

Tree decline in the Coorong and Tatiara, South Australia

Literature review and statement of research priorities



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Summary

Introduction

We conducted a literature review to evaluate the current knowledge of issues that potentially lead to tree decline and tree death in the Coorong and Tatiara district council regions. We aimed to highlight research priorities for the region. We reviewed issues that were highlighted by either the literature or by discussions with landholders and stakeholders in the region. We identified 13 tree decline issues for review.

Review of tree decline issues

We summarise the main findings for each of the tree decline issues below. Each issue is reviewed in greater detail in the body of the document.

Drought and low soil moisture. Drought is rarely the direct cause of tree death in the region, as trees that lose condition during drought generally recover. However, drought can increase the susceptibility of trees to other tree decline issues, such as wood borers and other insect infestations. The frequency and severity of droughts is predicted to increase in the coming decades, and research is needed on the interactions this may have with other tree decline issues.

Psyllid (Ierp insect) infestations. Tree decline and death can result from infestations of psyllids (Ierp insects). There have been several well-documented Ierp-infestations on Pink Gums (*Eucalyptus fasciculosa*) in the study region in the last 120 years. The issue may be related to Noisy Miners (*Manorina melanocephala*) excluding smaller insectivorous birds that would otherwise control psyllid populations. Other likely contributors to psyllid infestations relate to land modification and management. Research is needed on the extent and severity of tree decline due to psyllids. We also need better data on the population dynamics of species involved in insectivore–psyllid–tree interactions before we can propose potential management strategies.

Wood borers. A previous study by Paton *et al.* (2005) suggests that tree decline due to wood borers may have increased in recent decades. Studies have shown that borer populations increase following drought – and more specifically when wood moisture content is low – though our review explores other hypotheses for increased borer populations that may warrant investigation. Research is needed on the extent of damage by wood borers in the region, including some basic data on which borer species are prevalent in different tree species, and in which different parts of the landscape.

Damage by Galahs and Corellas. Galahs and Corellas nest in mature trees, and often cause damage to the nest trees by chewing on the bark, which can lead to tree death via ringbarking. Vegetation clearance and tree dieback have reduced the number of available nest trees in the landscape, while extra feed resources (due to cereal cropping) support greater populations of Cockatoos. Due to this imbalance, a higher proportion of trees are subject to damage. We need a better understanding of the extent of the problem, although it is unlikely to be resolved. Tree regeneration to replace mature trees should be prioritised. If methods to deter Galahs and Corellas

can be developed, they will likely only be useful for iconic or important trees, rather than a broad-scale solution.

Dryland Salinity. The issue of dryland salinity is well understood, and there are regional plans to deal with the issue. Past vegetation clearance has increased soil salinity, which leads to further vegetation loss as plants cannot cope with saline soils or waterlogging of their roots. There has been extensive research on the effects of salinity on production systems, although the effects on native vegetation (and biodiversity loss) have received less attention. Enactment of salinity management plans, based on our current knowledge, is a higher priority than further research into the effects of salinity on trees in the study region. Focussing efforts on curtailing the effects of salinity will have greater benefit than increasing our knowledge of exactly what these effects will be.

Chemical drift. We found no documented evidence of tree decline associated with chemicals applied to crops in the region, though there is anecdotal evidence that simazine can cause tree decline issues. Any general studies of tree decline in the region should consider the potential impact of chemical drift when other well-supported explanations cannot be identified. It is possible that chemicals may interact with other tree decline issues, such as wood borers or psyllids, by impacting on their natural enemies, though this has not been investigated.

Soil compaction. Soil compaction can reduce pore volume of soil and alter infiltration and water-holding capacity, all of which can result in poor tree health. The magnitude of the contribution of soil compaction to tree decline issues in the region is not known, and requires research. It has been reported as a significant concern for land managers and NRM managers.

Fire damage to trees. Burning of stubble in cropping paddocks can damage trees that are sensitive to fire, such as Buloke (*Allocasuarina luehmannii*).

Mundulla Yellows (MY). There are two competing hypotheses for the cause of Mundulla Yellows (MY) in south-eastern Australia. One is that MY is caused by an infectious disease (a virus or other pathogen). The other is that MY is lime chlorosis caused by the use of crushed limestone in roads and an underlying calcified bedrock layer. As limestone washes into the roadsides, dissolved carbonates increase the soil pH, converting essential nutrients to forms that cannot be taken up by trees, and causing deficiencies in nutrients such as iron and manganese.

Plant pathogens. Phytophthora Root Rot is a serious pathogenic threat in areas with greater than 500 mm.yr⁻¹ rainfall, and hence is more likely to the southern extent of the study region, around Padthaway. Irrigation may allow Phytophthora Root Rot in lower rainfall areas, though this is uncommon in the region as soil conditions in the region are generally not conducive to *Phytophthora* infestations.

Dodder Laurel infestation. Dodder Laurel (*Cassytha melantha*) is a parasitic vine that can impact on the health of its host. Infestations have been reported for roadsides in Mallee vegetation. Experimentation for its control is an option, and we provide suggestions for possible treatment methods that could be trialled. Research is also needed into the extent and severity of the problem.

Mistletoe. Mistletoes are a natural component of healthy woodlands, and are important resources for wildlife. However, heavy infestations of mistletoe can impact on tree health. We describe several factors that can impact on the processes that limit mistletoe abundance. Research is needed, primarily, on the extent and severity of the problem, and research may be necessary on interactions between mistletoe and factors such as birds and drought.

Witches' Broom. This disease, associated with phytoplasmas, is usually not lethal, and has a low incidence of symptomatic trees wherever it occurs. It is hence a low priority for research, unless it emerges to be a widespread and frequently lethal problem.

Lack of recruitment

We must expect that trees in the landscape will die, and hence there needs to be continuous recruitment in the landscape to replace senescent trees. We need to take advantage of the natural regeneration potential of isolated paddock trees while they are still alive. Livestock grazing, seed availability and the timing of rainfall are the most important factors for natural tree regeneration in agricultural landscapes (Vesk & Dorrough 2006). Excluding livestock or strategically grazing areas around paddock trees to allow natural recruitment may be the simplest solution, however other management barriers may need to be overcome and these may require further investigation.

Conclusions and research priorities

The overwhelming theme from the review is that we require a better understanding of the extent and severity of each issue across the region. This would provide an essential platform for better understanding the causal factors and devising management strategies. For each issue, we need to ask the following questions: How widespread is the issue in the region? Which species is it affecting, and which species is it not affecting? Is the issue associated with land management practices, specific parts of the landscape, soil types, or climatic events or cycles?

We propose the development of a database for compiling spatially explicit data on instances of tree decline in the region. The data could be interrogated in conjunction with available GIS data (e.g. soils, topographical and climatic data) to address the above questions for each tree decline issue. A user-friendly website would allow citizens to input their data and observations on instances of tree decline. This exercise has the potential to generate more data than could be collected using a randomised survey approach. We would also like to conduct experiments in the use of potential lime chlorosis treatments, such as stem implants to correct nutrient deficiencies.

The review has highlighted more research needs than can be addressed by the current research project. In this sense, the document can serve as a useful reference for future research into tree decline.

Abbreviations

CEM – Centre for Environmental Management, Federation University Australia

CTLAP – Coorong Tatiara Local Action Plan

EPBC Act (1999) – Environment Protection and Biodiversity Conservation Act (1999)

MY – Mundulla Yellows

SA – South Australia

USE – Upper South East (a natural resource management region of South Australia)

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1. Introduction

1.1. Purpose of this document

The Centre for Environmental Management (CEM), Federation University Australia, was contracted by the Coorong Tatiara Local Action Plan (CTLAP) to conduct research into issues of tree decline and death in the regions of the Coorong and Tatiara District Councils. This is a three-year project (July 2014–July 2017). The three main stages of the project are:

- Stage 1** – Literature and knowledge review, and statement of research priorities
- Stage 2** – Research and field assessments (to be guided by literature review process)
- Stage 3** – Stakeholder engagement and dissemination of findings and recommendations

This document is the product of the project's first stage. The two primary aims of this document are:

1. To review the state of knowledge on tree decline issues relevant to the study region; and,
2. To identify research priorities for addressing tree decline in the region, for both our further research into the issue, and as a resource for future research in the region.

To assess research priorities, we will be guided by the following question: *Which research is most likely to improve the ability to manage tree decline in the region?* The purpose of this review is not to provide management recommendations. This is the aim of stages 2 and 3 of the research project. It is preferable to make management recommendations after we have conducted our review and research project, at a time when we have a greater understanding of the tree decline issues, the region, and the feasibility of potential management strategies.

It should also be noted that this review will focus on those issues that directly influence tree health and tree decline. It is not a general review of natural resource management issues in the region, as has been done in the past (Coorong LAP Committee 2012, Foulkes & Heard 2003, SE NRM Board 2010, Tatiara LAP committee 2013). There is, however, a significant amount of overlap between the region's natural resource management issues and the region's tree decline issues, though we will be focussing on the aspects of these issues that are directly relevant to tree health.

1.2. Methods

There are many factors that potentially impact on tree health and influence tree decline in the study region. To determine the scope of this review, we needed to identify which of these factors were most important and hence warranted focus. We employed several processes to achieve this:

1. **Discussions with stakeholders and land managers.** We sent emails to stakeholders (including land managers) from a list provided by the CTLAP. This led to email correspondence, phone conversations, and site visits with a range of stakeholders. On the 8th–10th December, 2014, we visited a range of sites in the region to discuss tree dieback issues on-site with stakeholders.
2. **Meeting with LAP members.** On the evening of 9th December 2014, an informal meeting was held in Keith between members of the CEM (Nick Schultz and David Cheal) and a number of

CTLAP members to discuss the prominent tree decline issues in the region. The meeting allowed the CEM to gain an insight into the issues from the perspective of engaged and prominent regional stakeholders.

3. **Review of literature and other publications.** Reports, newsletters, and community resource brochures and booklets were informative resources for indicating the range of tree decline issues faced by the region. Online resources were also useful (e.g. Natural Resources South East 2015). There is limited region-specific scientific literature on tree decline issues, though some sources were very informative (e.g. Czerniakowski *et al.* 2006; Hanold *et al.* 2006; Luck *et al.* 2006; Parsons & Uren 2007; Paton *et al.* 2005).

We aimed to select issues for further investigation that satisfied one or more of the following criteria:

1. Issues that are known causes of tree death in the region
2. Issues that have a moderate to wide distribution in the region (i.e. we tried to avoid issues that were highly localised or had very few instances)
3. Issues that are likely to have been influenced by human land management
4. Factors that could potentially influence tree decline in the region, but for which little is known, or has not been well documented

The following tree decline issues were selected for a detailed review of the current knowledge of their extent and causes in the region:

- Drought and low soil moisture
- Psyllid (Ierp insects) infestations
- Wood borers
- Damage by Galahs and Corellas
- Dryland salinity
- Chemical drift
- Soil compaction
- Fire damage
- Mundulla Yellows
- Plant pathogens
- Dodder Laurel
- Mistletoe
- Witches' Broom

For each tree decline issue, we searched for both region-specific literature, as well as literature from other regions in Australia and, where appropriate, globally. For issues that had little or no region-specific research, we attempted to put research from other regions in context, and discriminate which findings might be relevant to help us determine research priorities for the study region. The review will firstly give an overview of the tree decline in the region, before addressing each of the tree decline issues individually. The review will conclude with a summary of our findings and research priorities for the region.

2. Background

2.1. Study region

The study region is the Coorong and Tatiara District Council regions (see Appendix 1), and lies within eastern Australia's *temperate, seasonally dry slopes and plains* agro-ecological region (Williams *et al.* 2002). Hutchinson *et al.* (2005) classifies the region as 'Classic Mediterranean climate with peaks of growth in winter and spring'. Winters are cool and wet, and summers are dry and mild to hot. Most of the region is between 400 and 500 mm.yr⁻¹ mean annual rainfall (mean annual rainfall is 471, 460 and 425 mm.yr⁻¹ in Meningie, Keith and Coonalpyn, respectively; BoM 2015), though rainfall is higher in the region's south east (515 mm.yr⁻¹ in Padthaway), and lower to the north-west (361 mm.yr⁻¹ in Tailem Bend). Rain falls predominantly in the winter months (Figure 1).

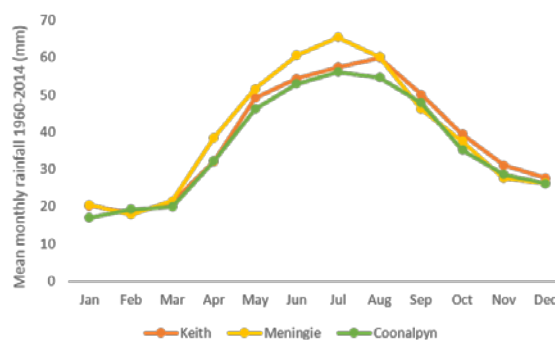


Figure 1. Annual rainfall distribution for Keith, Meningie and Coonalpyn.

To the north-west of the study region, the landscape is dominated by dunes of deep sand and sand over clay. The dunes run parallel to the coast line from north-west to south-east, and rise between 20–50 m between interdunal plains, which are inundated over winter and host a range of wetland systems. To the south-east of the study region in the Bordertown–Keith area, soils are characterised by a combination of loamy sand and some red-brown earths. The region has extensive areas of sown and fertilised pastures.

The land use history, landscape features, soils, and vegetation of the region have been detailed in several existing documents: (1) the Tatiara Natural Resource Plan (Tatiara LAP committee 2013), (2) the Coorong District Local Action Plan (Coorong LAP Committee 2012), (3) the South East Natural Resources Management Board Regional Natural Resources Management Plan (SE NRM Board 2010), and (4) the Biological survey of South East South Australia 199 and 1997 (Foulkes & Heard 2003). These features of the region will not be detailed further here. There is very little spatially-explicit information on tree decline in the region, and hence we make few specific references to landscape features in the region. Most information on tree decline issues is general in nature, and hence greater detail on the landscape features of the region is unnecessary for this review. However, such information may be vital to future research into tree decline.

2.2. Tree dieback in Australia

Much of Australia's woody vegetation has been severely modified in the 220 years since European occupation (Lindenmayer *et al.* 2005). Extensive clearing, particularly through south-eastern Australia's wheat–sheep belt, has drastically reduced the extent of native vegetation and the number of large mature trees in many regions. The health of trees has also been influenced by other major changes to the landscape, including introduction of exotic plants and animals, harvesting of trees, and changes to hydrology and fire regimes (Keane *et al.* 2000). In many agricultural landscapes, native vegetation is restricted to small isolated remnants, and large mature trees persist mainly in roadsides and as isolated paddock trees. Larger patches of remnant woodland are far more likely to occur on unproductive land, and hence are generally not representative of the pre-European vegetation across the rest of the landscape (Pressey 1994).

In many parts of Australia, the remaining mature trees are declining, both in vigour and total numbers (Landsberg & Wylie 1988), and there has been inadequate regeneration to replace them (Gibbons & Boak 2002). This decline in mature tree numbers is due to a range of factors, most of which can be attributed to land modification and management practices. Projections based on current rates suggest total loss of isolated and scattered trees from agricultural landscapes in 40 to 180 years. Scattered and remnant trees in the landscape have high social, economic and environmental value (see Reid & Landsberg 2000 for a review). Research into the decline of trees in agricultural landscapes, and options for its management and mitigation, are urgently needed (Vesk & Mac Nally 2006).

In addition to the impacts of clearing and landscape modification, many Australian tree species have also been planted in a range of environments that are different from those in which they evolved. This has resulted in the poor health of many trees, and has highlighted the broad range of physical and nutritional requirements of many Australian trees (particularly eucalypts), the importance of mycorrhizal associations, and the potential destructiveness of pests and diseases (Keane *et al.* 2000).

Several reviews of tree decline in Australia have been conducted. Two of these – Landsberg and Wylie (1988) and Juskis (2005) – review some of the general characteristics and explanatory theories behind tree decline in eastern Australia. These reviews highlight many situations and ecological processes that have led to tree decline, most of which can be related to human modification and management of the landscape. However, while we can apply some of this knowledge to the current study region (and we do, in this review), most of the processes leading to tree decline identified relate to combinations of factors that are regionally or locally-specific, and do not inform our study region and its specific problems.

It is clear that the trees of different regions will experience a unique set of stresses related to historic and recent clearing and land use practices (including cropping, grazing and fertiliser application), climate (including changes in climate) and introduced plants and animals. Reid *et al.* (2007) examine the causes of tree decline in the Namoi Valley, NSW, and provide an excellent example of the value of a regionally-specific analysis of tree decline issues, as the findings and management recommendations are directly applicable to landscapes within that region. As such, it is clear that the Coorong and Tatiara Districts will benefit from a regionally-specific review of tree decline issues.

3. Key tree decline issues

This section reviews the state of knowledge of 13 tree decline issues identified as being potentially important to the study region (see section 1.2). For each issue, we will attempt to identify:

1. The significance in the study region (including any information on the extent and severity of the issue in the region)
2. Any known causal factor, or possible causal factors
3. Gaps in the knowledge that affect our ability to manage the issue
4. Possible interactions with other tree decline or natural resource management issues
5. Any other information that may be relevant to managing the issues or setting research priorities relating to it.

3.1. Drought and low soil moisture

Rainfall and drought are strong *predictors* of woody vegetation cover in Australia (Fensham *et al.* 2005 and Fensham *et al.* 2009, Eamus *et al.* 2013) and world-wide (Allen *et al.* 2010). Drought and heat stress can kill individual trees and entire forests and mortality events may become more common with global warming (Allen *et al.* 2010, Eamus *et al.* 2013). Drought induced tree mortality has been well documented in northern Australian savannas (Fensham 2005, Fensham and Holman 1999; Rice 2004), Tasmania (Kirkpatrick and Marks 1985) and some areas of Western Australia, but there are few examples from South Australia in the literature where drought was the direct and only cause of tree mortality. Symptoms of drought stress in trees include yellowing of leaves, dying back from the growing tips and changed bark colour.

3.1.1. Effect of moisture deficit on trees

The likelihood of a tree being killed by drought depends on various factors including soil water holding capacity, and the tolerance and avoidance mechanisms of the species for coping with drought. McDowell *et al.* (2008) present a comprehensive review of various mechanisms of drought-induced tree mortality from a worldwide perspective. They describe three primary, mutually inclusive, mechanisms of drought induced tree mortality:

1. Biotic agent demographics, which involves a change in the demographics of insects and pathogens which then attack trees and eventually lead to tree death.;
2. Hydrologic failure, which occurs when the lack of available moisture causes the vascular system of the tree to collapse (cavitation), and;
3. Carbon starvation, where trees respond to a lack of soil moisture by closing stomata, which eventually leads to a lack of photosynthesis and carbon production.

These effects of drought are amplified if high temperatures coincide with moisture deficiency (Eamus *et al.* 2013).

Generally, eucalypts are well equipped to survive periods of drought. Most eucalypt species have vertical leaf alignment, hard leaf tissue, thick bark, lignotubers, extensive and deep root systems, periodic leaf shedding, and the ability to reduce transpiration through stomatal closure during dry periods (Florence 1981). Most eucalypt species that occur in drier environments must withstand

periods of drought or low soil moisture, with the exception of those that have continuous access to groundwater (e.g. River Red Gum, *E. camaldulensis*). However, even with these adaptations to cope with low moisture availability, widespread tree mortality can occur during prolonged droughts (Fensham *et al.* 2009, Horner *et al.* 2009).

The likelihood of some tree species to survive drought where others might perish could be related to groundwater access. Floodplain trees such as River Red Gum (*E. camaldulensis*) and Black Box (*E. largiflorens*) can access groundwater and are less dependent on rainfall or overland flows (Florence 1981, Akeroyd *et al.* 1998). However, river regulation and droughts have been shown to negatively affect *E. camaldulensis* (Doody *et al.* 2014) and *E. largiflorens* (Jolly *et al.* 1993) condition in the Chowilla Floodplain.

3.1.2. Drought in South Australia

In South Australia, tree death from drought has not been widely recorded. This may be due to a low rate of drought-induced mortality, or more likely, that it hasn't been recorded or published. There are some studies of tree mortality on the floodplains of the Murray River near the Victorian border (Doody *et al.* 2014; Jolly *et al.* 1993). However, these systems are closely linked to groundwater and flood processes, which may not be relevant to all areas of the study region. The Coorong and Tatiara Districts contain many different vegetation and soil types, which will have varying levels of susceptibility to drought and these should be considered on a case-by-case basis.

Within the study region, the coastal floodplains and wetlands are likely to be affected by human-induced low soil moisture. Water diversions for irrigation have resulted in a general reduction in the frequency and duration of floods in the lower floodplains and wetlands resulting in stressed native vegetation. Historically the floodplains would have been inundated for part of each year, but are now receiving less water and are adapted to surviving long dry periods.

The effect of drought on trees in the study region will be determined by a range of factors, including the water holding capacity of soils, evapotranspiration rates, rainfall timing and amount, and the ability of tree species to withstand periods of low moisture availability or to utilise groundwater. Fensham and Holman (1999) found that dieback was highest on alkaline igneous rock and lowest on alluvial soils. Indeed, trees growing on sandy soils are more likely to experience periods of low soil moisture availability than those growing on alluvial soils. These trees might be more adapted to surviving drought conditions since low soil moisture is a common occurrence in sandy soils. However, it is predicted that drought events will be more common and more severe with climate change, and hence drought-induced tree death may be more likely in the region in the future.

Despite the uncertainty of the influence of drought as a direct cause of tree mortality in the region, drought, and the increasing frequency and severity of droughts, may be a major cause of tree decline via its interaction with other tree decline issues. Drought can increase the susceptibility of trees to insect attack (section 3.2), wood borers (section 3.3), soil compaction (section 3.7) and mistletoes (section 3.12), and this will be discussed further in relevant sections.

3.2. Psyllid (lerp insect) infestations

Psyllids (Hemiptera: Psyllidae) are sap-feeding insects that can be significant pests of trees and shrubs. Psyllids include the 'lerp insects' that construct a protective sugary covering (a lerp) under which they feed (Figure 2). In the south-east of SA, there have been severe outbreaks of the psyllid *Cardiaspina densitexta* (Pinkgum Lerp) on *Eucalyptus fasciculosa* (Pink Gum), with prolonged and widespread outbreaks from 1914–1922 and 1956–1963 (White 1970; White 1969), resulting in tree decline and death.

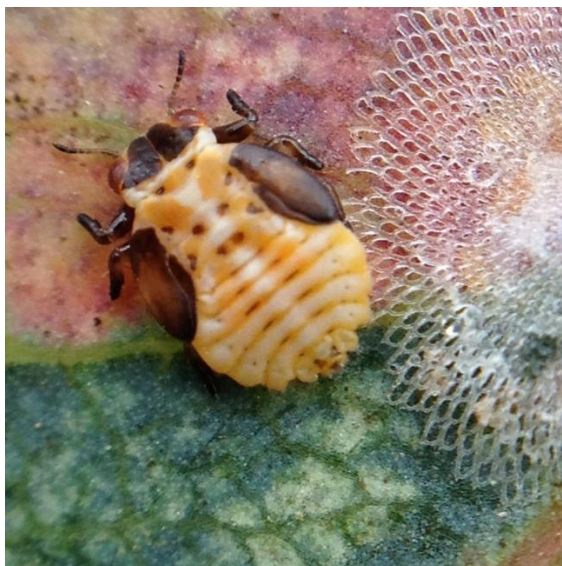


Figure 2. A psyllid, or lerp insect (*Cardiaspina* sp.). To the right of the insect is the protective sugary covering (a lerp) under which they feed.

Photo: Sophia Piscitelli

Psyllid populations sizes are generally controlled by density-dependent processes (Elliott *et al.* 1998). For example, the psyllid *Cardiaspina albipuncta* favours River Red Gum (*E. camaldulensis*) and Hill Red Gum (*E. blakelyi*). As the density of psyllids increases, a higher proportion is preyed on by birds, keeping the population in check. However, such density-dependent control of psyllid populations is not always evident. There are several theories regarding the factors that lead to psyllid outbreaks, and Morgan (1984) states that there is no apparent single factor that stimulates psyllid population increases, and it varies with psyllid species, their host, and their natural predators.

White (1969) proposed the 'stress index' hypothesis, suggesting that prolonged periods of stress increases the nutritive value of leaves, resulting in higher survival of young psyllid life stages and outbreaks on stressed hosts. This hypothesis is supported by conventional wisdom in the study region that outbreaks of Pink Gum Lerps are correlated with periods of drought (T. Strugnell, pers. comm., March 2015). Clark and Dallwitz (1974), however, propose that any of seven different factors can lead to population increases, and these include:

1. An abundance of the right age class of leaf
2. A low level of fruiting on trees

3. Inefficient natural control (e.g. by birds)
4. High levels of soil moisture
5. Low level of damage by other insects
6. Drought in the previous growing season
7. Favourable autumn and early winter temperatures

Collett (2001) provides a further review of the characteristics and causes of psyllid outbreaks.

One of the factors proposed by Clark and Dallwitz (1974) – inefficient natural control – has received attention in recent decades, particularly in relation to territorial competition between bird species, and the potential impact of these interactions on tree health. A decline in small insectivorous birds from parts of rural Australia is believed to be contributing to tree dieback via elevated severity and frequency of defoliation by insects (Ford & Bell 1981). Noisy Miners (*Manorina melanocephala*) can contribute to this decline in insectivorous birds by aggressively defending their territory, reducing the predation on defoliating insects (Grey *et al.* 1997). As such, Noisy Miners are associated with higher lerp abundance (Howes *et al.* 2010). Two small insectivorous bird species, Striated and Spotted Pardalotes (*Pardalotus striatus* and *P. punctatus*, respectively) have been excluded by Noisy Miners in south-eastern SA. Experimental removal of Noisy Miners from remnant patches of woodland (Grey *et al.* 1997) led to increased occupation by small insectivorous birds which persisted to at least 16 months. However, it is unclear if Noisy Miner population sizes stay reduced, or if this has any major or lasting effect on the health of trees in the remnant. Long-term monitoring of such an experiment may answer these questions.

Like many tree decline issues, many aspects of tree dieback related to psyllid infestations are difficult to assess, including:

- the extent of psyllid infestations across the region, and the distribution of infestations in the landscape
- the severity of psyllid infestation, which can be difficult to assess from a single sampling point in time as new leaves may have replaced leaves lost to psyllid damage (Paton *et al.* 2005).
- if increased psyllid population sizes are likely to be lethal, or simply part of the natural cycle of psyllid populations
- if increased psyllid population sizes are responding primarily to top-down processes (like altered bird predation), or if they occur more in trees that are pre-stressed by another tree decline factor, such as drought

Specific data on the extent of psyllid infestations and their implications for tree health may answer these questions.

3.3. Wood borers

Wood borers are insects that may be important tree dieback issue in south-east SA. Borers cause damage when their larvae tunnel through inner bark, cambium and in some cases, heartwood. Their presence in trees is often not detectable until adults emerge through holes they create in the bark. Borers can result in poor tree health by damaging vessels that transport water and nutrients, and can cause mortality by ringbarking the tree (Elliott *et al.* 1998).

We know of no published survey of wood borer communities in the study region. The most common borers in eucalypts in south-east SA are likely to be the Longicorn beetles (Coleoptera: Cerambycidae), and of these, the most likely are the Bulls-eye Borer (*Phoracantha acanthocera*), Long-horned Borer (*Phoracantha semipunctata*; Figure 3), and Ringbarking Borer (*P. mastersi*). *P. acanthocera* and *P. mastersi* are consumers of living trees (Wang 1995), while *P. semipunctata*, in its natural range, is primarily a consumer of dead or dying trees (though it is a known pest in plantation eucalypts outside of its natural range). Other borers in the region could include Scarab beetles (Coleoptera: Scarabaeidae), Jewell beetles (Coleoptera: Buprestidae) and wood-boring moths (e.g. Coleoptera)



Figure 3 Long-horned Borer (*Phoracantha semipunctata*)
Photo: Udo Schmidt (<http://creativecommons.org/licenses/by-sa/2.0>)

The lifecycle of most borers of standing trees involves female adults laying eggs under bark or in cracks on trees (Elliott *et al.* 1998). The larvae tunnel into the inner bark and sapwood (cambium). This leaves an engraved pattern on the sapwood surface that can be observed when bark is pulled away from the tree (Farrow 1996). Some species will tunnel into the heartwood to pupate. Many species cut exit holes in the bark, from which adults emerge. The life cycle of borers can range from weeks and months, to over three years, as is the case for some Longicorn beetles. Longicorn beetles make oval exit holes of 6-10 mm (along the long axis), while most other borers of standing trees have round flight holes (Elliott *et al.* 1998).

There is evidence that borer infestations have increased in south-east SA. A randomly stratified survey of trees in the Bordertown-Keith area (Paton *et al.* 2005) found borers (of unidentified species, but possibly predominantly *Phoracantha acanthocera*) in all of the six most common eucalypt species. Blue Gum (*Eucalyptus leucoxylon*) had the highest incidence of borers (39.8 % of trees surveyed; Table 1), followed by River Red Gum (*E. camaldulensis*; 26.1%). Paton *et al.* (2005) found that, relative to surveys conducted in 1993, the proportion of trees with borers had increased substantially: from 11 to 24% in paddock trees, 0 to 18% in remnants and 0 to 21% in roadsides. It should be noted that this was a measure of damage to trunks. The presence of borers is usually not apparent until adults emerge from holes in the trunks, at which point most damage has been done. The results of Paton's survey may reflect an increase in borers that has occurred over a longer period of time than since 1993. However, it would also be necessary to observe borer incidence from additional time points to establish a pattern, as it is unknown how regional borer incidence may fluctuate through time, and hence if Paton's results reflect a continuing trend, or two snapshots that reflect fluctuations

through time. Anecdotally, across the broader region it is *E. baxterii* and *E. arenacea* have had the highest visible impact from borers (T. Strugnell *pers. comm.* 2015).

Table 1. Borer incidence in trees surveyed in Bordertown-Keith area by Paton *et al.* (2005).

Species name	Common name	Borer incidence (% of trees surveyed)
<i>E. arenacea</i>	Sand Stringybark	19.1
<i>E. camaldulensis</i>	River Red Gum	26.1
<i>E. fasciculosa</i>	Pink Gum	23.9
<i>E. incrassata</i>	Yellow Mallee	3.9
<i>E. leucoxydon</i>	Blue Gum	39.8
<i>E. porosa</i>	Mallee Box	20.2

3.3.1. Which factors make trees susceptible to borers?

Longicorn beetles are common in Australian woodlands and forests, and generally attack stressed, dying or damaged trees. Drought conditions can result in borer population increases because borers prefer drier wood (Farr *et al.* 2000; Hanks *et al.* 1991; Nahrung *et al.* 2014; Pook 1981; Pook & Forrester 1984). Nahrung *et al.* (2014) showed that the severity of *Phoracantha solida* infestations was negatively correlated with bark and wood moisture, and that infestations were denser on the northern (drier) side of trees. Cracks in bark that can occur during drought can also provide sites for oviposition of longicorns (Old 2000; Pook 1981). After the 1964-65 drought in the Australian Capital Territory, the smooth-barked Scribbly Gum (*Eucalyptus rossii*) developed cracks that exposed the cambium, and this species was subsequently invaded by *Phorocantha* spp. and, in some cases, ringbarked. The fibrous-barked Red Box (*E. polyanthemus*) suffered only minor borer stem damage (Pook 1981).

Drought and tree stress may provide sufficient explanations for the potential population increases in south-east SA. However, we present four further hypotheses that may warrant consideration:

i. Loss of natural parasites of borers. There is little to no evidence to support this supposition. Borer populations have parasites that moderate their population sizes, e.g. the tiny wasp *Aventianella longoi* (Hymenoptera: Encyrtidae) is a natural parasite of newly-laid *Phoracantha* spp. eggs (Hanks *et al.* 1995). A loss of parasites could result from chemical and insecticide drift, or from loss of understorey species that support life stages of parasites. To assess this issue, data on the natural parasites of borer insects in south-east SA are required, including their abundance and distribution across different environmental and management gradients.

ii. Nutrient application may increase the feed suitability of wood and cambium for borers. This supposition is largely uninvestigated. It would be possible to test for increases in nutrient status of wood and cambium for trees in paddocks with varying history of fertiliser application. This would indicate if it were worthwhile performing the more complex research of determining if this has a causal relationship with wood borer infestations.

iii. Bark damage by birds is increasing the number of suitable sites for oviposition. Large populations of birds such as Galahs (see section 3.4) can create significant damage to bark on trees.

This may have a similar effect as drought on exposing sections of the trunk for oviposition. Damage by birds could also be directly related to the presence of borers. Boobooks, for example, feed on wood borers in South Australia (Penck & Queale 2002). Black Cockatoos are also known to pull off bark when feeding on wood borers (Farrow 1996).

iv. Factors other than drought that lead to low moisture content in wood or cambium favour borers. Based on previous studies, we would expect that any form of stress in trees in south-east SA that resulted in lower moisture content in wood or exposure of the cambium could promote borer infestation. Both salinity (section 3.2) and soil compaction (section 3.11) can result in low water uptake and can imitate the effects of drought on a tree.

It is also worth noting that trunk wounds by borers allow the entry of decay fungi (Old 2000). For example, van Wyk *et al.* (2007) found that the pathogenic fungus *Ceratocystis atrox* had a close relationship with the wood borer *Phoracantha acanthocera*, but its role in the biology of the insect is unknown. The potential role of pathogen–borer interactions could be considered in future tree decline research.

3.3.2. Research priorities

The main research priority for borers in the region is to determine the extent of the problem. We do not have a good understanding of the extent of borer infestations in trees in south-east SA, and whether or not this issue is responsible for a significant proportion of tree mortality or poor tree condition in the region, although the study by Paton *et al.* (2005) certainly suggests that borers are an issue. If borers are shown to be a significant problem, then data on the distribution and habitat preferences of different borer species would be an essential first step to comprehending the role of borers in regional tree decline.

Climate predictions suggest there may be more frequent droughts, and greater climatic variability in the future. Hence, it is possible that problems with tree decline and death due to borers will be exacerbated. Borers could be an important issue for research and management into tree health in the future.

3.4. Damage by Galahs and Corellas

Tree damage by Galahs (*Eolophus roseicapillus*) and Little Corellas (*Cacatua sanguinea*) is a commonly reported problem in the region. Most of the available literature describes Galah damage, and so, for simplicity we will discuss Galahs here, but Corellas are also causing problems in the region and this requires further investigation.

Large flocks of Galahs can chew at the bark of mature eucalypts, sometimes to the point of ringbarking the tree. Figure 4 shows Galah damage to the bough of a mature Blue Gum (*Eucalyptus leucoxylon*). Galahs can also snip foliage from the outer branches of trees. Our understanding of why Galahs damage trees in this way is not complete, but we have a reasonable understanding of why damage from Galahs is becoming more of a problem.



Figure 4. Galah damage to *E. leucoxylon* (Blue Gum)

Photo: David Cheal

Galahs have expanded their range and increased their population densities since European settlement. Formerly restricted to semi-arid regions, Galahs have spread east of the Great Dividing Range, south into the agricultural regions of south-east South Australia, and into the Western Australian wheat belt (Higgins *et al.* 1999). They compete for nest sites with other native species (Saunders 1990), some of which are declining or endangered—on Kangaroo Island, Galahs are a threat to the breeding success of the endangered Glossy Black-Cockatoo (*Calyptorhynchus lathami halmaturinus*), which have now disappeared from the South Australian mainland. The increases in Galah range and population sizes are related mainly to additional feed resources, including additional watering points in the landscape and crops of sunflower, summer sorghum, millet, canola, winter wheat, barley, oats and pulses on which they feed. Galahs have achieved these increases despite decreases in the number of hollow bearing trees in agricultural landscapes due to tree clearing for grazing and cropping (Gibbons & Lindenmayer 2002). The result is that a far greater proportion of the remaining trees will be subject to damage sustained when occupied by Galahs.

Galahs require mature trees for nests (Mawson & Long 1994). Unlike other hollow-using species such as Leadbeater's Possum (Lindenmayer *et al.* 1991), Galahs will use hollows in isolated paddock trees or single trees retained after logging (Rowley 1990). Galahs also show a high fidelity to nesting holes, frequently re-using the same nest hollow in successive breeding seasons (Rowley 1990). Chewing around the hole may be a strategy for territorial defence (Gibbons & Lindenmayer 2002). For example, Higgins *et al.* (1999) suggest that Galahs may remove bark from below nesting hollows to prevent predators such as goannas from accessing their nests. Chewing bark is also necessary for Galahs and other cockatoos to maintain their beaks at the correct length and condition (Rowley 1990).

Another hypothesis for tree damage by Galahs is that they may prefer a dead tree – possibly for larger or faster hollow formation, or to improve their view of the landscape. However, in Western Australia, Saunders *et al.* (1982) found that while Red-Tail Black Cockatoos (*Calyptrorhynchus banksii*) preferred dead trees as nesting sites, whereas Galahs did not.

Whatever the explanation for the behaviour, it seems that the combination of increased population sizes and a reduced number of large, hollow-bearing trees in the landscape at least partially explains why Galah damage has become a problem. Galahs have always chewed on eucalypt bark. However, when there were fewer Galahs and far more abundant large trees, chewing may have rarely resulted in any significant damage to any one tree, and if it did this would not be an issue in extensive woodlands.

It is unlikely that the problem of Galah damage will go away. District councils in south-east SA, including the Tatiara District Council, have previously obtained permits to destroy wildlife, allowing up to 200 Galahs to be shot, with the culling taking place mainly in towns where Galahs are damaging trees and seen as a nuisance. However, Fleming (1990, as cited in Bomford & Sinclair 2002) reviewed shooting to control bird damage, and found that shooting was time-consuming, expensive and ineffective at significantly reducing total population sizes, and that birds quickly learn to avoid shooters. Ford (1990) found that in NSW, Galah population sizes in cropping regions were lower than was perceived by farmers. Removal of hollow-bearing trees near feed crops will not reduce Galah population sizes, as Galahs will travel up to 50 km in search of food (Allen 1990). As such, any removal of hollows will presumably only increase Galah damage on the landscape's remaining trees.

We may need to accept further tree damage and losses from Galahs. This adds weight to the argument that we need greater tree regeneration across the landscape to compensate for the continuing loss of established trees (see Section 4 – Tree regeneration). However, tree regeneration *per se* will not restore Galah nesting sites for many decades, until trees grow large enough to form suitable hollows. Nevertheless, experimentation regarding deterrence may help limit the damage caused by Galahs to iconic, significant or otherwise remnant and large significant trees.

3.5. Dryland Salinity

Dryland salinity is a potential cause of tree death in affected areas of South Australia such as the coastal floodplains and wetlands of the Upper South East. In this section we will describe the current understanding and extent of dryland salinity in Australia, the specific causes of salinity in South Australia, how trees might be affected by salinity, and the key symptoms of tree damage from salinity.

Salinisation occurs when increased groundwater recharge causes water tables to rise. This mobilises salts stored in soil and rock, which can damage aquatic and terrestrial ecosystems. There are two main types of human induced or 'secondary' salinity. Irrigation salinity is caused by adding water to crops, most of this added water reaches groundwater through the soil and causes the water table to rise. Dryland salinity involves the clearing of deep-rooted perennial vegetation, which reduces the uptake of soil water derived from rainfall and results in increased infiltration of water through the soil and into the groundwater.

Dryland salinity occurs throughout Australia but is most widespread and severe in agricultural regions of southern Australia with winter-dominant rainfall that have been cleared extensively. The Australian Dryland Salinity Assessment 2000 (NLWRA 2000) estimated that the highest risk areas, based on groundwater depth and land-use practices, are found in south-west Western Australia, south-east South Australia, and western Victoria. These regions are already experiencing widespread salinity problems.

Clearance of native vegetation is the main cause of dryland salinity (Hatton & Nulsen 1999). Deep-rooted perennial vegetation is very effective at taking-up and utilizing rainfall, thus limiting (and often preventing) any run-off or leakage into the groundwater (Hatton & Nulsen 1999; Walker *et al.* 1999). The shift from deep-rooted native vegetation to shallow rooted crop and pasture vegetation has led to the transformation of the water cycle, from one that is relatively balanced (rainfall = transpiration + evaporation) to a more leaky system where much of the rainfall escapes past the root zone and goes into the groundwater (and waterways) causing water tables to rise (Hatton & Nulsen 1999). The winter-dominated rainfall in southern Australia compounds this 'leakiness' as rain falls during times of slow plant growth and low rates of evaporation (Walker *et al.* 1999).

Understanding the roles of recharge and discharge zones in salinity-affected landscapes is a vital part of addressing the problem and for assessing risk to vegetation. Recharge zones are higher parts of the landscape, dunes and hilltops, and they are so-called because they are generally the source of groundwater recharge. The type of vegetation in recharge zones will directly affect local water table heights but trees in recharge areas are unlikely to be affected by salinity directly, since groundwater is less likely to reach the root zone of trees that are growing on higher ground. Conversely, discharge zones occur in low-lying areas where groundwater is closer to the soil surface. In these areas, saline water can reach the root zone of plants and can be lethal, depending on the salinity level and the salt tolerance of the plant species. In low lying (discharge) areas of the landscape, where the groundwater is shallow and highly saline, bare scalds can form in which plants cannot survive.

3.5.1. Salinity effects on biodiversity

There have been very few studies on the effect of salinity on biodiversity and tree health (ANZECC Task Force 2001; Briggs & Taws 2003). The National Dryland Salinity Assessment 2000 report estimates that 631 000 ha of remnant and planted perennial vegetation are at risk of degradation from salinity, however there are no specific details of the type of vegetation included in this estimate and other reports only provide vague mention of the 'risk to biodiversity' that salinity poses (PMSEIC 1998). Briggs and Taws (2003) outline the few studies that have investigated the effects of salinity on biodiversity and describe their own unpublished results in which salinised woodland sites have high rates of tree dieback compared to unsalinised woodlands. The lack of research around native vegetation responses to salinity may be due to the low cover of native vegetation in areas affected by salinity and the onus on primary production in agricultural regions, as opposed to biodiversity conservation. However, retaining trees in these regions is vital, not only for their ability to reduce groundwater recharge, but also because they provide safe havens for native flora and fauna in otherwise highly-modified agricultural landscapes.

3.5.2. Salinity in South Australia

In SA, 80% of salinity problems occur in the Upper South-east Natural Resource Management region (hereafter the USE region), which has a high degree of overlap with the Coorong and Tatiara regions (State Dryland Salinity Committee 189/90). This is due to a combination of factors including an already shallow water table, vegetation clearing, periodic flooding, winter-dominated rainfall and permeable dune ranges (Barber & Parsons 1993; Bulman *et al.* 1993; Holmes 1960). An estimated 95% of agricultural land in the USE region has been cleared, and unvegetated sandy dunes with high infiltration rates have contributed to rapidly rising water tables. Furthermore, winter dominated rainfall (with little transpiration or evaporation) and periodic flooding of the interdunal flats recharge groundwater, while the evaporation of flooded areas in summer brings salt to the surface and kills vegetation (State Dryland Salinity Committee 1990).

Rising groundwater is occurring at surprisingly rapid rates in the USE region with marked differences between cleared and uncleared land. Groundwater beneath cleared land is rising by 100mm per year whereas groundwater beneath uncleared land is only rising by a few millimetres per year (USE Dryland Salinity and Flood Management Plan Steering Committee 1990). While this suggests that revegetation may be effective at reducing the rate of groundwater rise, studies from WA suggest that revegetation would need to occur on a large scale (>50% of land) to have widespread positive effects (George *et al.* 1999). This is because the effects of above-ground vegetation on groundwater levels is local and changes to vegetation lead to local changes to groundwater levels. However, there is a lot of research into the use of revegetation as a tool for managing salinity and rising water tables (Barrett-Lennard 2002; Pannell 2006) and landholders in south-east SA have adopted widespread planting of perennial dryland lucerne to address salinity (Angus *et al.* 2001; Pannell & Ewing 2006). More direct measures have been employed in the USE region, specifically the installation of a deep open drainage network aimed at removing water from the system (USE Dryland Salinity and Flood Management Plan Steering Committee 1990).

3.5.3. Salinity and tree dieback

Saline water and water table depth were identified by Litchfield (1955) as one of the major factors influencing plant distributions in south-east SA, indicating that the effects of salinity could vary among plant species. Plant growth is negatively affected by salinity by reducing the osmotic potential of the soil water, thereby reducing water availability to the plant (which may manifest in the same way as drought). Indeed, Jolly *et al.* (1993) showed that the primary mechanism by which trees die in salt affected areas is by water stress. Salinity can also directly affect plant growth by increasing the concentration of sodium ions in plant cells, which disrupts metabolic processes.

Waterlogging of the soil is common in low-lying areas, which are periodically flooded such as those found in much of the USE region. In the Coorong district, woodlands and riparian tea-tree are at high risk of damage by salinity (ANZECC Task Force 2001). It was noted by Litchfield (1955) that eucalypts would be eliminated from saline hollows between sandhills in the USE region whereas heath species could persist. This suggests that eucalypts are relatively intolerant to waterlogging and salinity, or simply that their root systems extend deeper and are thus the first species to show the adverse effects of rise in the saline ground water. However, there have been reports that even tea-trees

(*Leptospermum* sp.) are dying in the worst affected, low lying areas of the USE region (USE Dryland Salinity and Flood Management Plan Steering Committee 1990).

3.5.4. Symptoms of salinity in trees

Trees affected by salinity exhibit slowed growth and dead patches on leaves, particularly on the margins and tips with leaf death starting at the base of the canopy, spreading upward (State Dryland Salinity Committee 1989/90). Salt tolerance varies between species and mature trees are generally more tolerant than juveniles. Waterlogging also reduces a plant's ability to tolerate salinity. Salinity generally affects patches of vegetation, and not individual trees/shrubs in a patch (unlike other causes of tree dieback). The presence of salt tolerant plants, and/or salt crystals on soil surface of seepage areas nearby, may also indicate that tree decline symptoms are caused by salinity.

3.6. Chemical drift

The use of pesticides (including insecticides, herbicides, defoliant and fungicides) is widespread throughout Australia and may cause tree dieback in some areas. An estimated 20% of the Coorong and Tatiara District's developed land is cropped each year. The main crops include wheat, barley and oats along with a smaller proportion of pulses and canola crops (Tatiara LAP Committee 2013). Herbicides and insecticides are likely to be the main pesticides used in the region. The Environmental Protection Agency South Australia (2005) noted that inappropriate pesticide use has caused some damage to native vegetation.

Reid *et al.* (2007) provides a detailed review of the effects of pesticides on tree dieback in the Namoi Valley, NSW, though they focus on pesticide use in cotton cropping, the prominent crop type in that region. They found that defoliant used in cotton production have detrimental effects on the health of nearby trees, but these defoliant are not used in cereal cropping enterprises.

Cereal crops generally require broad-spectrum herbicide application prior to sowing (especially in no-till operations), as well as various insecticides to control pests when necessary. It is not known what effect these pesticides have on tree health. The extent to which an individual tree is affected would depend on its proximity to crops, leaf architecture (broader leaves will intercept more spray drift) and whether or not the tree is up- or down-slope of the crop. Reid *et al.* (2007) reported some effects of herbicides on tree health, but reports of tree death associated with herbicide use on crops are largely anecdotal.

A separate issue is the use of the direct application of chemicals, including herbicides, on roadsides and native vegetation. There have been reports of tree death and poor health following the spraying of understorey vegetation with herbicides. The use of chemicals in such close proximity to trees certainly increases the probability of impacting on non-target species.

The effect of chemical drift on tree health requires further investigation. A survey of land managers and landholders for information on the potential link between chemical drift and tree decline would be a solid starting point for further investigation and might provide information on the extent of the problem.

3.7. Soil compaction

Soil compaction, which can be caused by livestock trampling, is likely to reduce the pore volume of the soil and alter infiltration and water holding capacity (Greenwood & McKenzie 2001). In a forestry setting, soil compaction has been found to reduce the growth of trees (Kozlowski 1999), including eucalypts (Williamson & Neilsen 2003). Soil compaction is often cited as a potential factor contributing to tree decline, but its effects are likely to be indirect and are difficult to measure. Most published studies on the effect of soil compaction on tree health are forestry studies, which may be inapplicable to open woodlands or scattered paddock trees in an agricultural landscape (Landsberg & Wylie 1988).

The effect of livestock trampling and stock camps on soil surface condition have been well studied (Braunack & Walker 1985; Yates *et al.* 2000). Yates *et al.* (2000) compared grazed and rarely grazed/ungrazed Salmon Gum (*E. salmonophloia*) soil properties and found that heavily grazed woodlands had surface soils with higher bulk density, higher penetration resistance and lower infiltration rates than rarely grazed/ungrazed woodlands. These results suggest that livestock grazing can have large and persistent effects on surface soil properties, which could affect tree health by altering rainfall infiltration rates. However, studies of soil surface condition do not often measure its effect on tree health, instead focusing on understorey plant composition and growth (Prober *et al.* 2002; Yates *et al.* 2000).

All soils that are grazed by livestock are compacted, to some extent (Greenwood and McKenzie 2001). The extent to which soils are compacted depends on many factors including soil type, organic content of the soil, soil moisture and the amount of herbaceous groundcover and roots in the soil. Stock camping, i.e. the tendency for livestock to spend more time beneath paddock tree canopies, can lead to higher levels of soil compaction, increased nitrogen and phosphorus, and decreased pH (Wilson 2002).

There are no studies of soil compaction and its effects on tree health in the study region, although discussions with landholders and natural resource managers suggest that soil compaction may be a major factor contributing to tree decline and health in the region. More research is required to investigate how compaction might directly and indirectly contribute to tree decline in the study region.

3.8. Fire damage to trees

Fire is a natural part of most Australian ecosystems and many native tree species recover well after fire (depending on the fire severity), either by resprouting from lignotubers or through epicormic regeneration. However, some native species are killed by fire and must regenerate from seed.

Bulokes (*Allocasuarina luehmannii*) are killed by fire. The south-eastern extent of the study region includes 'Buloke Woodlands of the Riverina and Murray-Darling Depression Bioregions' (hereafter Buloke woodlands), which are listed as an endangered ecological community under the EPBC Act (1999). As such, any threats to the status of Bulokes and Buloke woodlands must be addressed. The habitat threats and recovery objectives for Buloke woodlands are detailed in the national recovery plan for Buloke woodlands (Cheal *et al.* 2011).

One threat to Buloke woodlands relevant to the region is the sensitivity of Buloke and other components of Buloke woodlands to fire (Cheal *et al.* 2011). This threat is particularly pertinent to scattered Bulokes in, or at the edge of, paddocks. The practice of burning stubble in cropping paddocks poses a threat to Bulokes, which may experience mortality if not protected from such fires.

Buloke woodlands, in addition to receiving protection from the EPBC Act (1999), may also be important for other tree decline issues in the region. Maron and Kennedy (2007) suggest that these habitats can be important refuges for smaller birds, as they are not the preferred habitat of Noisy Miners (*Manorina melanocephala*). As such, Buloke woodlands may be important for moderating Noisy Miner populations and problems associated with their overabundance such as psyllid damage in eucalypt-dominated woodlands (See section 3.2).

3.9. Mundulla Yellows

Mundulla Yellows (MY) is a dieback disorder of eucalypts and other plant species in the south-east SA. Farmers have been aware of the MY disorder for over 70 years (Parsons & Uren 2007), and MY symptoms were documented in River Red Gum (*Eucalyptus camaldulensis*) around 1975 by Geoff Cotton, an apiarist based in Keith who was instrumental in raising the profile of MY.

The first symptom of MY is distinct interveinal yellowing of leaves (see Figure 5). Yellowing is generally observed first on immature leaves on a single branch, and subsequently on mature leaves. Affected branches are eventually defoliated, and any epicormic growth is stunted and chlorotic (yellow). The symptoms will appear progressively on other branches, eventually leading to tree death over several years (Hanold *et al.* 2006). There have been no observed instances of trees recovering from the early stages of MY (with the exception of a single glasshouse experiment, described below).



Figure 5. The leaves on the left show interveinal yellowing, a prominent symptom of Mundulla Yellows. Photo: David Paton (Paton & Cutten 2000).

A range of symptoms of ill-health of trees in southern Australia has been attributed to MY, and many disorders of trees include yellowing of leaves (Keane *et al.* 2000). For the purposes of this review, we will strictly consider MY as the condition which starts as interveinal yellowing and eventually leads to

death of the tree. We will primarily consider MY as a disorder trees in south-east SA. Broadening the scope of our review, and including trees with MY-like symptoms elsewhere requires too many assumptions about the cause and potential spread of MY.

3.9.1. Distribution of MY symptoms

There has been no systematic determination of the local or national distribution of MY (MYTG 2004). Nevertheless, there is clear evidence that in the South east of SA, MY is almost exclusively limited to roadsides, with the only exceptions being symptomatic trees along creeks and flood ways near roadsides, and a small number of paddock trees near roadsides (Paton & Cutten 1999; Paton *et al.* 2005). Paton (2005) randomly selected tracts of land in the Mundulla and Keith region to survey, and found that MY symptoms were restricted to roadsides, and that trees in other parts of the landscape suffered from other non-MY ailments, such as mistletoe infestation, lerps and borers.

MY was first described in *Eucalyptus camaldulensis* (River Red Gum), and it is this species that has undergone the most severe and conspicuous dieback from MY. Other species commonly expressing MY symptoms include *E. leucoxylon* (Blue Gum in SA; Yellow Gum in Victoria), *E. arenacea* (Sand Stringybark or Desert Stringybark), *E. fasciculosa* (Pink Gum), *E. incrassata* (Yellow Mallee) and *E. porosa* (Mallee Box) (Luck *et al.* 2006; Paton *et al.* 2005). The Mundulla Yellows Task Group (2004) report that 87 species of 29 genera have been documented as expressing MY-like symptoms. However, there are doubts about the consistency of symptom expression for species included in this list, and there are many plant disorders that cause yellowing of leaves. Hence, without a diagnostic test available to identify MY, the true number of species and distribution of MY cannot be determined.

3.9.2. Evidence of association with soil properties

There is strong evidence that MY is associated with abiotic soil properties. Czerniakowski *et al.* (2006) compared soil properties from under 40 trees (*E. camaldulensis*, *E. leucoxylon*, and *E. cladocalyx*) from 10 sites in SA and Victoria. They showed that soil from under symptomatic trees had significantly higher pH and Electrical Conductivity (EC), and significantly lower available Fe, than in soil from under asymptomatic trees. In addition, the aqueous soil extract from soil under symptomatic trees had significantly higher levels of carbonates ($\text{CO}_3^{2-}/\text{HCO}_3^-$, or carbonate and bicarbonate, respectively, the concentrations of which cannot be separated using ion chromatography). This study provided strong evidence for an association of MY with abiotic soil conditions, and we will demonstrate in this review the way in which these results provide a well-supported and parsimonious explanation for the cause of MY.

The results of Czerniakowski *et al.* (2006) counter some of those presented by Hanold *et al.* (2006), who provide evidence that pH is unlikely to be associated with MY. However, the study of Hanold *et al.* is based on soil samples from south-west Western Australia. It cannot be stated with certainty that trees in WA were suffering from the same condition as the trees in south-east SA when the cause of MY is unknown and the expression of symptoms varies between these regions (Hanold *et al.* 2006). Furthermore, the soil comparisons in Hanold *et al.* (2006) were based on paired symptomatic and asymptomatic trees in close proximity, and so the trees could be experiencing similar soil conditions, whereas Czerniakowski *et al.* (2006) ensured 2km separation between symptomatic and

asymptomatic trees. For these reasons, the study of Czerniakowski *et al.* (2006) should be considered a more relevant and stringent test of the association of pH with MY in south east SA.

Foliage analysis by Czerniakowski *et al.* (2006) showed that symptomatic trees had lower levels of iron (Fe) and manganese (Mn), and higher levels of sodium (Na) and chloride (Cl) than asymptomatic trees. This result was more pronounced for trees in SA than at their Victorian sites. South Australian trees had suboptimal Fe in the foliage (56.9 ± 7.4 and 48.3 ± 8.7 mg.kg⁻¹ at the two SA sites). Adequate levels of Fe for juvenile foliage of *E. camaldulensis* is 84-170 mg.kg⁻¹ and for mature foliage is 110-170 mg.kg⁻¹ (Boardman *et al.* 1997; De Barros & De Novais 1996). These results suggest that Fe deficiency in MY trees derives from a paucity of Fe in the soils or an inability to extract Fe into the trees' roots. Additionally, Czerniakowski *et al.* (2006) found that individual trees with the lowest concentration of Fe and Mn in their foliage displayed the most severe MY symptoms. Czerniakowski *et al.* (2006) also provide preliminary results that Fe application corrects MY symptoms.

Fe deficiency in plants results in a well-known plant disorder termed lime chlorosis. Other names for the same disorder include lime-induced chlorosis, iron chlorosis and iron-induced chlorosis. We will adopt the term lime chlorosis for its brevity, for continuity with Parsons and Uren (2007, 2011), and because the term can also incorporate chlorosis induced by Mn, zinc (Zn) and copper (Cu) deficiencies (see discussion below). Fe is required by plants to produce chlorophyll, and as such the primary symptom of lime-induced chlorosis is yellowing in the interveinal margins of leaves, while the veins may remain green. The symptoms of lime chlorosis are indistinguishable from the symptoms of MY. As such, strong evidence that MY is a result of lime chlorosis is provided by low available Fe in soil under MY-affected trees, and low Fe in MY-affected foliage. The lime chlorosis hypothesis is given even greater support when we consider the strong association of MY with roadsides, and the fact that most roads in SA have crushed lime as either their base or the entire road.

The use of limestone in roadsides would be expected to raise the level of carbonates and pH in the soil, and subsequently decrease the Fe availability in the soil. Limestone is rock composed primarily of calcium carbonate (CaCO₃) that is soluble in water and weak acid. Dissolved calcium carbonate will increase the concentrations of calcium and carbonates, and consequently the pH and electrical conductivity. At high pH, ferrous (Fe²⁺), which is the form of Fe most easily taken up by plants, is oxidised to ferric (Fe³⁺), which could lead to Fe-deficiency. The soil properties measured by Czerniakowski *et al.* (2006) reflect these changes that would be expected from adding limestone dust to slightly acidic soil – increased pH, carbonates and calcium ions, and decreased available Fe. It is important to note that Czerniakowski *et al.* measured DTPA-extractable Fe, which is better-correlated with the Fe available for plant uptake than is total soil Fe (Liang & Karamanos 1993).

The explanation that limestone roadsides result in MY receives further support when we consider plant adaptations to their natural environment. Some species are adapted to, or tolerant of, acidic soils, similarly with more alkaline soils. The regions most affected by MY, the low-lying areas of Mundulla and Keith, have slightly acidic soils. The native trees of this region would be adapted to, or at least tolerant of, acidic soils. These trees would likely become stressed following the addition of carbonates

to the soil. As such, all well-documented cases of MY are of trees on acidic soils that have been made more alkaline (Parsons & Uren 2011).

3.9.3. Mechanisms of lime-induced chlorosis

Understanding the precise mechanisms by which lime from roadsides may induce chlorosis may be necessary for identifying research questions and developing management strategies. Here, we will review the physiology of Fe uptake and transport in plants.

There is generally more Fe in soil than is needed by plants. However, Fe deficiency is common as plants can only take up Fe^{2+} ions, or Fe^{3+} in a suitable complex. All dicotyledonous plants (most trees, shrubs and herbs) and non-graminaceous monocotyledonous plants are known as Strategy I plants (Marschner 1995). When a Strategy I plants detect low Fe status, two mechanisms are instigated at the tips of the plants roots:

1. An enzyme (ferric reductase) is upregulated in the plasma membrane (at the surface of the root). This enzyme helps reduce ferric to ferrous, so that it can be taken up by the plant (Romheld 1987).
2. Proton extrusion pumps are activated in the plasma membrane, to transfer H^+ protons from the root to the soil nutrient solution. This lowers the pH of the soil solution, aiding the reduction of ferric to ferrous (Chaney & Bell 1987).

Both of these mechanisms require energy expenditure by the plant, and are shut down when normal Fe status is restored. The effectiveness of these mechanisms is inhibited by bicarbonate and high pH, a cause of severe lime chlorosis (Graham & Stangoulis 2003).

There has also been much debate about the effect of high soil carbonate levels on the availability of Fe to leaves (Nikolic & Römheld 2002). Fe is delivered to leaf tissue via the leaf apoplast – essentially the space between leaf cells. It has been proposed that high soil bicarbonate increases the pH of the apoplast, such that Fe is reaching leaves, but is not physiologically available to leaf tissues for the use in chlorophyll (Mengel 1994). However, Nikolic and Römheld (2002) show that this is not the case, and that disruption of the Strategy I Fe-deficiency response is the primary effect of high carbonate that leads to chlorosis.

The roles of Mn, Cu and Zn must also be considered when evaluating lime-induced chlorosis. In addition to Fe deficiency, chlorosis can also be caused by inadequate absorption and internal transport of Mn, Cu and Zn, and the visible symptoms of these disorders are essentially indistinguishable (Dell 1996; Parsons & Uren 2007). Studies by Grigg *et al.* (2009) and Fife & Michael (2009) both present cases of eucalypts suffering from Mn deficiencies, and both note the similarity of symptoms to MY.

The presence of high perennial grass cover may buffer trees against lime-induced chlorosis. Unlike trees, which are Strategy I plants, grasses are Strategy II plants and have a different response to low Fe status. Strategy II plants excrete phytosiderophores (PS) into the soil, which chelate ferric ions so they can be subsequently absorbed (Römheld & Marschner 1986). It has been shown that higher

grass cover can improve Fe nutrition of chlorosis-susceptible citrus trees (Cesco *et al.* 2006). The use of perennial grass cover as a management strategy to buffer against tree decline is a hypothesis that could be tested in south-east SA.

Increasing atmospheric CO₂ may further exacerbate MY symptoms. Czerniakowski *et al.* (2006) and Luck (2005) propose that atmospheric CO₂ can result in increased weathering and dissolving of limestone. This proposal should be tempered by the observation that MY has been found almost exclusively on roadsides, and rarely in undisturbed native vegetation. Nevertheless, rises in atmospheric CO₂ have been shown to cause increased rates weathering leading to increased soil alkalinity (Andrews & Schlesinger 2001; Karberg *et al.* 2005), and this may require further investigation. Increased mobilisation of carbonates from rising water tables may provide another possible mechanism by which soils could become increasingly alkaline independent of roadside associations.

3.9.4. Evidence of biotic causes

Much of the early research and literature on MY considered it to be a new, contagious and spreading biotic disease (Hanold *et al.* 2002). Strong evidence has been provided that MY is due to abiotic causes by Czerniakowski *et al.* (2006) and Luck *et al.* (2006). Nevertheless, since the publication of these studies, a biotic cause of MY has been re-stated (Hanold 2010), and further research in the search for a biotic cause of MY has is being undertaken (Randles *et al.* 2010). As such, we will review the evidence for and against the hypothesis of a biotic cause of MY.

The study by Luck *et al.* (2006) showed that pathogenic agents were not likely to be the primary cause of MY. They found no evidence of an association between MY and pathogenic fungi, bacteria, phytoplasmas, insect pests or vectors in a systematic comparison of symptomatic and asymptomatic trees and their associated soil. Luck *et al.* (2006) also found that MY symptoms were not transmissible by seed, mechanical inoculation, or grafting using plant material from symptomatic trees. The only positive association they found between symptomatic trees and a biotic factor was that of the nematodes *Merlinius* spp., which were associated with the soil (but not roots) of symptomatic trees. This association could be an artefact of nematode association with grasses under symptomatic trees, and is unlikely to be the directly associated with MY. In addition, sterilised soil from under MY-affected trees induced MY symptoms in healthy eucalypt seedlings, providing further evidence of an abiotic cause of MY.

The following arguments have been made in support of the hypothesis that MY has a biotic cause: (1) the distribution is consistent with that expected of an infectious disease, (2) irreversibility of symptoms, (3) transmissibility of symptoms, (4) asymmetry of symptoms within a tree, and (5) the presence of specific nucleic acids in MY-affected trees. We will review the evidence for each of these arguments.

Randles (1999) claims that the distribution of MY-affected trees is consistent with that expected of an infectious disease. This may be true, but the distribution of MY-affected trees fails to provide evidence of a biotic cause when evaluated in comparison to the strong association of MY with limestone roadsides. The abiotic hypothesis provides an explanation and causal relationship for the distribution

of the symptoms. The irreversibility of symptoms is also provided as evidence of a biotic cause. However, symptomatic trees remain in the same abiotic conditions, so irreversibility does not provide evidence that a biotic cause is more likely than an abiotic cause. The evidence presented by Czerniakowski *et al.* (2006) that Fe application can alleviate the symptoms of MY suggest that the observation of irreversibility in the field may be related to persistently poor abiotic conditions rather than a biotic agent.

Transmissibility via patch bark grafting is provided as evidence of a biotic cause of MY by Hanold *et al.* (2006). In that study, bark patches from nine symptomatic trees and one asymptomatic tree were grafted onto healthy *E. camaldulensis* seedlings. Three years after grafting, 13 of the 147 surviving seedlings that were grafted with bark from symptomatic trees showed yellowing or mottle. However, one of the 19 surviving seedlings grafted with bark from the asymptomatic tree also showed yellowing. This is insufficient replication of asymptomatic control trees to demonstrate that the cause of yellowing was transmission from the symptomatic trees. Luck *et al.* (2006) also tested for transmissibility via grafting. That study grafted branch pieces from both symptomatic and asymptomatic trees onto healthy *E. camaldulensis* rootstock. They also found that both symptomatic and asymptomatic trees demonstrated some yellowing in the foliage, which was corrected using Aquasol and Osmocote. This correction showed that the yellowing observed was not due to a biotic agent. The study provided evidence that MY-symptoms were not transmissible by grafting.

Asymmetric yellowing on single plants with MY has been used as evidence of a biotic agent (Hanold *et al.* 2006). However, Czerniakowski *et al.* (2006) showed that there is variability in abiotic soil factors beneath single trees related to the location of added limestone: MY symptoms were generally associated with the side of the tree closest to the limestone roadside, and soil conditions directly under symptomatic and asymptomatic sections of the tree differed significantly in pH, available Fe and carbonate levels. This demonstrated the coupling of sections of the roots to sections of branches. The mobility of Fe within a tree provides a further explanation of asymmetry of symptoms independent of soil variability: Fe is required for the synthesis of chlorophyll, but does not easily move out of old leaves for redistribution (Dell 1996; Randles 1999), and hence chlorosis of young leaves is an early symptom of iron deficiency (Dell 1996). There is no reason to expect that lime chlorosis would appear symmetrically on all branches of a tree, and hence no reason that asymmetry should be considered evidence that MY has a biotic cause.

Hanold *et al.* (2006) detected distinct nucleic acids in MY-affected River Red Gums (*E. camaldulensis*), which they termed MY-RNA. They claimed that these nucleic acids were unusual, and possibly associated with a virus or viroid. However, they note that these nucleic acids have also been detected in trees without MY symptoms. Hanold *et al.* (2006) suggest this may be evidence that the MY-RNA is associated with the cause of the disease, and hence are present before symptoms appear. However, a more parsimonious explanation is that the RNA is detected in both symptomatic and asymptomatic trees because it is not related to MY.

Hanold *et al.* (2006) presented evidence of MY in other states, including Western Australia and Victoria. However, the trees in this survey include those that do not necessarily display interveinal

yellowing, and hence may represent trees suffering from a range of different stresses or diseases. Given that a biotic cause of MY has not been established, it would be prudent to limit the search for associated factors to trees that exhibit interveinal yellowing, and that demonstrate a similar progression of symptoms.

3.9.5. Research questions

What is still unclear – at least from the published literature – is the distribution of MY in the region. Are there clear examples of interveinal yellowing in trees that are not associated with limestone roads? If so, in which part of the landscape do they occur?

The available evidence suggests that MY is lime chlorosis. This means that MY is not the large threat to trees in the region (and beyond) that it was once considered, as it is not likely to be observed away from areas of artificially elevated carbonate levels, and will not spread like a disease caused by a biotic agent may. Nevertheless, the use of limestone in roads is extensive, so that even if MY is restricted to roadsides, there is still significant potential for loss of trees. However, some questions remain about the specific mechanism by which lime chlorosis is occurring, which may be important for developing methods to manage and mitigate the issue in some areas. Is Fe the main deficient nutrient, or do other nutrients such as Mn play an important role in MY? Is there any possibility that lime chlorosis may be caused by increased weathering of underlying limestone or mobilisation of salt from rising water tables? In any case, plant species are unlikely to survive in soil that has been made significantly more alkaline than that to which they are adapted, and the use of crushed lime in roadsides is making soils more alkaline.

Management options for lime chlorosis require further research. There are a wide range of lime chlorosis correction techniques, including trunk injectors (Zamora & Escobar 2000) and stem implants (Scott *et al.* 2013), which can bypass the unfavourable soil condition to deliver nutrients to the leaves. If nutrient application can alleviate chlorosis, the longevity of this technique and its feasibility and cost-effectiveness require further investigation. It may be that no method of nutrient application will be a feasible, long-term solution, and that replanting areas of dead trees with species better-adapted to the conditions is the best management option. Future research could investigate the potential of using *E. camaldulensis* provenances adapted to alkaline soils, such as from Wiluna, Western Australia, or Lake Albacutya, Victoria (described in Marcar *et al.* 2002). Past and future planting of trees in lime-affected soils should also be monitored and evaluated as an adaptive management project, to determine the suitability of different trees and shrubs to these soil conditions. These questions are hypothetical at this stage, although they may reflect the future direction of MY and lime-induced chlorosis research.

3.10. Plant pathogens

Phytophthora root rot is a condition in trees that leads to premature tree death. It is caused by a soil-borne water mould *Phytophthora cinnamomi*. It is a serious pathogenic threat in areas with more the 500 mm average annual rainfall, and hence is more likely to be a problem in the southern extent of the Tatiara region, around Padthaway. Irrigation may allow Phytophthora Root Rot in lower rainfall areas, though this is uncommon in the region as soil conditions in the region are generally not conducive to

Phytophthora infestations. The cause, progression of symptoms, effects and environmental limits of *P. cinnamomii* are well-known, and have been comprehensively reviewed by Shearer and Smith (2000). As such, we will not review this issue further here, other than to acknowledge it as another potential tree decline issue in the study region. As for many of the tree decline issues, the most pressing research priority is to determine the extent and severity of the problem in the region.

3.11. Dodder Laurel infestation

Dodder-Laurels belong to the genus *Cassytha* (Lauraceae). There are 14 *Cassytha* species in Australia. Infestations of *Cassytha* have killed trees in central and central-western Victorian Box Ironbark forests (Reid and Yan 2000). In the study region, *Cassytha melantha* infestations have been observed along roadsides in Mallee vegetation. The effect of and/or rate of infestation by Dodder Laurels is likely to be influenced by other factors that cause tree stress, such as drought which means that it may become a bigger problem in the region as the incidence of drought increases under climate change.



Figure 6. *Cassytha melantha* (a) showing twining stem with suckers into the stem of host plant), (b) fruiting body with distinctive lack anthers, (c) infestation on Netherton Road, Netherton.

[Photos: a and b – Atlas of Living Australia 2015, c – L. Cattle]

Research into removing *Cassytha* infestations is needed to determine the best management option. *Cassytha* has a high number of contact points (haustoria) on its host, so any form of hand or

mechanical removal is unlikely to be complete, and the plant will recover. Two methods that could be trialled at small scales in Mallee vegetation include:

1. Burning of infested areas
2. Lopping of infested trees and subsequent burning. This should only be considered for Mallee eucalypts that resprout from the base. Once *Cassytha* is established, it abandons its contact with the soil, so lopping a tree may be the only way to starve the *Cassytha* of its water and nutrient source. NOTE: this is only a recommendation for a trial to determine management options – it is not a recommendation to lop trees with *Cassytha* infestations. Any research should gain the requisite permission to remove trees and adhere to the relevant legislation relating to tree removal.

3.12. Mistletoe

Mistletoes are hemiparasitic plants that tap into the xylem of host plants. Birds disperse mistletoe seeds between host plants (Reid 1989; Reid *et al.* 1994). Host species for mistletoes are mostly *Eucalyptus* and *Acacia* species (Downey 1998). Some mistletoe species (*Amyema miquelii* and *A. pendula*, Figure 7) are capable of killing eucalypt trees, but only under heavy infestations (Reid *et al.* 1994). Trees that are along the edges of remnant patches and isolated paddock trees are more susceptible to infestation than trees that occur in denser stands (Bowen *et al.* 2009; Reid *et al.* 1994). Mistletoe is preferentially eaten by folivores due to higher nutrient content than its hosts' foliage, and is more susceptible to fire, frost and drought than the hosts. A decline in mistletoe folivores and fire suppression has been proposed as a possible cause for their increase in agricultural landscapes (Reid *et al.* 1994).

Changes in the behaviour of dispersers of mistletoe seeds (birds) and reductions in numbers of arboreal marsupials that feed on mistletoes may have led to an increase in mistletoe abundance (Reid *et al.* 1994). The total number of trees in agricultural landscapes has decreased dramatically and this means bird dispersers visit the remaining trees more frequently, which results in higher infestation rates of remaining trees (Reid *et al.* 1994).

South Australia has 17 native species of mistletoe. Although they occur on many different host plants, they are most common on eucalypts in higher rainfall regions. Most of the common eucalypt species occurring in the study region are known hosts for mistletoe species (Downey 1998). Drooping Mistletoe (*Amyema pendula*) and Box Mistletoe (*Amyema miquelii*), the two most often-reported damaging species, occur in the district (Stewart *et al.* 1998).

Mistletoes could pose a threat to the health of scattered trees throughout the Coorong and Tatiara districts, due to the history of heavy clearing and agricultural practices, factors that have been associated with an increase the abundance of mistletoes in other regions of Australia (Bowen *et al.* 2009; Reid *et al.* 1994). Tree death can occur when other stressors such as drought accompany a heavy infestation of mistletoe. However, (Reid & Lange 1988) found that mistletoe species are more susceptible to drought mortality than host trees in which case increases in the frequency and severity of drought may reduce infestation levels in host trees.

As mistletoe represents an essential component of healthy, functioning native vegetation, and only becomes an issue when present in high numbers, it is difficult to assess the severity of mistletoe as a tree dieback issue in the Coorong and Tatiara Districts. Like many of the other issues, better data on the distribution and extent of tree decline caused by mistletoe is required.



Figure 7. Drooping Mistletoe (*Amyema pendula*)

Photo: Google (<http://creativecommons.org/licenses/by-sa/3.0>)

3.13. Witches' Broom

Witches' Broom, or little leaf disease, has been associated with the presence of phytoplasmas in trees exhibiting stunting and a reduction in leaf size. Trees with Witches' Broom can show signs of dieback or can die prematurely. However, the cause of Witches' Broom symptoms is difficult to identify due to the nature of the disease and difficulty working with eucalypt plant material (Wardlaw *et al.* 2000).

Although Witches' Broom has been reported to occur widely, research into potential causes and treatments has received little attention, probably because incidences of the symptoms are low and it is not usually lethal. Reports of symptoms occurring in several eucalypt species including Forest Red Gum, Flooded Gum and Tasmanian Blue Gum (*E. tereticornis*, *E. grandis* and *E. globulus* respectively) and are primarily from plantations (Wardlaw *et al.* 2000).

In the study region, Witches' Broom has been reported, although the extent and importance of the problem is unclear. Research into the condition does not appear to be a priority, unless it emerges to be a widespread and frequently lethal problem, which it does not appear to be at this stage.

4. Lack of recruitment

This review focuses primarily on the causes of tree death and decline in the region, particularly that of mature trees. However, it is important to consider the lack of recruitment of juvenile trees as a factor contributing to declining tree numbers in agricultural landscapes. We must expect that trees in the landscape will die. For native trees to remain part of the landscape, continuous recruitment to replace senescent trees is vital.

The lack of tree recruitment in the landscape may influence tree decline issues in several ways:

1. Issues that may have always acted on trees will be more conspicuous, due to lower tree numbers in the landscape. For example, borers have always caused some tree mortality after a drought, but in a landscape with high tree cover and frequent tree recruitment, this would not be a problem, but rather a natural part of the population dynamics
2. Lower tree numbers may increase the pressure exerted by some tree decline issues on the remaining trees. For example, as the ratio of Galahs to trees increases, so may the pressure exerted by Galahs on the remaining trees.
3. Some organisms may rely on the early life-history stages of eucalypts for survival, and this may influence factors such as natural pest control on mature trees.

Paddock trees are vitally important for natural regeneration. When grazing pressure is eased, a ring of seedlings can often be observed around a large paddock tree. In this sense, a large paddock tree can provide a focus for surrounding revegetation efforts (Lindenmayer *et al.* 2005). However, many isolated paddock trees are older than European settlement, and are senescing (as well as suffering from the range of tree decline issues). As such, we need to take advantage of the natural regeneration capabilities of isolated paddock trees. Dorrough and Moxham (2005) estimate that this window of opportunity may only be a few decades, after which time a far greater proportion of the current cohort of isolated paddock trees in eastern Australia's wheat-sheep belt will have died.

Reduced grazing pressure, however, will not always result in natural tree regeneration, which requires viable seed availability, suitable conditions for germination, and a competitive advantage over co-occurring species (Standish *et al.* 2007). If these conditions are not met, direct seeding and tube-stock planting will be required for tree regeneration.

We may be powerless to manage many of the tree decline issues, especially when exacerbated by factors beyond our control, like periodic drought. In this sense, research into the factors that influence and limit natural tree regeneration will be important for ensuring the persistence of trees in the landscape. Research already suggests that livestock grazing pressure is likely to be the biggest limitation (Spooner & Briggs 2008; Weinberg *et al.* 2011), although there is variability in the effects of grazing on tree regeneration (Manning *et al.* 2006; Vesk & Dorrough 2006).

5. Summary and key research questions

This review has highlighted more research questions than can be addressed by the current broader research project. In this sense, we hope the document can serve as a useful reference for future research into tree decline. Here, we attempt to prioritise potential research questions, and judge which research is most likely to improve our ability to manage tree decline in the region.

5.1. Determining the extent and severity of tree decline issues

The overwhelming theme from the review is that we do not have a good understanding of the extent and severity of each tree decline issue. Dryland salinity may be the exception, but even then there are interactions with other tree decline issues that may confound this understanding. Many previous documents and publications have listed and described the range of tree decline issues in the region. Other documents list land management or natural resource issues, which often manifest themselves as tree decline issues. But these studies rarely indicate the extent of each problem, nor do they rank the issues from most to least concern. This is understandable, due to the large number of interacting issues. The problems consequently seem insurmountable.

A better understanding of the extent of each of these issues across the Coorong and Tatiara districts would provide an essential platform for devising management strategies, and for gaining a better understanding of the causal factors. For each tree decline issues reviewed, we need to know:

1. How widespread is the issue in the region?
2. Which species is it affecting, and which species is it not affecting?
3. In which parts of the landscape does the issue occur, and on which soil type?
4. Is the issue associated with any land management practices?
5. Is the issue correlated with climatic events or cycles?

A conventional method for addressing the lack of understanding of the extent of the various tree decline issues would be to conduct extensive surveys of trees in the region. A stratified random approach to compiling a snapshot of the region could be used. Paton *et al.* (2005) used such an approach and provided some valuable insight into tree decline issues in the Keith and Bordertown areas – i.e. that Mundulla Yellows is limited to roadsides, and that paddock trees are generally suffering from other issues, such as borers and lerps. However, a stratified random survey is better suited to a smaller study region than the entire Coorong and Tatiara Districts. The resources required to obtain useful data across the whole region (and for the whole range of tree decline issues) would be too great for the current research project. Any detailed survey across a smaller subset of the region would miss some portion of the suite of tree decline issues.

We propose to develop a user-friendly website to allow citizens to input their own observations and data on tree decline. We believe that by using a citizen-science approach to data collection, a greater amount of data will be compiled than would be possible by a group of researchers conducting field observations. The data collection will also be more cost-efficient. This method also allows stakeholders (in this case, the whole community) to participate and take ownership of the tree decline

issue. The process would also respect and utilise the vast knowledge amongst the community on tree decline issues and instances of tree decline and death.

The development of such a database would not preclude us from gathering data, and we intend to generate new data for the database from field surveys. The database could also incorporate past datasets (such as that of Paton *et al.* 2005). Finally, the database could continue to be used after we have completed the current research project, either by us, by other researchers or by community members or stakeholders. Given the novelty of the citizen data approach, there may be a higher level of uncertainty about the quantity and quality of data collected than if an extensive survey was conducted. However, we believe this uncertainty is outweighed by the potential for a larger dataset and a more cost-effective means of data collection.

5.2. Other research priorities

Research needs and knowledge gaps regarding tree decline issues have been identified throughout the review. The scope for further research within the current research project is limited. However, we believe there is a strong need for experiments addressing treatments for lime chlorosis or other nutrient deficiencies in eucalypts. We appreciate that treating individual trees is unlikely to be feasible over wide areas. However, a single tree can be a significant resource, and the potential to rescue significant or iconic trees could be valuable to the community, as well as having benefits for biodiversity. We would like to conduct an experiment that tests different nutrient correction methods in trees, including stem implants which are commercially available and easy to apply.

We also feel that obtaining spatially-explicit data and gaining a better understanding of the extent of different tree decline issues (as proposed in Section 5.1) will help identify which of the remaining knowledge gaps are high priority for further research.

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