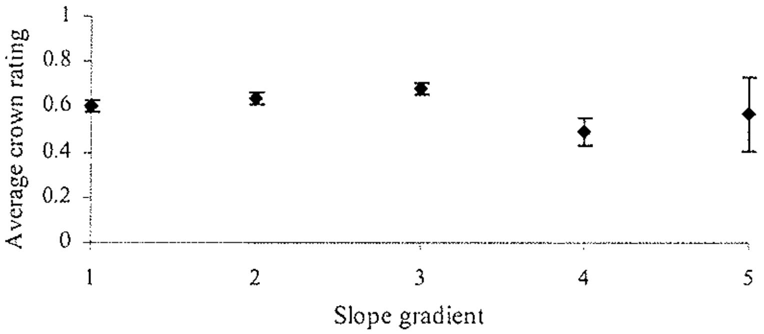


Figure 7: Slope gradient and Average crown rating

4.1.2. Results of multiple regression analysis

Initial analysis confirmed that the main factor related to disease severity was the proportion of dead trees at a site. Although this confirmed that crown rating was an effective surrogate for the level of tree death and so was a useful means of assessing and rating decline, this result was uninformative in identifying potentially causative factors. Thus, we re-analysed the data without this variable as a potential predictor.

The multiple regression analysis showed that crown decline rating was significantly related to the predictors ($F_{7,119}=6.47$, $p<0.0001$) but only poorly predictable ($R^2=0.28$). Variables identified as statistically significantly related to crown decline score were (in order): insect damage group (p=0.0033), isolated stands (p=0.0047) and those adjoining reserves (p=0.0097), litter cover (p=0.0116) and fire interval >30 yr (0.0169). All except insect were positively correlated with crown decline score.

4.1.3. Parameters related to site location and history

Significant parameters relating to site history and showing correlations were % of trees with minimal or no impact ($p<0.05$), presence of fruit ($p<0.05$) and presence of buds ($p<0.05$) (Figs. 8-10). All three parameters increased with increasing crown health, the first being predictably a direct correlation and the others a more general correlation. Regarding age of epicorms ($p<0.05$), none present or growth greater than five years old related to higher crown ratings (Fig. 11).

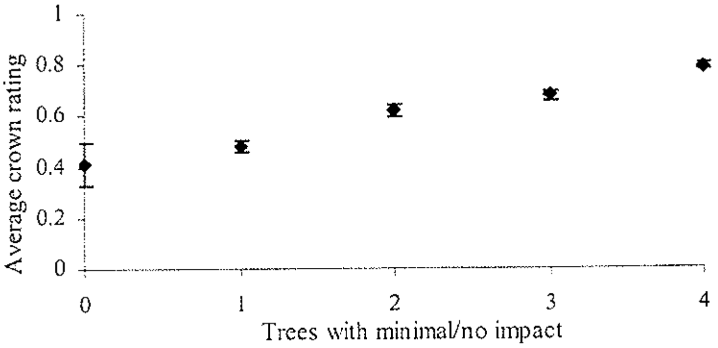


Figure 8: % Trees with minimal or no impact and Average crown rating

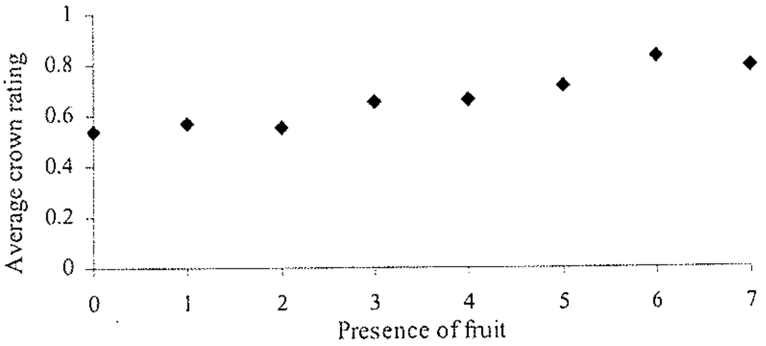


Figure 9: Presence of fruit and Average crown rating

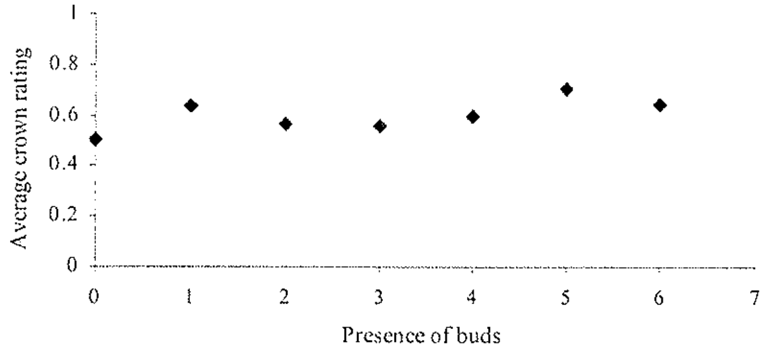


Figure 10: Presence of buds and Average crown rating

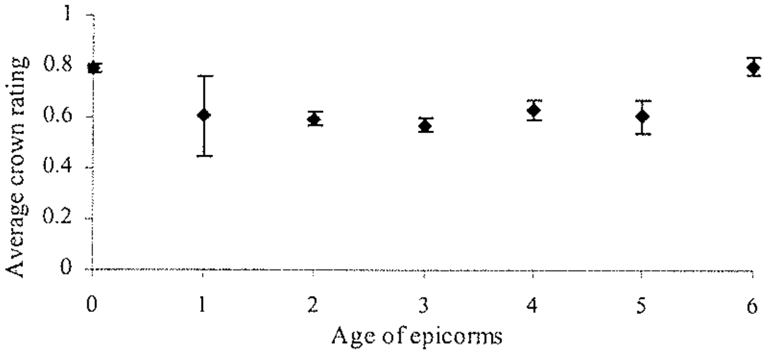


Figure 11: Age of epicorms and Average crown rating

4.2. General trends along transects

Observations along the transects showed that the present decline pattern was often overlaid onto other earlier decline patterns. Temporal and spatial trends in decline were apparent and separate decline events had occurred, or were occurring, that may be distinct from one another.

4.2.1. Patterns of present decline

The present decline pattern was broadscale, variable and not continuous across the landscape. Canopy loss was both very recent and up to the approximate age of 10 years. Stands and individual trees often displayed very little or no decline symptoms while decline was evident nearby. This was characteristic along all transects, even in zones of marked decline (Plate 1). Also characteristic was the sporadic occurrence of trees with fresh patches of discoloured leaves, indicating the beginning of, or a new cycle of, decline (Plate 2). Average crown health within quadrats was improved by the presence of fire-regenerated dense stands of young wandoo trees (Plate 3), usually between 15 and 30 years old and by other regeneration that established after soil disturbance (such as on road verges) and did not display the decline variability of mature trees (Plate 4). They appeared to be less affected, or more commonly not affected at all, by the decline while older trees were.

4.2.2. Temporal and spatial trends

Distinguishable decline events were long term dieback greater than 10 years but probably decades old (Plate 5), salinity-related dieback, both recent and long term (Plate 6), and the present decline pattern, witnessed over the last decade. The rapid crown defoliations (occurring and documented in 1991), due to extreme summer temperatures, can be considered a separate decline event. This pattern was not witnessed in this survey (Plate 7). Throughout the survey, both long term and salinity-related dieback were coincident or separate from the present decline pattern. Salinity-related decline was recognisable by trees, in an obvious saline environment, that had died back some years before and now existed with a contracted crown. These trees were often unaffected by the present decline pattern.

Increased incidences and impacts of the present decline fell within the approximate geographical area where there was increasing natural occurrence of wandoo (Map 1). Increasing decline correlated with increasing rainfall moving west on the northern transect, with decline more evident at about the 450 mm rainfall isohyet (Fig. 12a). Moving west along the central transect, decline became more evident at Narrogin on the 450 mm isohyet. Crown health generally improved on this transect at sites near or within the state forest around the 650 mm isohyet (Fig. 12b). On the southern transect, however, decline was more evident at the 400 mm isohyet but became less evident just east of the 650 mm isohyet near Frankland (Fig. 12c).

Plates 1 and 2: Healthy wandoo tree, in the vicinity of defoliated trees, showing no symptoms of present decline (left) while a tree previously showing minimal or even no impact (right) has evidence of a fresh outbreak of discoloured patches of leaves. Note the old epicormic growth (>10 years) on the stem.

Plate 3: Regeneration stands of wandoo, displaying no decline symptoms, were typical throughout the survey. **Plate 4:** Nearby this regeneration was an example of the typical variability of decline displayed by older trees.

Plate 5 (right): Long term decline of wandoo was often characterised by crown dieback, followed by refoliation to a point where trees survived under changed environmental conditions with a contracted crown. Note the absence of the present decline pattern on this individual.

Plate 6 (below left): Salinity related decline may be fatal to wandoo but trees may similarly survive with a contracted crown.

Plate 7 (below right): Early stages of rapid crown defoliations, that occurred after extremely high temperatures in 1991 and were not witnessed in this survey. After leaf discolouration and loss of the whole crown, trees generally recovered with no cyclical decline and recovery pattern following the initial decline event.

MAP 1: WANDOO HEALTH BASED ON CROWN ASSESSMENT

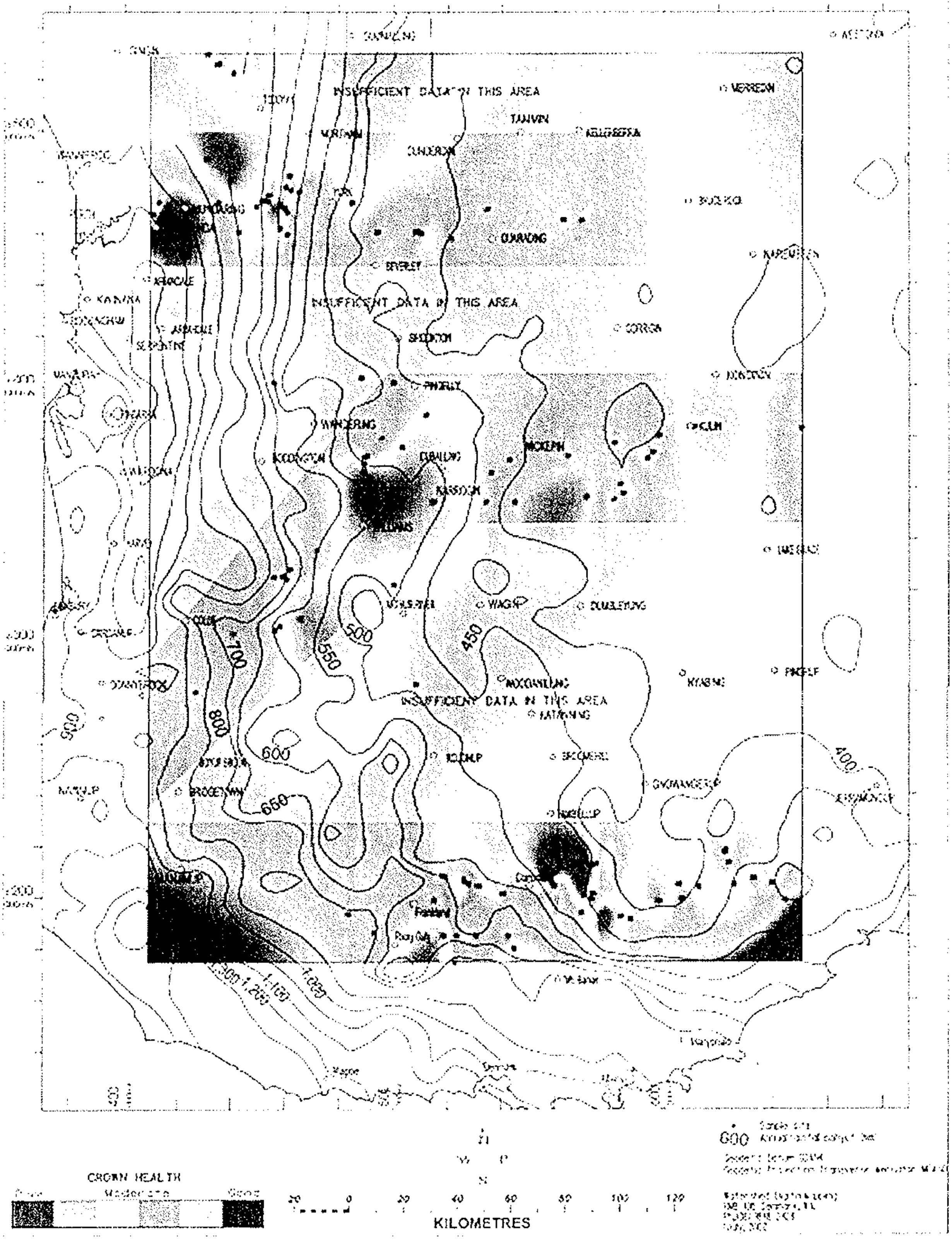


Figure 12: Relationship of wandoo crown health to increasing rainfall

Crown health and rainfall trends along the northern (12a), central (12b) and southern transects (12c). The general trends moving east to west, illustrated by a fifth order polynomial for crown ratings, showed that crown health decreased in the vicinity of the 400 and 450 mm rainfall isohyets for the southern and central transects. At the 650 mm isohyet, there was a general increase in crown health, particularly for the southern transect. For the northern transect crown health declined at the 450 mm isohyet.

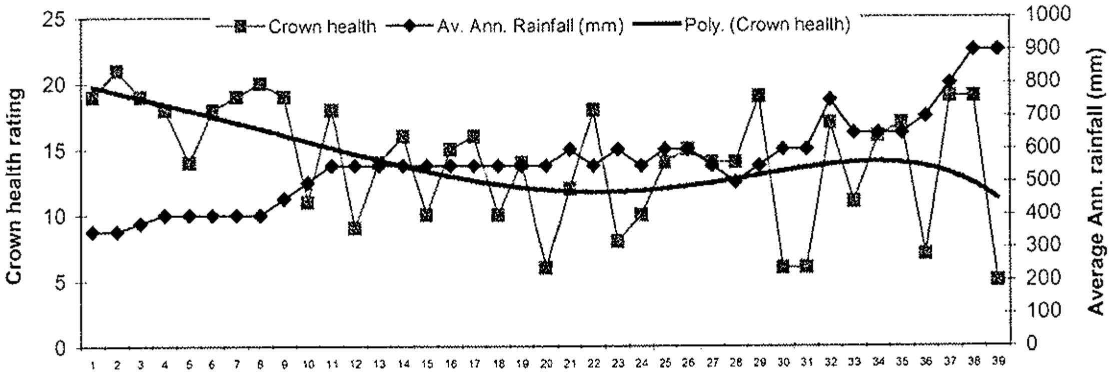


Figure 12a: Northern transect

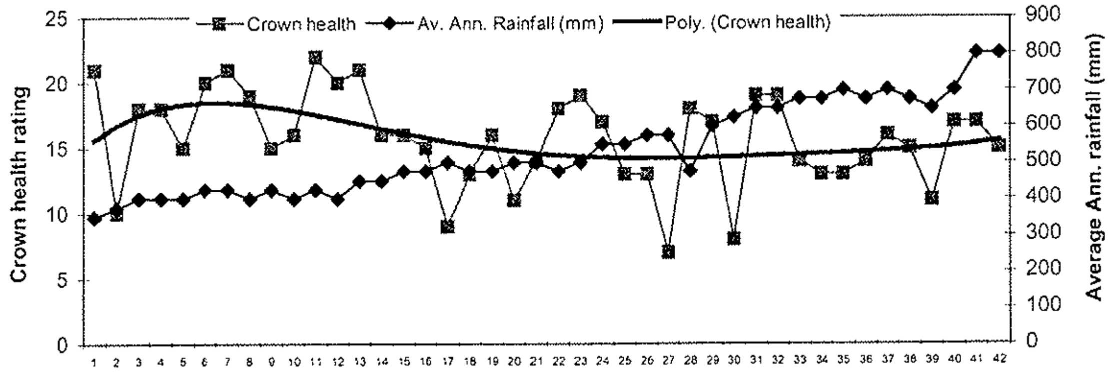


Figure 12b: Central transect

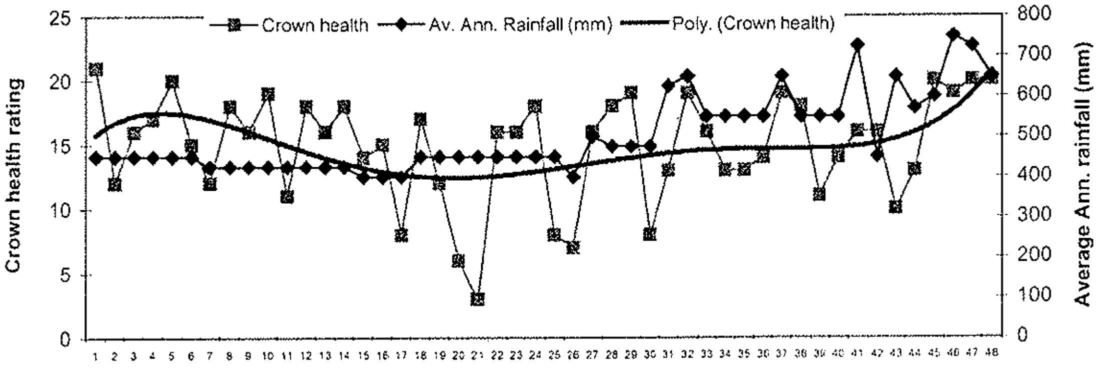


Figure 12c: Southern transect

4.3. Comparison of 1991 and 2002 data at Boyagin, Noombling and Popanyinning

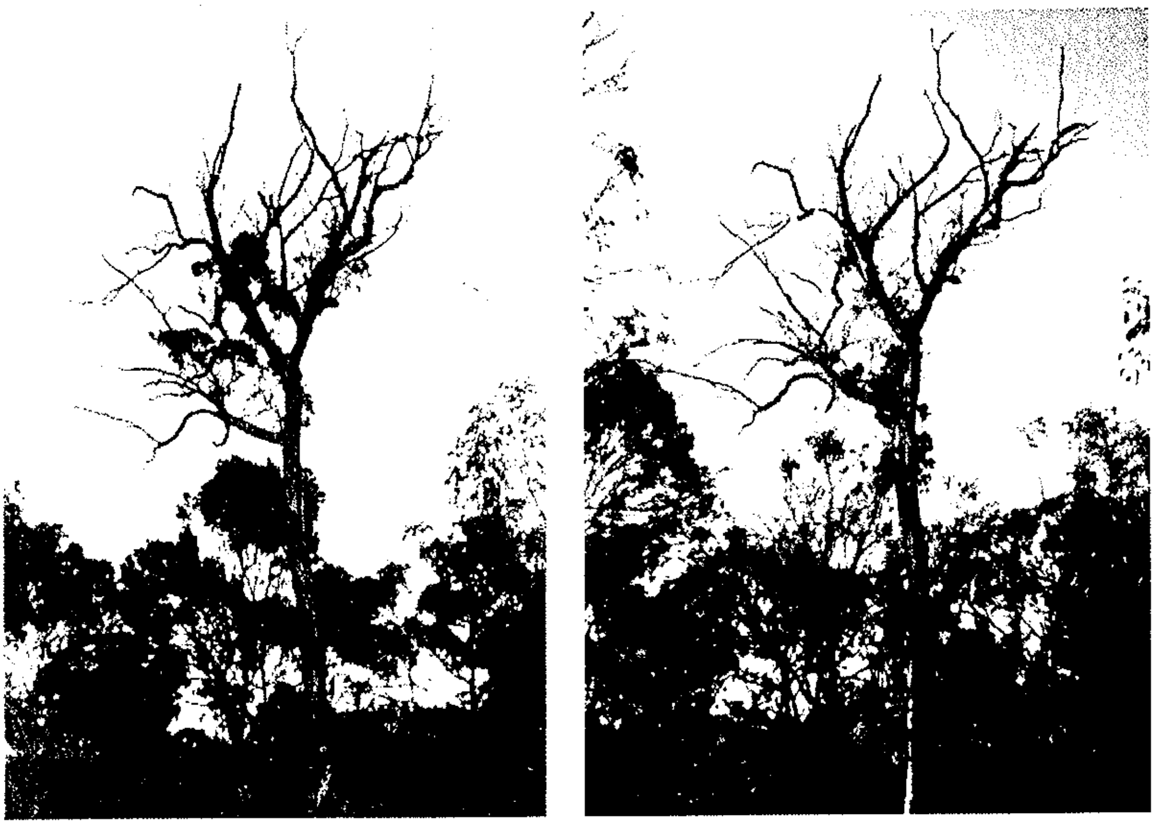
Data collected and photographs taken in 1991 and 2002 showed that there was overall little change in the structure of wandoo canopies during the intervening 11 years at Boyagin, Noombling and, to a lesser degree, Popanyinning (Plates 8-13). Boyagin was the healthiest site in 1991 and showed no evidence of the present decline pattern in 2002. Noombling, the intermediate site in 1991, showed some limited symptoms of the present decline, mainly defoliation from about 3-5 years ago, with no cyclical pattern present. Popanyinning, classed as degraded in 1991, showed more advanced symptoms and impact from the present decline, including ongoing leaf discoloration, defoliation and exposed dead branchlets. The 1991 site photographs and several other images of wandoo from that time did not give any indication that symptoms of the present decline pattern were present. At Popanyinning and Boyagin, older decline symptoms displayed in veterans as "stagheads" showed little change over 11 years with limited defoliation in some upper canopies on close inspection (Plates 14-17). At Boyagin, a healthy wandoo tree in a paddock also showed little change (Plates 18 and 19).

Plates 8 and 9: Boyagin site in 1991 (left) and 2002 (right). The wandoo canopies have remained stable over 11 years at this relatively inaccessible site with no sign of the present decline.

Plates 10 and 11: Noombling site in 1991 (left) and 2002 (right). There has been loss of canopy leaf density and defoliation of mainly small branchlets was minimal.

Plates 12 and 13: Popanyinning site in 1991 (left) and 2002 (right). There was little structural change over 11 years. Ongoing leaf discolouring and defoliation were evident, due to the present decline pattern. This site was classed as degraded in 1991, more affected than Boyagin and Noombling by the present decline.

Plates 14 and 15: Wandoo veterans at Popanyinning from 1991 (left) and 2002 (right), displaying gradual decline over 11 years. Note the retention of branches and branchlets in the canopies over this time. Note also the defoliation of the tree in the background, typical of the present decline.



Plates 16 and 17: A veteran at Boyagin from 1991 (left) and 2002 (right), also displaying gradual decline over 11 years. Note the relative stability of the young trees and 30+ year old regeneration in the background. There was no evidence of the present decline pattern at this site.

Plate 18 and 19: Images of a coppiced wandoo in a paddock next to Boyagin Reserve in 1991 (left) and 2002 (right) showing little change, apart from a slightly thinner canopy, and no symptoms of the present decline.

4.4. Reported declines of wandoo – a literature review

Following large-scale clearing of the original south-western woodlands, remaining wandoo woodlands are now mainly found in a few scattered reserves, road verges and privately owned remnants or exist as paddock trees (Saunders and Hobbs 1989). Reports over the last 40 or so years, discussed below, collectively showed that remaining wandoo appeared to be in decline for reasons largely unknown. One consequence of land clearance has been rising water tables and increasing secondary salinity (Conacher 1990), and there is general acceptance that this has impacted wandoo on valley floors and lower slopes where their salt tolerance threshold has been exceeded.

4.4.1. Brief reports on wandoo decline

In 1963, wandoo deaths were occurring on the middle to lower slopes in the Dale region and east of the Gleneagle division (Podger undated). Declining trees were noted near settlements, in logged areas and in virgin stands well within the woodland belt, which effectively ruled out salt toxicity as a causal factor. Fire damage and fungal infection were also ruled out, with no further information given. Tree deaths occurred quite rapidly but vigorous wandoo regeneration, to about 5 m in height, remained unaffected.

Kimber (1981) reported that wandoo and other trees had been declining within the wheatbelt since the early 1970's, with affected trees more common on road verges and in paddocks and less frequent in remnant woodlands. Drought, together with agricultural practices and opening up the woodlands, was implicated. Curry (1981) reported increased dieback in wandoo during the drought years of 1975-1980. Young trees and coppice growth appeared to be less affected than old trees. Drought, soil salinity and defoliating and sap-sucking insects were implicated. Kimber also reported that parasitising by mistletoe was increasing, but its contribution to dieback was questionable because both recently dead and vigorous trees were affected. Brown et *al.* (1990) reported that mistletoe was common along roadsides in wandoo trees. More structured studies (discussed below) were undertaken in 1991, 2000 and 2001. Appendix 2 summarises the history of wandoo decline through documented reports.

4.4.2. Findings of 1991 study on wandoo decline

Mercer (1991) reported that general causes and effects of wandoo decline did not appear to be consistent with those reported for woodlands in eastern Australia. Relationships between wandoo decline and (i) foliar nutrients, tree stress and herbivory; (ii) impact of fertilizers causing tree stress and increased herbivory; and (iii) serious fungal infections and associated biotic agents, could not be substantiated. Changes causing lower leaf specific weight and higher leaf water content (all proven indicators of woodland dieback in eastern Australia) were not apparent in wandoo. Higher foliar nitrogen as an indicator of tree stress was not apparent but may have been masked by seasonal changes in leaf nitrogen. Soil and foliar nitrogen and phosphorus were generally low compared to other eucalypt woodlands. Insect herbivory was generally low and within the range shown for other eucalypt ecosystems.

Secondary salinity and waterlogging have caused widespread tree decline and death in the wheatbelt and may have been causing or contributing to dieback of wandoo, at one site. High soil salinity was evident but wandoo showed tolerance by excluding salt. Cited research suggested that wandoo acquired tolerance to salinity after juvenile growth. Combined salinity and waterlogging, however, appeared to predispose trees to stress and decline which was indicated by high sodium to potassium ratio in leaf tissue. Soil properties were relatively consistent from site to site with little deviation from those characteristic of wandoo areas. Soil compaction was evident at one site, but was not caused by livestock or vehicle movements and did not appear to be adversely affecting trees. In conclusion, regional decline of remaining wandoo implicated a long term pattern of decreasing rainfall (especially since 1945) along with periodic drought, the long term effects of weather fluctuations, climate change, and a lack of fire that has resulted in little or no fire-reliant wandoo regeneration. Wandoo dieback was indisputable, however, and much of the evidence was likely due to an event 15-20 years before 1991. Older epicormic growth suggested that recovery was under way, but it was assumed that dieback symptoms on younger trees signalled a general increase in wandoo decline.

4.4.3. Rapid crown defoliations in South-western Australia

In early 1991, extensive defoliation of several tree species was reported over a wide area in the south-west of Western Australia after a series of extreme daytime temperatures, from 42-46°C, in mid to late summer. Comparisons were made between these symptoms and wandoo dieback symptoms in the Pingelly-Brookton district, to observe if similar patterns were apparent (Mercer 1991). No wandoo had died between preliminary and final observations, although some residents reported a few deaths. There was a general recovery with epicormic buds appearing about six weeks after the temperature extremes. Trees had responded with only light to moderate regrowth. Various studies have reported about desiccation of leaf tissue, vulnerability of trees in the agricultural landscape and crown defoliation as a survival mechanism for other eucalypt species. Extremes in weather may have predisposed wandoo to stress and that these trees were thus susceptible to dieback or defoliation before the extreme temperatures. Tolerance levels for susceptible trees may have been reached and defoliation of crowns occurred. The data showed that, where rapid defoliations were observed, there was a return to average annual rainfalls for 1988-1990 relative to below average rainfalls for 1985-1987. Thus, there was a weather extreme from wet to dry over a relatively short period.

4.4.4. Findings of 2000 and 2001 wandoo decline studies

Reports on wandoo crown decline in the York district (Wills et *al.* 2000, 2001) suggested several causes including increasing soil salinity, insect or fungal attack, fire damage and drought. Regardless of the origins, the same pattern of defoliation and crown decline may have been apparent. The decline pattern was variable and not continuous across the landscape. Canopy loss was described as both recent and long term. Several types of environmental stress had probably contributed to canopy declines in the area. Trees examined within a small area showed wide variation in the expression of effects of environmental stress. Canopy loss was not followed inevitably by tree death.

Canopy decline in Talbot forest block did not coincide with unusual insect attack or salinity and was most likely related to drought. In Wambyn Nature Reserve, however, crown decline was coincident with, though not necessarily caused by, salinity in part of this reserve. Decline was reported in apparently non-saline areas but some decline due to salinity was also reported. Because insects and fungi were not implicated as primary causes of decline, resistance of trees to their defoliating impact was not expressed clearly. In Talbot forest block canker fungi increased in activity following initial foliage losses, indicated by cyclical deaths of successive epicormic shoots. Canker fungi were not present on all declining trees. The sap-sucking psyllid, *Creiis periculosa*, was not considered a significant contributor to crown decline near York, although wandoo can carry high populations of this species that cause defoliation. On some roadside and paddock trees, stem borers may have been implicated in a high rate of "girdling" and eventual loss of branches. "Mundulla Yellows" syndrome that was affecting *Eucalyptus camaldulensis* (river gum) and other species was not observed in this survey.

Crown decline was observed in both dense regrowth and old open stands, subject to regular fuel reduction burning, and open stands of mature trees, probably unburnt for several decades. This suggested that fire exclusion was probably not a contributor to environmental stress in extensive decline. It would be difficult to identify wandoo that was genetically resistant to the crown decline as it was difficult to separate variation in exposure to environmental stress from phenotypic variation in the expression of decline. It was also concluded that the extensive wandoo crown decline in the York district was not unusual and was probably linked to below average rainfall in 1997, 1998 and 2000. For Talbot block, 1997 and 2000 were within among the driest 30% of all recorded winters.

The crown declines were a phase in a cyclical process and the crowns would eventually stabilize and recover over several years, but there would be some of stand thinning. Dead branches from this decline would remain in the recovered canopies for many years. In Talbot block, wandoo on valley floors were observed to have more severe crown decline than those higher in the landscape. Wandoo on valley floors may be subjected to soil salinity that has restricted the rooting depth and increased their vulnerability to winter droughts.

5. DISCUSSION

5.1. Average annual rainfall

The significant relationship of crown health and average annual rainfall suggested that this parameter may be implicated in wandoo decline. Declining health, however, was not related to any direct correlation with rainfall with the most marked decline between the 400-450 mm and 650 mm isohyets, particularly on the southern and central transects. Since the mid-20th century, May-July winter rainfall in south-western Australia has decreased sharply. In the last 25 years from 1976-2001, May-October average rainfall has been 85-90% of the preceding 50 year average from 1925-75 (IOCI, 2002). The mapped contours, representing the range of these % changes (ibid. pp 2), roughly coincide with those contours on Map 2 that illustrate a zone of marked decline in the Narrogin, Williams and Darkan Shires. Other zones of marked decline (Cranbrook, Tambellup and York district) fall within where there has been 90-95% rainfall of the preceding 50 year average. IOCI reported that this rainfall decline was not gradual but abrupt, in the mid-1970s, and may not have allowed older wandoo to adapt. The relationship between wandoo decline and decreasing rainfall, or fluctuations in rainfall patterns, warrants further investigation within the survey area, particularly concerning the last decade and the present decline pattern.

5.2. Insect damage

Overall insect damage and lerp insect damage may be implicated in the decline but this was more likely to be a contributory than a primary cause. Insects may also be acting as a vector for fungal infection of susceptible trees. As previously mentioned, Wills et *al.* (2000) reported that aerial canker was present on some but not all declining trees, which implicated this pathogen as a secondary or even tertiary contributing factor to decline. Several authors have documented sequences in decline that generally place insect (and fungi) attack as contributory or tertiary (Palzer, 1981; Podger, 1981; Ogden, 1981; Houston, 1987; White, 1986). Insect damage appears to be an auto-correlation with respect to increasing or decreasing crown rating. Further investigation is warranted to determine the role of insects and fungi in wandoo decline.

5.3. Fire history

Fire, that was intense enough to scorch tree canopies, may bring disturbance that allowed the present decline pattern to be expressed in trees, since the longer without fire, the healthier tree crowns were. There was a progressive sequence from fire damage, fungal rot and then termite activity established by Perry et *al.* (1985). High intensity fires at the Salt River Road and Red Gum Pass sites in the Stirling Range National Park (Plates 20 and 21) appeared to have encouraged the typical symptoms of the present decline to rapidly accelerate and ultimately cause the highest death rates and lowest crown ratings recorded in this survey. The condition appeared to be related to the destruction of a post-fire response flush of crown and epicormic growth after the wildfires. The deaths of approximately 25%, 40% and 50% of trees recorded at three plots related to respective crown ratings of 7, 6 and 3. These results appeared to represent the surrounding areas that had been burnt. At Salt River Road, the typical decline pattern had rapidly accelerated after a high intensity fire in the autumn of 1994 but recovery was evident in 2002 with no new decline cycle observed. At Red Gum Pass after high intensity fire in the spring of 2000, the same pattern was evident and ongoing decline was apparent. Epicormic shoots, that appeared to be less than one year old and that indicated a characteristic post-fire recovery response, were mostly destroyed. High intensity fires may have weakened the resilience of the wandoo to the present decline. If there were water deficits related to the present decline, any epicormic growth may have died back due to lack of water. In particular, the fire at Red Gum Pass was in the year of a severe winter drought. The 1994 fire also followed below average winter rainfall and a record dry 1993/94 summer. This may be difficult to substantiate because, observations of the post-fire outcomes on Salt River Road before the present survey were limited. At Red Gum Pass, however, further observations of the post-fire situation present an opportunity. Alternatively, fire damage may have predisposed trees to a fungal pathogen.

Wills (et *al.* 2000) observed the present crown decline pattern in both dense regrowth and old open stands, subject to regular fuel reduction burning, and open stands of mature trees, probably unburnt for several decades. The findings of this survey suggested that fire exclusion was probably not a contributor to environmental stress in extensive decline. Previous research in Tasmania and Victoria may contradict that healthier eucalypt crowns were related to longer periods without fire. Understorey succession in the absence of fire has been implicated in eucalypt declines. Withers and Ashton (1977) and Ellis et *al.* (1980) showed that healthier, more vigorous understorey was related to declining eucalypt crowns, due to long periods without fire. The introduction of fire created a more favourable environment for eucalypts by encouraging their regeneration and crown vigour in mature trees and largely destroying the presence and vigour of fire-sensitive understorey. Further research is needed to establish the optimum fire frequency and intensity for different eucalypt species that facilitate perpetuity of those eucalypt-dominated systems. For the wandoo sites, longer periods without fire may have allowed more time for crowns to recover from fire damage. Therefore, crown assessment would likely give higher crown ratings that were interpreted as less symptoms of decline. Hatch (1960) and Burrows et *al.* (1990) showed that intense fire was an important mechanism for the perpetuation of wandoo, by promoting regeneration on ashbeds formed by fallen, burning trees. Some of the more definitive results in this survey were regarding the relationship with high intensity fire and the present decline, and thus warrant further investigation.

Plates 20 and 21: In the Stirling Ranges, wandoo decline appeared to be accelerated after a high intensity fire in 1994 (left). The typical decline pattern had rapidly accelerated in 1995 and 1996 with the destruction of the epicormic growth that was a response to the fire. There was general recovery recorded in 2002 with no evidence of fresh decline but about 25% of trees died. After a wildfire in 2000 (right), new epicormic recovery was similarly impacted. Deaths of trees were about 40-50% and severe decline was ongoing. A severe drought at the time of the fire may also have been implicated.

5.4. Position in the landscape

Crown health improved with higher position in the landscape and the present decline appeared to have more impact on the lower slopes and valley floors (both saline and non-saline). Wills et *al.* (2001) observed, for the Talbot block, that decline was more severe on broad shallow valleys and less severe in upper parts of the landscape (although this was not quantified). A tentative explanation for this is that in the higher areas, where clearing generally did not occur, wandoo have not been affected by rising watertables. Therefore, root systems in the deeper profiles have not been compromised and the trees were more resilient to reduced soil moisture storage exacerbated by a water deficit. Wandoo in the lower elevations has been directly subjected to major disturbances, usually related to agriculture, that were likely to predispose them to decline. Crombie (2000) presented models representing how paddock trees become susceptible to rising watertables as their deeper root systems are compromised or drowned by permanent inundation. Excavations of wandoo root systems, on the crest of a hill in granitic/doleritic profiles, have shown roots penetrating up to 23 m down into the profile (John Bartle, DCLM, pers. comm.). Wandoo on higher elevations may have adapted to less available soil moisture (possibly linked to more extensive root systems), which offered protection from recent rainfall deficits. Outcrops and ridges are also often characterised by exposed and sub-surface boulders of variable sizes. These formations may create an effective local water-gaining and water storage site for adjacent vegetation. Alternatively, some of the assessed sites in higher positions may occupy the original lateritic surface where deeper soils are able to store and re-supply water to trees (J McGrath, CALM, pers. comm.). According to White (1969), however, large outcrops have shallow soils over granite and high clay content, which is typically poorly drained in wet conditions and prone to desiccation in hot weather. Consequently, trees on these areas would be susceptible to stress and dieback if there were extremes in weather that created a water deficit. This does not appear to be the case for wandoo.

There is little explanation for the lowest crown ratings on the valley floors in forested catchments. Shallow saline soils may sometimes be associated with these low-lying areas and contribute to decline in the same manner as described by Crombie (2000). Soil salinity readings for the 2002 survey were low but possibly not to an adequate depth. The deepest measurement was to 1 m below the soil surface with the EM-38 salinity meter. Broader observations still suggested that wandoo could adapt to survive a degree of salinity, often displaying a contracted crown (see section 4.2.2.). Wills et *al.* (2001) reported that soil salinity did not appear to be a factor in crown decline at a site in Talbot block. Further research is required to remove speculation and establish why rainfall deficits have not impacted wandoo as might be expected.

5.5. Land use and connectivity

With respect to land use and connectivity, sites within National Parks, Nature Reserves and inside other reserved bushland exhibited lower crown ratings. Private remnants, followed by road reserves, exhibited the highest crown ratings. A plausible explanation is that uncleared bushland supported high stem densities (of both trees and understorey), which may increase competition for moisture and predispose wandoo to crown decline in times of low rainfall. Woody understorey species have been shown to compete with canopy trees for available moisture and used more water than pasture (John Bartle, DCLM , pers. comm.). This survey recorded few sites, however, where understorey appeared to be stressed or declining, as the wandoo were. It would be expected that moisture stress would generally work from the upper to lower soil profiles, if lower rainfall was a factor in decline. Also, Lamont (1985) reported that wandoo can suppress understorey species by competing successfully for available moisture. Therefore, decline or death of understorey species should have been more evident, where wandoo trees were also displaying decline. For private remnants and road reserves, healthier crowns may have resulted from increased availability of moisture after clearing. For road reserve trees, available moisture may have increased due to the catchment effect created by the camber of road surfaces, or the damming effect sometimes created by road construction (which can also trigger localised secondary salinity). Most of the private remnants and some Nature Reserves were small in area. The degree of connectivity, to a larger reserve or remnant, appeared to offer no buffer against the present decline pattern, with the healthiest sites being isolated or adjoining bushland. Earlier reports documented that road reserve or paddock trees were more susceptible to decline than trees buffered by bushland (Kimber, 1981; Mercer, 1991). If connectivity acted as a buffer against increasing wandoo decline, then competition for moisture in areas of higher stem density may be a more pivotal factor. Further investigations into rainfall history, particularly over the last decade, may reveal more with respect to the above results. Also, further studies regarding the significance of position in the landscape and slope gradient may show that sub-surface impacts on root systems in the lower landscape are linked to wandoo decline.

5.6. Other parameters

A higher percentage of trees with minimal or no impact, increasing presence of fruit and increasing presence of buds related to higher crown ratings and generally indicated healthier sites. The relationship to the first parameter and crown rating was a predictable auto-correlation. Mercer (1991) indicated that higher density and more even distribution of fruit, buds and new leaves related to healthier crowns or crown recovery in wandoo (there were few recordings of leaves and flowers throughout this survey due to the time of year). Finally, higher crown ratings, where epicormic growth was absent or greater than 5 years old, were a general indicator that the present decline pattern was minimal or absent and there was an overall healthy stand of wandoo.

5.7. General trends along transects

Both Wills et *al.* (2000) and this survey found the decline pattern to be variable and not continuous across the landscape. Canopy loss was described as both recent and long term in the former report but was described as recent and up to 10 years old in the latter survey. The occurrence of unaffected individual trees or stands of trees suggested that soil and/or moisture conditions have not predisposed trees to the decline. It was also possible that, if any pathogens were contributing to the decline, that some trees were showing genetic tolerance. Younger trees may be able to adapt to changing conditions and remain unaffected or only slightly affected. Although Wills et *al.* (2000) reported that young regeneration stands were declining in Talbot block, Podger (undated) and Curry (1981) reported this was not the case. Mercer (1991) reported that older trees showed more decline but decline in some younger trees (not including regeneration stands) may signal a general increase in dieback.

This survey found that the present decline pattern, long term dieback and salinity-related dieback were likely to be separate events occurring over different time frames that may overlap. The present decline and recovery pattern appeared to have a duration of around 3-10 years, with successive epicormic responses experiencing cyclical decline until they began to display resilience with foliage growth stabilising. Several sites assessed in this survey have not, and may not, reach this state as ongoing decline was evident.

5.7.1. Long term decline

There was the long term event (or events), possibly occurring over several decades, where there had been cyclical decline and recovery that was not related to, or did not display typical symptoms of, the present decline. In most cases, declines were distinguishable from one another but it was often the case that trees displayed both patterns. Long term decline was usually distinguishable from that now being witnessed by the bleached appearance of dead branches and branchlets still in the canopy and/or their loss from the canopy. Also recognisable were large branches protruding above a contracted canopy. Mercer (1991) reported that much of the evidence of decline was from an event 15-20 years earlier. Kimber (1981) and Curry (1981) reported on events in the 1970's, and Podger on an event in the early 1960's. Recovery and contraction of crowns may be normal as trees adjust to worsening or improving conditions and this pattern would likely include senescent trees (see Section 4.4.3. and Plate 5). With respect to the drought in the mid 1970's, for instance, anecdotal evidence was that some wandoo that had died back at this time had refoliated when conditions improved. When observed in 1991, notwithstanding closer observation, affected trees appeared to have fully recovered. This survival mechanism is supported by Jacobs (1955), Houston (1984) and Pook (1986).

5.7.2. Salinity-related decline

Salinity-related decline events were usually more recognisable. This decline pattern was distinguishable by EM-38 soil salinity measurements and by appearance when taking into account the impact on the surrounding landscape and the ascendance of salt-tolerant plant species, for example, *Melaleuca cuticularis* (salt water paperbark) and *Halosarcia species* (samphire). Salinity-related decline may be abrupt or gradual when rising watertables and secondary salinity continue to impact on remaining wandoo. The species may also decline to a level (see Plate 6) where salt tolerance is acquired and trees sacrifice growth for development of sap solutions to counter the osmotic gradient created by saline soils (Morris 1968; van der Moezel et *al.* 1988; Mercer, 1991). Therefore, salinity-related decline may be evident over variable time frames. Long term wandoo decline due to salinity was often similar in appearance to other symptoms such as droughts, fire damage, absence of fire, bark-borers, or agricultural chemicals, or combinations of these factors.

5.7.3. Rapid crown defoliations

The rapid crown defoliations, after temperature extremes in 1991, should also be considered a separate decline event and pattern (see Section 4.4.3.) Crown defoliations appeared to be an isolated response. Leaf death and defoliation took only a few days and recovery was evident six weeks later (see Plate 7). Recovery of trees was generally slow and confined to within the tree crowns and extremities of branches that did not die back. Burrows et *al.* (1990) reported that wandoo were slow to recover after a fire event, and therefore may respond similarly to any major disturbance. No cyclical pattern of decline and recovery was evident after the initial defoliations. Observations supported that road reserve and paddock trees were more affected than those in remnants. Paddock trees may have been more vulnerable to watertable fluctuations, when compared to woodland, in particular with respect to alternating years of wetter and drier cycles. Models by Crombie (2000) showed how paddock trees became susceptible to rising watertables when their deeper root systems were compromised or drowned by permanent inundation. These trees were further compromised by exposure to more sunlight, more wind, less humidity and increased re-radiation which increased moisture losses from leaf surfaces. Pook (1986) suggested that trees under the stress of a water deficit may be susceptible to defoliation and that already stressed eucalypts would undergo defoliation, which would be advantageous to their survival. Pook also showed that *E. maculata* leaves were killed when subjected to 46°C for one hour and 51°C for half an hour. White (1969, 1976 and 1986) suggested that tree stress was caused by fluctuations in weather. Jacobs (1955) suggested that eucalypts may defoliate as a mechanism of survival and refoliate again when environmental conditions were more favourable. Houston (1984) suggested that trees recover once the stress mechanism passed. It should not be assumed, however, that these impacts were relevant to wandoo. It should also be considered in retrospect that leaves in wandoo canopies were simply killed when their tolerance threshold to high temperatures was reached. If no predisposing mechanisms were implicated, however, one might expect that canopy loss would have been more widespread and uniform.

5.7.4. Overview of separate transects

Southern transect

On the southern transect, one of three plots (S 34° 17' 112" E 118° 31' 352") at the Greaves Hill Nature Reserve site showed advanced symptoms but also some recovery, whereas the nearby plots were relatively healthy. The next site on this transect with advanced symptoms was on the north-west corner of the Stirling Range N. P. (S 34° 17' 476" E 118° 22' 125") and may have also been affected by salinity. A site on Salt River Road and inside the Park (S 34° 19' 785" E 117° 46' 502") showed evidence of serious decline dating back to around 1995, after an autumn wildfire in 1994. Two plots on Red Gum Pass (S 34° 23' 822" E 117° 50' 860" and S 34° 23' 790" E 117° 50' 810"), also inside the Park, were similarly affected after a wildfire in 2000 (see Section 5.3.). Moving further west toward Frankland, evidence of decline was progressively less, as mentioned. At Randell Road Nature Reserve (S 34° 28' 566" E 117° 12' 096"), decline appeared older and not related to the present event. In general, symptoms of the present decline were less along the eastern and western extremities of this transect. Anecdotal evidence suggested that the decline in the vicinity of the southern transect began north of the Stirling Ranges on the higher slopes around 1993 and 1994 but eventually appeared across the landscape including valley floors. Ashbed regeneration trials of wandoo in the same area, dating back to 1992 and 1993, were unaffected by the present decline while nearby mature trees were affected.

Central transect

On the central transect, moving west, the beginning of serious decline was not as definitive with the first advanced symptoms at just one farm site east of Kulin on Flat Rock Road (S 32° 45' 911" E 118° 01' 697"). There was a general improvement in crown conditions west of this site until just east of Wickepin where serious and ongoing decline reappeared on roadside trees. The Narrogin Water Reserve (S 35° 56' 684" E 117° 09' 506") showed serious decline symptoms from an older event of the present decline. North-west of Narrogin, two sites in the Dryandra reserve system were relatively healthy, despite evidence of typical decline, while one site had been impacted quite heavily. Not far from these sites, on Yornaning Road, decline was marked and ongoing with low crown health masked by dense epicormic foliage. Sites on Albany Highway were similarly affected but also with fresh outbreaks of leaf deaths (before defoliation) evident. Further observations between North Bannister and Cranbrook supported that this cyclical decline pattern on Albany Highway (in a north to south direction) was widespread, but still, sporadic stands or individual trees in paddocks, remnants and road reserves appeared unaffected. From Williams to Collie, typical decline was less evident with other decline mechanisms, such as fire damage or an older drought event, more likely to be implicated. Despite this, scattered paddock trees just west of Collie were showing typical decline symptoms with fresh outbreaks evident.

Northern transect

On the northern transect, the most easterly site assessed was near Kwolyn, where the occurrence of wandoo was sparse. Further east of this site on the Yarding Road, a roadside stand of *Eucalyptus capillosa* was inspected and showed no typical symptoms of the present decline. Obvious decline symptoms in wandoo became evident just east of York on the York-Quairading Road (S 31° 53' 414" E 116° 50' 456"). About 20 km west of York in woodlands on the Ebenezer Flats (S 31° 53' 034" E 116° 30' 567"), severe decline was evident and widespread. Nearby on Bowercutty Road, some stands of *Eucalyptus accedens* on outcrops were showing the typical early discolouring symptoms of what appeared to be the same decline pattern.

5.8. Comparison of 1991 and 2002 data

Sites at Boyagin, Noombling and Popanyinning appeared resilient over 11 years, despite a gradual progression of the present decline at Popanyinning and minimal impact of this pattern at Noombling. Considering that Popanyinning was chosen in 1991 as a degraded site, apparently affected by salinity, the increase in decline symptoms recognised at that time was much less than predicted. There was no evidence in 1991 of the present decline pattern at any sites or in the surrounding landscape. It was, however, documented as early as 1992 in Helena Valley (Hussey, 1999). More severe symptoms of the present decline were now evident at Popanyinning. A fresh outbreak was affecting old epicormic growth and buds were aborting. There were epicormics less than one year old, indicating some recovery, but there was ongoing discoloration and loss of leaf biomass. Mistletoe was also present. Boyagin, chosen 11 years ago as a control well within the Boyagin Nature Reserve, showed the least change of all three sites in 2002. There was no evidence of the present decline pattern and epicormic response was minimal. A correlation can be drawn between the site assessments of 1991 and 2002 with respect to the earlier and the present decline. Its impact graduated from being absent at the healthiest site, to having minimal impact at the intermediate site, through to being more advanced at the degraded site. It was possible that, before the advent of the present decline, the greater the environmental stresses were, the more predisposed wandoo became to new decline. This may be a relevant topic for a future investigation to follow.

At Boyagin and Popanyinning, veteran wandoo were similar in appearance to 1991 observations and displayed long term dieback symptoms not related to the present decline and probably older than the decline being witnessed in 1991. Both trees appeared to have mostly retained the large and small bleached branches, and even some branchlets, that had been long dead 11 years ago. One veteran at Popanyinning had further declined with loss of epicorms observed in 1991 but replaced by what were now 3 to 5 year old epicorms. The other veteran at Boyagin was impacted by bark-borers and had similarly shown gradual decline. The paddock wandoo near Boyagin appeared to still be healthy with slight loss of leaf biomass. Comparison of old and new images, however, generally point to less leaf biomass on wandoo throughout the southern wheatbelt.

5.9. Reports on wandoo declines

A set of common factors became apparent when comparing cited literature. Drought or rainfall deficits, fire regimes, fungal pathogens, insect attack, waterlogging and salinity, agricultural practices and lack of regeneration were common themes implicated in decline events. Also apparent was that younger trees and regeneration were generally less affected or not affected at all by reported declines. Wills et *al.* (2000) and Mercer (1991) did report some impacts on younger trees. Wandoo in all positions in the landscape had been impacted by one or more decline events. Overall, the reported declines of wandoo remain largely unexplained. In retrospect to the 1991 studies, results also appeared to show an inherent resilience in wandoo. As previously mentioned, the present decline pattern was not apparent at the time of the 1991 study. Several photographs taken at the time throughout the central and southern wheatbelt and Darling Scarp (outside the 1991 study area) did not indicate any symptoms in wandoo crowns that have recently been observed in relation to the present decline pattern.

Wills et *al.* (2000) identified that a canker fungus was effecting some, but not all, declining wandoo in their survey. This was an important finding because it contradicted a view in the community that there was a ubiquitous "disease" that was causing crown decline and death in wandoo. Davison and Tay (1983) reported that canker fungi were often associated with other causes of tree stress, such as, drought, frost and insect attack. White (1986) considered insect and fungal attack to be contributory to decline. Landsberg (1988) considered fungal infection an unlikely predisposing factor. Podger (1973) suggested that protracted dry conditions break down host resistance to secondary attacks. Other research in Australia and overseas similarly supported the theory of predisposition, where the impact of fungal pathogens was more likely to be a tertiary or secondary contributing factor in tree decline. Secondary fungal and insect attack may, however, ultimately play a greater role in woodlands decline (Pook 1981). Woodland trees in eastern Australia have returned to pre-drought status after replenishing rainfall (Landsberg, 1985) and there was evidence to support this response for wandoo. If rainfall deficits were implicated in wandoo decline, it was plausible to assume that fungal and insect agents will increase the fatalities of this species across its range. The presence of a disease, acting as an independent variable should not, however, be completely discounted.

Wills et *al.* (2000) and the 2002 survey similarly described the present decline pattern to be variable and not continuous across the landscape and canopy loss was both recent and long term. Similarly described was the apparent recovery of wandoo. Although recovery was often evident after a decline event and considered by some authors to be part of a survival mechanism, the cumulative impact on the remaining wandoo population was likely to be an increasing rate of decline and death across its range as older trees capitulated and little recruitment took place.

6. CONCLUSION

The present decline of wandoo is one in a series that have been documented in the latter half of the 20th century. This latest survey explored several factors in order to document the spatial extent of the present decline and determine likely potential causes. Several factors have been implicated but no definitive cause or set of causes has been isolated.

A reliable indicator of healthier wandoo throughout this survey was a higher percentage of trees with minimal or no impact, where epicorms were not present or very old and increasing presence of fruit and buds. Insect damage, and specifically damage by lerp insects, may be implicated in the decline but this was more likely a contributory rather than primary cause. Insects may also be acting as a vector for fungal infection of susceptible trees. The longer a site was without high intensity fire, the healthier the trees crowns were, suggesting that fire-associated disturbance allowed or initiated tree decline. Similarly, there was evidence of a strong relationship between recent hot fire events and the acceleration of the present decline pattern. Two sites affected by wildfire in 1994 and 2000 showed epicormic recovery after the fire but the new growth was destroyed by mechanisms that displayed symptoms of the present decline pattern.

Crown health was better at higher position in the landscape and steeper slopes also exhibited some of the higher crown health ratings. The higher areas where wandoo still exist, however, have not been cleared or affected by rising watertables and their deeper root systems have not been compromised. The trees may thus be more resilient to drought-induced soil moisture storage reduction. Alternatively, lower crown health within National Parks, Nature Reserves and other bushland remnants, suggested that higher stem densities usually associated with these areas were predisposing wandoo to less water availability during drought periods. Remnants on privately owned land and in road reserves exhibited the highest crown ratings.

There were some findings that reflected a temporal and spatial trend in decline across the wheatbelt. The decline was broadscale, the pattern was variable and not continuous across the landscape and canopy loss was both recent and long term. The zones between the rainfall isohyets of 400-450 mm and 600-650 mm showed the most marked crown decline on the southern and central transects. On the northern transect, there was no definitive improvement of crown health west of the 500 mm isohyet. From east to west, the relationship between average annual rainfall and crown decline suggested that rainfall is relevant to wandoo decline, but could not be correlated directly with rainfall. However, recent rainfall deficits may be implicated in wandoo decline because zones of marked crown decline roughly coincided with areas where rainfall deficits have been recorded.

Long term dieback, salinity-related dieback and the present decline pattern appeared to be separate events with variable but overlapping time frames. Apart from salinity, the underlying predisposing factors for all these decline events may have been the same. There was little structural change within 3 sites assessed for wandoo decline in 1991, and again in this survey. Old decline symptoms remained much the same. With regard to the present decline pattern, sites classed as healthy, intermediate and degraded in 1991 showed no impact, minimal impact and advanced symptoms of the present decline 11 years later, in that order. Therefore previous site condition may have predisposed trees to greater impacts from the present decline.

Over the past few decades, reports on wandoo decline documented several common factors that may be causal. The greatest impact has been land clearing for agriculture, which has reduced the extent of wandoo and fragmented the remaining stands. Increased salinity and waterlogging, consequences of clearing, were recognisable causes of decline. Some agricultural practices, such as chemical use, may also be having negative impacts. Climate change, periodic drought and decreasing annual rainfall may be contributing to broadscale decline of the species. A changed fire regime in the south-west of Western Australia was also implicated. The cumulative impact on the remaining wandoo population was likely to be an increasing rate of decline and death across its range as older trees capitulated and little recruitment took place.

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Appendix 1. Assessment of wandoo crowns

Leaf density (exclude epicormics on bole)

9	very dense
7	dense
5	average (refers to ideal, not the stand)
3	sparse
1	very sparse
0.5	all leaves dead
0	leaves absent

If much fruit is present, increase the score by 1.

Incidence of dead branches

9	none present
8	< 50% of branchlets dead
7	> 50% of branchlets dead
6	< 50% of small branches dead
5	≥ 50% of small branches dead
4	< 50% of large branches dead
3	≥ 50% of large branches dead
2	< 50% of primary branches dead (epicormics present)
1	≥ 50% of primary branches dead (no epicormics)
0	all branches dead

Contribution of epicormic branches to foliage

6	no epicormics present (foliage concentrated at extremities of branch)	
5	on crown or bole	< 25%
4	on crown or bole	> 25-50%
3	on crown or bole	> 50%
2	on crown and bole	< 50%
1	on crown and bole	≥ 50%
0.5	on crown and bole	100%
0	tree is dead	

Appendix 2. Survey of previous studies documenting wandoo decline

Author	Period	Location	Where recorded	Explanatory factors mentioned
Podger, undated	Early 1960s?	Dale and east of Gleneagle.	Mid to lower slope near settlements, logged areas and virgin stands well within woodland belt.	Unknown. Not fire, fungus, salinity. Regeneration unaffected
Kimber, 1981	Early 1970s	Wheatbelt.	More in road reserves and paddocks, less in remnants.	Drought, agricultural practices, opening up woodlands.
Curry, 1981	1975-1980	Wheatbelt.	Not specified.	Drought, soil salinity and defoliating and sap-sucking insects. Young trees and coppice growth less affected.
Mercer, 1991	1970s, 1980s or even earlier	Central and southern wheatbelt.	Road reserves, steep gully, high elevations, mid to low slopes.	Canopy loss both recent and long term. Lack of regeneration. Changed vegetation structure, spread of fire sensitive species. Dry period for last 20+ years. Evidence of long term affects. Evidence of decline in some saline areas. Younger trees less affected.
Mercer, 1991	February 1991	Southern wheatbelt	Road reserves, high elevations, paddocks, mid to low slopes.	Possible 3 year dry followed by 3 year normal rainfall period, then extreme temperatures in 1991. Wet winters also followed by very hot summers. Trees buffered by remnants less affected. No cyclic decline.
Wills et al, 2000	Late 1990s	York district	Topographic location of occurrence in broad valleys (sometimes)	Broadscale across whole area surveyed. Canopy loss recent and long term. Pattern variable not continuous across landscape. Current decline associated with dry period. Canker fungi not present on all declining wandoo. Evidence of healthier trees higher in the landscape. Evidence of long term effects/ cyclic effects.
Mercer et al, 2002	1990s	Wheatbelt	All positions in landscape	No factors isolated but several implicated. Healthier trees related to less fire, higher position in the landscape, rainfall, more fruit and buds. Canopy loss recent and up to 10 years but present decline event decipherable from other events. Pattern variable not continuous across the landscape. Broadscale across the whole area that is surveyed. Fire and roadside regeneration 10 to 30 years old less affected.