Murray River nesting tree selection by the South Australian eastern regent parrot Polytelis anthopeplus monarchoides

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Equations

Acronyms

BOM	Bureau of Meteorology
BRDF	bi-directional reflectance distribution function
DEW	Department of Environment and Water
DEWNR	Department of Environment, Water and Natural Resources
GDA	Geocentric Datum of Australia
KDE	kernel density estimate
MDBA/C	Murray Darling Basin Authority/Commission
nm	nanometres
NDVI	normalised difference vegetation index
NIR	near infrared
RPRT	Regent Parrot Recovery Team
SAMDB	South Australian Murray-Darling Basin (Authority)
SD	standard deviation
UTM	universal transverse Mercator

Abstract

The eastern regent parrot (*Polytelis anthopeplus monarchoides*) is a vulnerable bird sub-species in South Australia. It is found in its seasonal breeding habitat in the riparian zone of the main rivers of the Murray-Darling Basin between September and November. For the rest of the year the birds disperse throughout the Mallee woodland regions to the north and south of the Murray River making it difficult to record their behaviour and specific habitat niche. Habitat destruction and fragmentation have greatly reduced the natural nest tree availability, since the birds select nest hollows in healthy, old River Red Gums (*Eucalyptus camaldulensis*), a keystone species in riparian zones across Australia. Ongoing Eucalypt dieback, as a result of drought and increasing groundwater salinity causing increased stress and susceptibility to disease, is responsible for a reduction in viable mature aged River Red Gums in the breeding habitat. The effects of climate change on maximum temperatures, abnormally high seasonal rainfall, and its associated floods prevent seed germination or kill fragile seedlings before they establish stable root systems and reduce recruitment of new generations of River Red Gum to the ecosystem. Using nest location data, collected between 2003 and 2015, spatial vegetation and water datasets, satellite imagery, LiDAR elevation data, rainfall and river water level datasets, I confirmed the active selection of both healthy and drowned trees by South Australian eastern regent parrots, in contrast to the almost 100% selection of healthy trees in the eastern states. Normalised Difference Vegetation Index (NDVI) values for trees in the study area showed an increase in photosynthetic activity and crown leaf density, and hence vigour, in response to increased river water availability. This correlated with a significant nest hollow selection shift away from drowned trees to that of healthier trees in the years after 2010's drought breaking rainfall. Previous research relates higher fecundity to nests situated in healthy tree hollows, and, in combination with the prolonged improvement in tree health in the riparian zone of the Murray River after periods of bank fill and inundation identified in this research, ecologists could argue for increased volumes and frequency of environmental flows to the South Australian Murray River from upstream regions of the Murray-Darling Basin. This would benefit not just the flora of the lower Murray River ecosystem, but also fauna species reliant on its rich native biome. The riparian zone is, however, a dynamic system and has already changed from what we consider its 'natural', before the Anthropocene, state. This altered ecosystem's composition and productivity must be taken into account before making management changes that could change the current balance of the terrestrial and aquatic flora and fauna in this area.

Declaration

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Acknowledgments

I would like to thank all the Flinders University geospatial team (Robert Keane, Professor David Bruce, Tessa Lane, Marcio da Silva and Steve Fildes) for their support and encouragement throughout this thesis, prolonged as it has been! The patience and positivity they showed when I had to change supervisors and study direction has been immeasurable in getting me to this point. Robert Keane in particular has been available to offer gems of information just when I asked and is an inspiration whenever we speak maps and stuff. May he live long and prosper. David kept me true to my purpose as best he could when I would wander off course, and Tessa gave me optimism when I struggled. Marcio da Silva showed me what I should have done and how to do it more efficiently, if only I'd paid more attention.

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Gerry, my long-term partner, has suffered silently through this process by my side. He has listened to my moaning, walked the dog and cooked more than ever before to allow me to finish on time, while putting up with his own trials. I could never have done it and remained sane or avoided a gastric ulcer without his support.

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1 Introduction

The analysis of geospatial data is becoming more common in ecological science, although maps or presence and underlying topography and abiotic features have always been an important part of any species distribution modelling process (Gibson et al., 2004). The visualisation of data in a Geographical Information System (GIS) can highlight patterns which may be less obvious in the field or tabular form (Brambilla et al., 2009). When investigating a declining population of animals, the ability to include multiple layers of variables, including elevation, aspect, underlying soil, vegetation cover, rainfall as well as anthropogenic factors such as urban development or transport corridors may illustrate previously unrecognised barriers to migration, hotspots of activity or sites of small sink habitat sites which may benefit from connective corridors to facilitate population interactions (Carter, Stolen & Breininger, 2006; Liu, McShea & Li, 2017; Store & Kangas, 2001). In this study I shall use a GIS and satellite image data to research nest site locations of a vulnerable sub-species of parrot in South Australia and identify if any correlation exists between nest tree selected and proximate river water levels.

Eastern regent parrots (*Polytelis anthopeplus monarchoides*) are listed as vulnerable in South Australia under the national Commonwealth Environment Protection and Biodiversity Conservation Act 1999, and the National Parks and Wildlife Act 1972 of South Australia. There were fewer than 400 breeding pairs in South Australia recorded in 2011 (Baker-Gabb & Hurley, 2011; Garnett, Szabo & Dutson, 2011; Schultz, 2006). The western sub-species (*P. a. anthopeplus*) is currently still breeding successfully in the Wheat Belt of Western Australia.

This medium-sized parrot, up to 200 g weight, was previously commonly found nesting in hollows of old *Eucalyptus camaldulensis camaldulensis* (river red gum) along the length of the Murray River in New South Wales, Victoria, and South Australia. During the breeding season, eastern regent parrots forage on surrounding food resources, some up to 15 kilometres away in the nearest Mallee areas, returning frequently to feed the nestlings. After breeding in spring, the birds would disperse throughout the Mallee regions of the Murray Darling Basin for the rest of the year and could be seen in large flocks foraging for grasses, chenopods and Mallee scrub seeds and forbs.

Eastern regent parrots have decreased since the late 1800s when they were hunted for sport or captured for the pet trade (Burbidge, 1985). Populations have declined further due to habitat loss as a result of grazing and destruction of the riparian zone's understory, the agricultural clearing of their primary feeding habitats in the more distant Mallee regions of the Murray Riverland, and removal of mature river red gums along the riverbank for human habitation or tourism use (Baker-Gabb & Hurley, 2011; Burbidge, 1985). Anthropogenic climate change has changed the hydrology and plant diversity of previously successful breeding locations leading to geographic range contraction and the creation of small metapopulations (Corlett, 2016). Competition for nesting hollows from heterospecific species, predation by lizards, feral cats and foxes, and human-related mortality such as poisoning or pollution effects all reduce successful fledging and adult population size (Ford, 2011; Goulson, 2003; Ireland & Ryan-Colton, 2016).

Eastern regent parrot Conservation Management Plans, including the National Recovery Plan (Baker-Gabb & Hurley, 2011; Schultz, 2006), are already active in South Australia to protect important ecosystems and increase public awareness of the sub-species' status. Data of bird sightings have been collected since 1992 in South Australia (unpublished data by K.W. Smith), with some studies dating from 1985 (Beardsell, 1985; Burbidge, 1985; Oldroyd, Lawler & Crozier, 1994; Smith, Pressey & Smith, 1994). These data enables this analysis of temporal trends in breeding colony numbers and locations. Although breeding locations are identifiable based on recognised tree characteristics and proximity to the Murray River, studies suggest that the isolation of these suitable nest sites from safe Mallee foraging areas is the primary obstacle to their use (Baker-Gabb & Hurley, 2011). The presence data collected by the Regent Parrot Recovery Team do not corroborate this assumption that the highly fragmented landscape is a primary factor dictating breeding numbers, since they frequently observe males foraging opportunistically on local horticulture and riparian vegetation in close proximity to the nest tree, and do not record the long absences required by flights to distant Mallee sites (Ireland & Ryan-Colton, 2016). The survey data record the associated tree's health, and indicate that South Australian populations sporadically used dead and drowned trees, in contrast to the 100% selection of live trees in eastern states. Their use of dead/drowned trees might be necessary given the ongoing reduction in mature, healthy stands of river red gum habitat along the Murray River. Many studies show the relationship between river red gum vigour and anthropogenic impacts on altering local water regimes (Colloff, 2014; Cunningham et al., 2007; Cunningham et al., 2011; Doody et al., 2014; Mensforth et al., 1994; Sims et al., 2012; Vivian et al., 2014).

Until now, no published studies have been done in South Australia to identify nest tree selection and what factors influence the number of successful breeding pairs in the state; however, the positive relationship between tree health and fertility has been documented (Burbidge, 1985; Cantor et al., 2019; Ireland & Ryan-Colton, 2016). The standard ground-based methodology to identify vegetation health along the 392 km of the Murray River study area requires a large investment in personnel to record tree canopy cover and health over a distance of up to 300 m from the riverbank. Annual measurement of changes in the vigour of riparian vegetation would be expensive and unfeasible for most government departments. A quicker and more cost-effective alternative would be to use satellite multispectral imagery providing separate image bands for the blue, green, red, and near infra-red wavelengths to calculate vegetation indices highlighting photosynthetic activity and biomass for each pixel in the image.

The increasing availability of remotely sensed imagery from online resources, such as Planetscope (Planet Team, 2020), US Geological Survey (Earth Resources Observation and Science (EROS) Centre) and open-data government websites including NatureMapsSA (Enviro Data SA, 2020) enables exploration of the distribution and state of riparian vegetation and can potentially quantify change in the health of tree stands, as well as their response to changes in water availability. When mapped with contemporaneous locations of parrot nests, correlations can identify patterns of site selection or avoidance based on the underlying tree's photosynthetic activity as a proxy for its overall canopy cover.

The aim of my research is to produce a time series of vegetation-health maps from 5 m pixel normalised difference vegetation index images that coincide with the study area and period of nest surveys. An initial qualitative analysis of these datasets will determine possible spatial and temporal patterns of nesting colonies in the Murray River of South Australia, and test whether eastern regent parrot residence and nesting in South Australia correlates positively with *Eucalyptus camaldulensis camaldulensis* health. Declining total numbers of nests in South Australia in the last 4 years makes this research ever more important for evidence-based recommendations to the Murray Darling Basin Authority and federal government for increasing water allocations for environmental purposes. A successful outcome would be the identification and improvement of nesting colony areas of riverbank environment for this vulnerable parrot, and indirectly improving population numbers. Restoration of the river red gum zones may also benefit other local species, such as the Murray cod (*Maccullochella peelii)*, Murray crayfish (*Euastacus armatus*), southern bell frog (*Litoria raniformis*) and Murray carpet python (*Morelia spilota)*(Threatened Species Scientific Committtee, 2013), but attempts should be made by ecologists and managers to retain areas of established, but altered, riverbank and floodplain ecosystems without river red gums, that successfully host other native species (Colloff & Baldwin, 2010).

1.1 Research hypotheses

In this study I aim to test the hypothesis that the eastern regent parrot in South Australia selects healthy river red gums with full canopies for nesting over less-healthy trees with patchy to no canopy density.

I hypothesise that higher water flow will improve tree health and canopy cover, and that this can be identified using normalised difference vegetation indices calculated from moderate spatial resolution, multispectral serial satellite images.

1.2 Thesis structure

This thesis consists of six sections: (1) a general introduction with a literature review and a description of the study area, (2) methods , (3) results for the initial selection hypothesis test, spatial analysis of nest locations, and a sub-section on vegetation indices and tree health, (4) and (5) discussion of the findings with a summary of the outputs and their potential utility in biodiversity conservation for the state, and (6) appendices containing study area maps and distribution of river red gums along the Murray River, detailed flood polygon maps, python script and attributes associated with the Department of Environment and Water dataset.

1.3 Literature review

1.3.1 Overview

I aim to identify knowledge gaps in the predictive modelling of eastern regent parrots in South Australia's Murray Darling River Basin. More specifically, I will investigate whether new methodologies using remotely sensed imagery and geospatial data could produce an improved distribution model of potential breeding sites, identifying currently used breeding sites, but also areas that could be restored to increase the local capacity for successful eastern regent parrot breeding in South Australia. A clear picture of what makes the optimal mature river red gum nesting tree for the eastern regent parrot is required to identify the locations along the Murray River most suitable for the breeding pairs as they return from the Mallee in which they spend the rest of the year. The major causes of population decline and alteration in historical nesting colonies are widely accepted to be due to habitat destruction over the last 150 years, and more recently, those of anthropogenic climate change.

I will first describe the historical habitat and range of the eastern regent parrot from recorded sightings. I will then focus on the current conservation status and specific habitat requirements and their breeding niche. Using sightings recorded by local expert ecologists and bird watchers, I will identify the most important habitat features for use in modelling. I also assess studies of the eastern regent parrot in other states for utility in South Australia's situation. Then, I will discuss the different remote-sensing techniques, geospatial information systems, and other spatiotemporal analyses that correlate climate conditions and flora/fauna indicators.

1.3.2 Ecology of the eastern regent parrot

The main breeding range of the eastern regent parrot extends from the intersection of the Darling River with the Murray River in New South Wales, and the bottom 30 km of the Murrumbidgee River where it intersects the Murray River in Victoria, along the Murray River into South Australia and down to Swan Reach (Figure 1). Some breeding-season sightings have also been recorded along the riverbanks in the Mallee woodland conservation areas of Murray-Sunset, Wyperfield and Hattah-Kulkyne National Parks, and the Annuello and Bronzewing Flora and Fauna Reserves of Victoria.

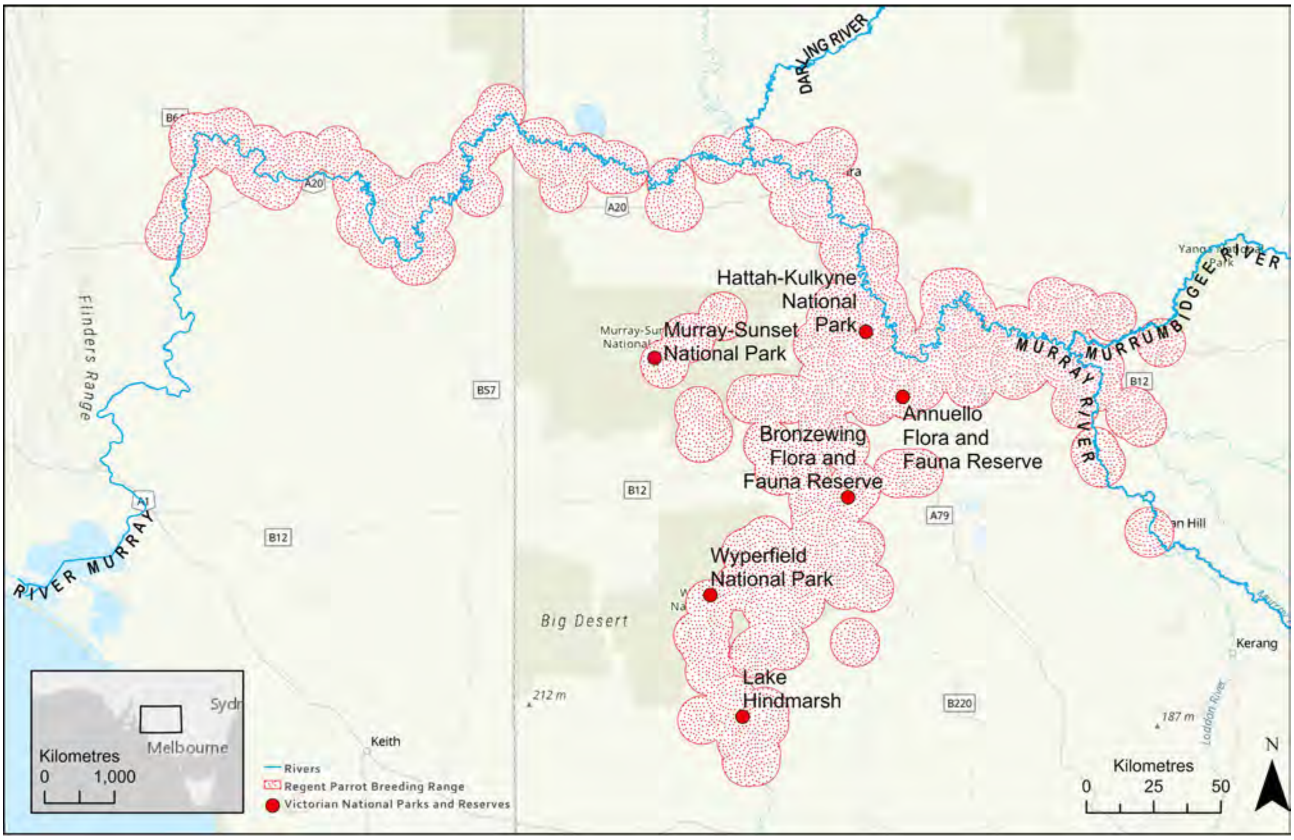


Figure 1: Range of the eastern regent parrot in breeding season

Regent parrots are ground foragers and rely on the seeds, flowers and buds of Mallee scrub as their primary food source during the year. Mallee is composed of several *Eucalyptus* species, including red mallee, *E. oleosa* subsp. *oleosa*, yorrell *E. gracilis,* and the white Mallee *E. dumosa*, and many ground and understorey vegetation species — grass, chenopods and bluebushes, including *Maireana erioclada* and *M. pentatropis,* climbing twinleaf *Zygophyllium eremaeum,* but the eastern regent parrot will occasionally supplement its diet with larvae, psyllids or lerps (Beardsell, 1985; Burbidge, 1985; Higgins, 1999; Webster, 2001). Apart from their recognised Mallee habitat preferences, eastern regent parrots also eat fruit from vineyards, olive groves and almond orchards, which provide food for up to 6 months of the year in the agriculturally rich Riverland environs (Attwood et al., 2009; Bennett, Radford & Haslem, 2006; Luck, Hunt & Carter, 2015; Luck et al., 2014; Watson et al., 2014). During breeding, colonies of eastern regent parrot pairs will select hollows in mature, large river red gums within 100 m of the banks of the Murray River or Darling River and their tributaries. In New South Wales and Victoria, these ancient trees are at least 27 m high and often 1.6 m diameter at breast height (Webster, 2001), while those in South Australia average 24–25 m high, and 1.5 m wide at breast height (Baker-Gabb & Hurley, 2011; Burbidge, 1985). South Australian eastern regent parrots use both dead and live river red gums, unlike in the eastern states where they only appear to use live trees (Beardsell, 1985). Hollows can be reused annually, with birds showing some degree of natal philopatry (loyalty to birth location), although the colony site often prevails over exact hollow fidelity due to hetero-specific competition (Department of the Environment, 2017). Some species such as feral bees (*Apis mellifera*), little corellas (*Cacatua sanguinea*) and yellow rosellas (*Platycercus elegans flaveolus*) compete aggressively for eastern regent parrot nest hollows both during the breeding season, and also when the hollows are empty in the non-breeding period (Burbidge, 1985; Goulson, 2003; Higgins, 1999; Lewis et al., 2019; Oldroyd, Lawler & Crozier, 1994; Smith, 2001; Webster, 2001). Males forage constantly during the day, using the lignum shrubland found along the riparian understorey composed predominantly of *Duma florulenta* and species of *Chenopodium, Acacia* and *Atriplex*, returning to the nest up to 20 times a day (Schultz, 2006) to feed the mother and her nestlings (Cantor et al., 2019). The more distant the optimal feeding areas, the more difficult it is to rear offspring successfully (Stojanovic et al., 2015). In a mosaic landscape of inhospitable pastoral or arable farmland, open semi-arid scrub, or black box *Eucalyptus largiflorens* woodland, the male parrot will try to fly between structures such as solitary gum trees and connective corridors along fences and roadside verges to the feeding area to reduce predation risk (Bennett, Radford & Haslem, 2006; Law & Dickman, 1998; Lindenmayer & Nix, 1993; Manning, Fischer & Lindenmayer, 2006; Watson et al., 2014; Wilson & Lindenmayer, 1996). The distances they are willing to expose themselves to open sky are not documented, but isolation of Mallee from breeding sites by suitable connective routes is a major determinant of selection of nesting hollows (Baker-Gabb & Hurley, 2011; Burbidge, 1985; Schultz, 2006; Watson et al., 2014; Webster, 2001).

There are knowledge gaps regarding the movement of eastern regent parrots during the non-breeding season, with citizen science providing some Mallee sightings between November and August every year (Enviro Data SA, 2020). Regent parrot recovery teams continue to collate data on non-breeding season locations and individual bird movements using wireless trackers in conjunction with Zoos SA veterinarians and Department of Environment and Water officers.

1.3.3 Causes of declining bird populations

Agriculture (Bennett, Radford & Haslem, 2006; Luck, Hunt & Carter, 2015; Luck et al., 2014; Manning, Lindenmayer & Barry, 2004; Miller & Cale, 2000; Spooner, 2013; Watson et al., 2014), human developments including residential and tourism ventures, transport corridors and changed natural water regimes (Davies & Lawrence, 2019; Poodat et al., 2015; Wilson & Lindenmayer, 1996), and climate change (Chambers, Hughes & Weston, 2005; Garden, O'Donnell & Catterall, 2015; Gonzalez, Scott & Miles, 2011; Keith et al., 2008) directly or indirectly alter natural ecosystems. These changes fragment landscapes and lead to the loss of specific habitats for some specialist species, including the eastern regent parrot (Catterall, Lynch & Jansen, 2007). High mortality has also resulted from agriculturists unintentionally poisoning large groups of birds by rodenticide-treated seed, and by horticulturists shooting parrots they believed to be damaging stone-fruit crops (Schultz, 2006).

Another potential stressor is reduced flooding in the South Australian section of the Murray River, and the effect of irrigation on raising the level of the groundwater aquifer and the salt-rich soil layers above it results in increasing salinity (Johns et al., 2009; Macinnis-Ng et al., 2016; MDBA, 2018), which degrades soil and reduces flora and fauna diversity throughout floodplain and riparian ecosystems (Baldwin et al., 2013; Mac Nally et al., 2011; Overton & Jolly, 2004; Stokes, Ward & Colloff, 2010; Threatened Species Scientific Committtee, 2013). The alteration of the riparian soil composition encourages encroachment by more tolerant feral species, or aggressive and abundant native species, e.g., yellow rosellas and noisy miners *Manorina melanocephala*, at the expense of threatened species already living in narrow niches.

Evidence from conservation research advocates the preservation of remnant patches that are as large as possible and of high quality as more important than connectivity between patches (Major, Christie & Gowing, 2001), although the conservation of patches of the mosaic of multiple different habitats is recommended to maintain diversity and opportunity in a largely cleared agricultural landscape (Ford, 2011; Law & Dickman, 1998). These patches are often used by vulnerable species at different stages of their lifecycle, including the eastern regent parrot, whose Mallee habitat during the non-breeding season in the Adelaide Plains has been cleared by > 90% for agricultural development (Figure 2) (Bradshaw, 2012). Edge effects, connectivity between remnants, and relative landscape scale of suitable habitat requirements reduce the benefits of smaller remnant patches to small prey animals such as the eastern regent parrot (Fahrig, 2003; Miller & Cale, 2000; Murray et al., 2008; Pullinger & Johnson, 2010; Watson et al., 2014).

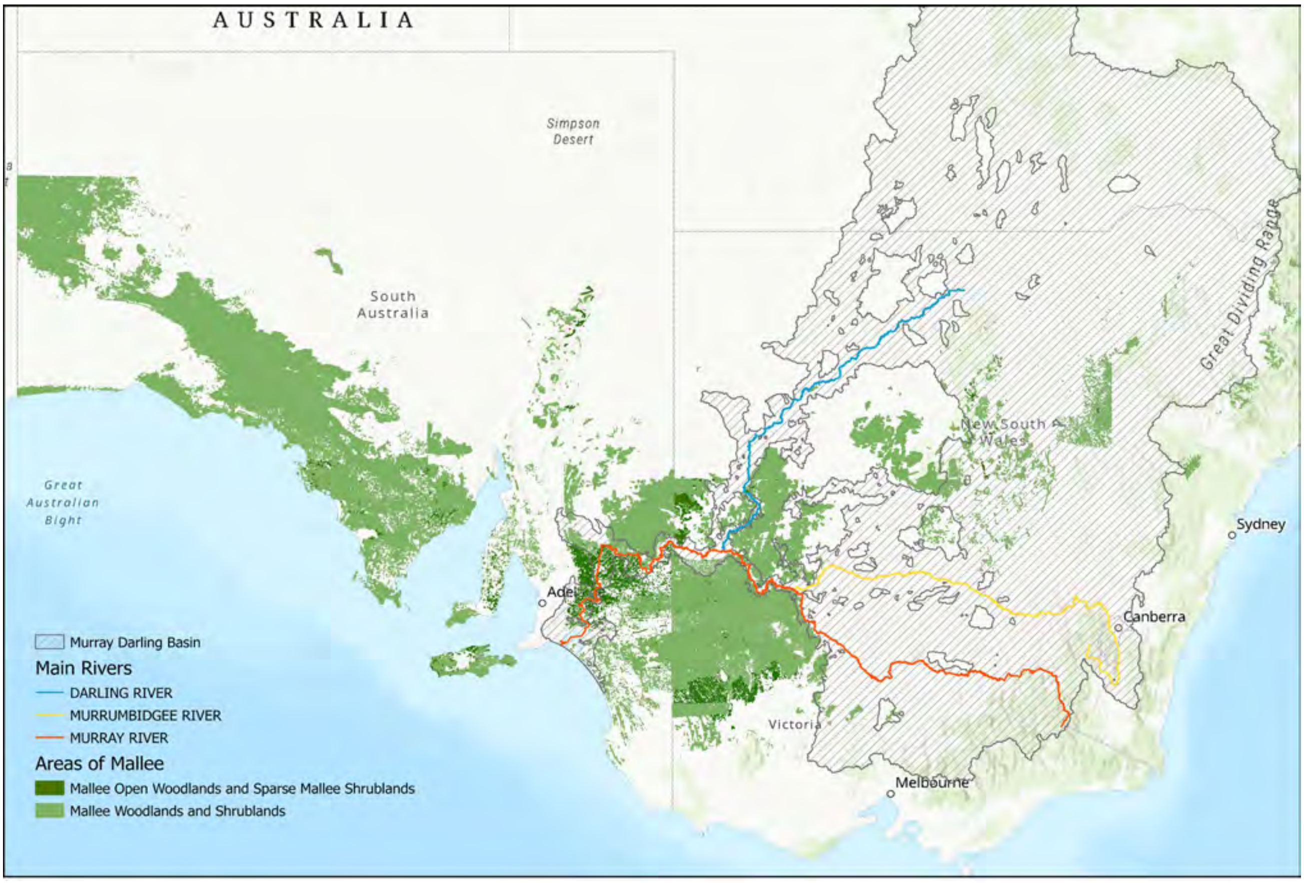


Figure 2: Current extent of Mallee Woodlands and Shrublands (MVG14) (source: environment.gov.au/NVIS, 2020)

The eastern regent parrot is a non-aggressive bird (except in defence of its nestlings); however, even in their most aggressive mode they are unable to protect their nestlings against predators, such as magpies or monitor lizards (Baker-Gabb & Hurley, 2011; Luck, Possingham & Paton, 1999; Richards, 2014). Their ground-foraging habit leaves the adults open to predation by feral species, including foxes, dogs and cats (Priddel, Wheeler & Copley, 2007).

Declines in native vegetation quantity and quality through the introduction of pest flora and fauna cause an associated decline in threatened species' habitat, such as those of the eastern regent parrot and Mallee fowl (EPA, 2013; O' Loughlin, O' Loughlin & Clarke, 2015). The importance of suitable tree hollows for nesting birds and their relative shortage is listed as one of many recognised features of the physical habitat that limits recovery of the eastern regent parrot (Crates et al., 2017; Goldingay, 2009; Stojanovic et al., 2017).

1.3.4 *Eucalyptus camaldulensis camaldulensis habitat and decline*

South Australian eastern regent parrots have only been identified nesting in river red gums within 270 m of the Murray River riverbank, despite Regent Parrot Recovery Team observers searching up to 500 m from the riverbank during surveys. Their selection of a nest hollow in a mature tree with healthy foliated canopy provides shade and protection from extremes of weather and predators. These tree hollows only exist in mature trees of at least 100 years old and at least 24 m tall that shed branching limbs due to environmental stress, e.g., drought, or trauma to the bark structure, to expose tree boles from which the hollows form (Colloff, 2014; Conservation Partners Programme, 1999).

The river red gum is one of the most common tree species in Australia, and not protected in federal legislation (Colloff, 2014; CSIRO, 2004). Its various sub-species form wide expanses of forest throughout Australia, and less-dense woodland areas and riparian bands up to 5 trees deep along water courses through the drier inland regions (Figure 3) (Elith & Bidwell, 2004).

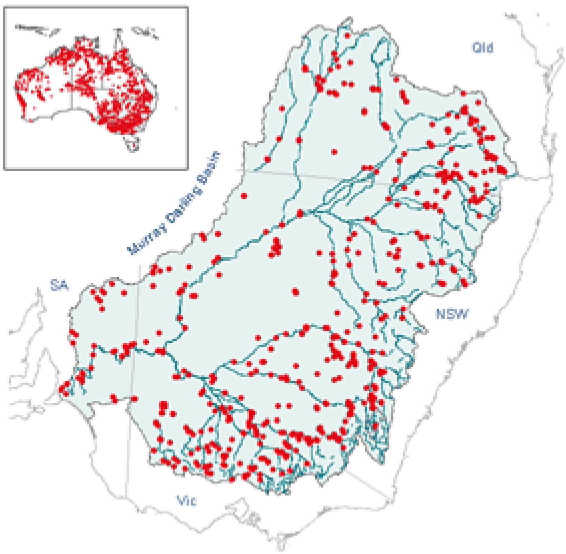


Figure 3: Location of Eucalyptus camaldulensis Dehnh. woodland and forest in Australia, and the Murray Darling Basin, in which the sub-species E. camaldulensis camaldulensis is found (CSIRO, 2004)

Recurring, prolonged droughts and a long-term decrease in rainfall and increase in maximum temperatures are highly detrimental to large areas of river red gums in the driest areas of Australia, in particular the Murray Darling Basin (Cunningham et al., 2007; Cunningham et al., 2011; Doody et al., 2014). Concurrent clearance for agriculture and the associated diversion of historic river channels has further deteriorated tree health because they depend on cycles of short-term (2-3 years) drought followed by flood to encourage reproduction by seeding or sprouting of fallen trunks (Colloff, 2014; Colloff & Baldwin, 2010; Doody et al., 2014).

Eucalyptus camaldulensis camaldulensis is the common sub-species in South Australia and, while smaller than its eastern state counterparts, some individuals have still been documented at over 500 years old and 30 m tall (Colloff, 2014; CSIRO, 2004). Saplings sprout after flood inundation of dropped seeds, rapidly sending down long tap roots that continue to extend to reach underlying groundwater sources for survival throughout their lifespan. Young trees can produce their first flower heads after 8-10 years if un-affected by low water availability or other unfavourable influences, such as over-browsing in drought periods, extreme temperatures at sprouting, or the inundation or soil moisture conditions during their first 5-6 months of growth (Colloff, 2014; Doody et al., 2014). Most trees are sustained by the 3-4 yearly floodplain inundations, without which seedlings cannot germinate nor saplings survive. Floods arriving out of season (e.g., in late spring) can drown new seedlings, or if in summer, after upstream agricultural irrigation releases, are too late to encourage germination for that year (Johns et al., 2009). The rapid growth of adventitious roots and aerenchymatous tissue — a spongy material that creates air spaces in the saplings enabling the exchange of gases between the above-ground/water-level parts and the roots, permit the young seedlings to survive immersion for a short period of time. This ability to survive inundation increases with age, those more than 2 months of age can survive one month of waterlogged roots, and saplings 40 cm tall up to 4 months (Baldwin et al., 2013; Colloff, 2014). This ability to recover after submergence allows them to outcompete less-tolerant grasses and vegetation for resources (Colloff & Baldwin, 2010). The wide, fanlike extension of the sinker root system is vital to supply oxygenated resources to the tree during times of inundation round the base, and is also responsible for the hydraulic redistribution process which regulates the flow of within-tree water through the xylem system during times of water stress and hot weather (Colloff, 2014).

In sites where the groundwater table is more than 12 metres below the soil surface, the growing tree is more likely to suffer from dieback due to increasing salinity and water stress, despite its supportive superficial sinker root system designed to absorb surface water (Bickford, 2003; Cunningham et al., 2011; Doody et al., 2014; Fu & Burgher, 2015; Macinnis-Ng et al., 2016; Mensforth et al., 1994; Overton & Jolly, 2004). The groundwater aquifers' salinity and depth below ground level varies widely across the Murray Darling Basin. Sites in east Victoria have shallow almost fresh water (< 5 mS/cm) (Cunningham et al., 2011), but the average electrical conductivity of the combined aquifers below the South Australian Murray River is > 32 mS/cm, more saline than sea water, although in some areas below the floodplain can be above 140 mS/cm. Groundwater aquifer surfaces under the Murray River in South Australia have been measured from 0.7 m below the surface to a maximum of 61 m (DEW, 2020). It is this disparity between groundwater salinity levels from the east to west of the Murray darling basin which has led to the much greater decline in the river red gum in the more arid western areas. Even where the water table is within the reach of the sinker roots for access during periods of drought and low river flow inundation, the high salinity causes stress to the tree when used as an alternate water source resulting in dieback. The associated reduction in freshwater lateral bank recharge and wash-out effect of floodwaters on the more superficial soil salinity, also results in higher water salinity for the superficial root system of the trees.

The continuing decrease in Murray River flow and rainfall in the Murray Darling River Basin over the last 20 years has led to a large decrease in the area of healthy river red gum along the South Australian section of the river, despite the intermittent floods since the Millennium Drought broke in 2010 (Cunningham et al., 2011; Doody et al., 2014). The permanent loss of previously healthy, old trees has reduced the number of available tree hollows for eastern regent parrots until new generations of *Eucalyptus* mature enough to provide new hollows fitting the requirements of size and security. The identification of trees that might still respond positively to improved environmental water flow and reduced groundwater salt concentrations, by improvements in foliage cover and vigour, could direct remediation efforts to these reaches of the river (Johns et al., 2009; Stokes, Ward & Colloff, 2010).

Surveys of riverbank river red gum dieback were historically labour intensive using a standardised survey to classify tree vigour on a scale based on canopy cover, epicormic growth, dead branches, height, and diameter at breast height (Cunningham et al., 2007; Souter, 2019). Newer, more time-efficient methods incorporate geospatial information systems and remotely sensed satellite imagery to quantify photosynthetic activity and leaf area on trees, as proxies for tree vigour, which allow the rapid mapping of riparian vegetation health over much larger areas at a higher temporal resolution to detect responses to water influx, pollution, or identify sites of illegal tree clearing (Goetz, 2006; Le Maire et al., 2012; Macfarlane et al., 2017; Miltiadou et al., 2018; Sims & Colloff, 2012). These techniques enable identification of areas where vegetation ecosystems are changing rapidly, allowing management to respond quickly to resolve issues before the effects become irreversible.

1.3.5 Spatial analysis of vegetation health using remotely sensed imagery

Remotely sensed datasets include satellite multispectral outputs, Airborne LiDAR (Light Detection And Ranging), aerial photography and multi/hyperspectral images (Jensen, 2014). Remotely sensed imagery is used to incorporate topography of landscapes (Cianfrani et al., 2010), quantify areas of certain landscape types or areas of water, map climate change related hydrology and drought/flooding/wetland regions (Garden, O'Donnell & Catterall, 2015), or map temporal patterns in deforestation/habitat fragmentation (Randin et al., 2020). The use of remotely sensed data can reduce the time-consuming and expensive fieldwork required to survey the vegetation, land use, and water sources over broad scales or in inaccessible regions (Gottschalk, Huettmann & Ehlers, 2005), but can also provide measures of land surface temperature (Ibrahim & Abu-Mallouh, 2018) or monthly rainfall (Naumann et al., 2012). LiDAR imagery allows 3-dimensional representation of structural characteristics of the surface, which can include fine scale details of tree canopy fullness, bare branches of dead trees and understory vegetation presence. This element of remote sensing combined with the often coarser scale multispectral images, provides a more comprehensive picture of ecosystem physical structure and physiological vigour for the researcher.

Some issues do arise with satellite remotely sensed data as the coarseness of the spatial resolution, such as that seen in Landsat's 30 m^2 pixels, greatly influences the accuracy of data derived because of mixed land uses (Crosetto, Ruiz & Crippa, 2001; Zheltukhin, Puzachenko & Sandlerskii, 2009). However, in combination with ground-truthing to validate land-use classification, the spatial resolution of Quickbird and/or GeoEye, below 3 m, or even Planetscope's 4 m pixels, permits the researcher to identify many finer details of landscape features (Congalton & Green, 2019) — for example distinguishing Mallee vegetation from eucalypt forest, semiarid scrub land, horticultural produce types, arable cropping, and agricultural grazing (Brambilla et al., 2009; Rozenstein & Karnieli, 2011).

Airborne hyperspectral data, which have more than 10 spectral wavelength band sensors onboard the platform, but often ≥ 30 (Jensen, 2014), can have resolution of 5-10 cm, and provide even more precise recognition of fine habitat features, and the ability to differentiate between plant species and soils without the need for field surveys (Meneguzzo, Liknes & Nelson, 2013). The use of airborne LiDAR data to create 3D images of the vegetation structure of landscapes, enables a detailed representation of habitat heterogeneity, and its influence on species diversity and occupancy at different levels/structural complexity (Almeida et al., 2019; Arroyo et al., 2010; Davies & Asner, 2014; Ediriweera et al., 2014; Miltiadou et al., 2018). Combining high-resolution multispectral vegetation indices as a proxy for habitat vegetation complexity with GIS topographical layers of abiotic variables, including slope and aspect and presence/absence data, can enhance prediction of suitable habitats or identify areas in which ground surveying would be most successful (Gibson et al., 2004; Randin et al., 2020; Syartinilia & Tsuyuki, 2008).

Using satellite multispectral data to monitor changes in vegetation biomass and photosynthetic activity allows large areas to be surveyed repeatedly over time with considerably less effort and expense than using an on ground team (Carlson & Ripley, 1997; Pettorelli et al., 2005; Sims & Colloff, 2012; Wang et al., 2016). The normalised difference vegetation index (NDVI), and other indices calculated from different combinations of remotely sensed spectral bands, can be used to quantify vegetation presence, photosynthetic activity, biomass (leaf area index), canopy density and groundcover by vegetation over soil (Carlson & Ripley, 1997; Doody et al., 2014; Fu & Burgher, 2015; Le Maire et al., 2012). NDVI values > 0.3 indicate vegetation which has healthy leaf structures and are 'green', with pixels of value 0.05 – 0.3 associated with exposed dry rock, soil or low photosynthetic/stressed (dry and damaged leaf structure) vegetation. NDVI below 0 are associated with water or water-logged surface pixels. Water-filled pixels are easily differentiated from bare soil and vegetation areas using indexes such as the soil adjusted vegetation index (SAVI) and the normalised difference water index (NDWI) (Huete, 1988; Namikawa, Körting & Castejon, 2016). Using satellites, such as RapidEye, with higher spatial resolutions and red edge wavelength bands, accurate tree species and location can be detected, especially when combined with airborne or terrestrial LiDAR-derived vegetation surface elevation point clouds to identify characteristic tree morphology (Almeida et al., 2019; Arroyo et al., 2010; Ediriweera et al., 2014; Gökkaya et al., 2015; Verma et al., 2016). In the study of riparian ecosystems, such as the South Australian Murray River, using remote sensing data in combination with ground-truthed field studies provides researchers with repeatable vegetation datasets along rivers influenced by varying water levels, flood inundation, affected by pollution or increasing groundwater salinity effects in times of drought (Fu & Burgher, 2015; Huylenbroeck et al., 2020; Macfarlane et al., 2017; Michez et al., 2017). Analysis of these datasets allows the response to influential factors over both time and space to be modelled, and predictions made on how different management regimes may alter riparian system outcomes (Doody et al., 2014; Doody et al., 2015; Fu & Burgher, 2015).

1.4 Area of study

The South Australian section of the Murray River extends westwards from the Victorian/New South Wales border to Morgan before turning south towards the Coorong on the south coast of South Australia. The river passes through what was historically Mallee country and expansive areas of river red gum and black box woodland and forests. Approximately 50% of the riparian native vegetation remains with minimal destruction in fragmented patches along the river length, and of this, 45% has been protected in conservation parks (Landscape South Australia, 2020). A part of the Murray-Darling Basin, an area of 1.061 million km^2 whose extent reaches to south Queensland, the far east of New South Wales and the Mornington Peninsula in Victoria, the Murray River mouth terminates the 77,000 km long network of connected rivers (Figure 4) (Murray-Darling Basin Authority, 2019). The historical river channel varies in width from 10 km wide in the Chowilla floodplain just north of Renmark, to under 1 km wide between the high river cliffs of the downstream areas below Morgan, but the river itself averages 200 m wide.

The eastern regent parrot nesting habitat extends along the Murray River from the Victorian border to Swan Reach in South Australia, 120 km to the north-east of Adelaide, a total length of 392.7 km (Figure 1). Nest trees are found up to 270 m away from the closest riverbank in South Australia, and they rarely nest in the backwater areas, away from the main Murray River channel.

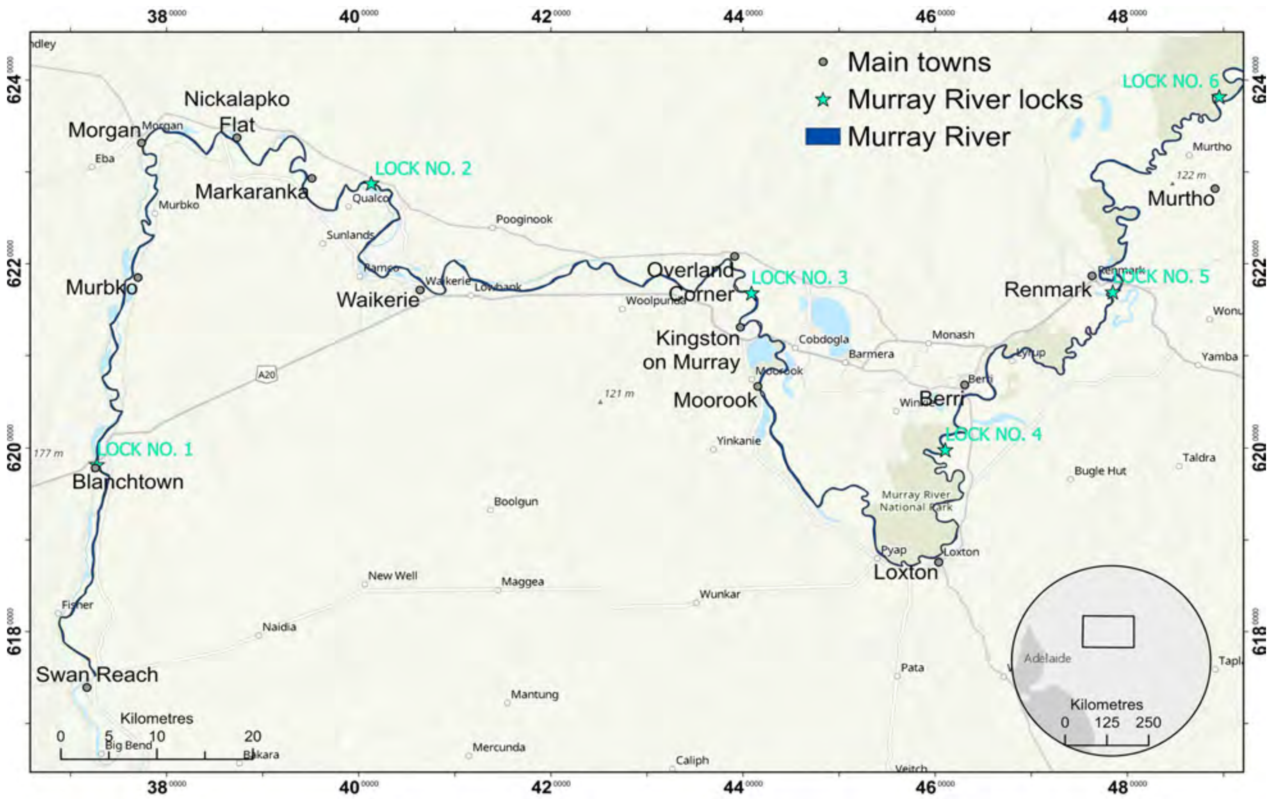


Figure 4: Study Area (Coordinate system GDA 1994 Zone 54)

1.4.1 Laws relevant to riparian habitat

Crown land designated under the *Crown Land Management Act 2009*, with its associated legal restrictions on development, includes the riverbank 50 m from the water line, but does extend farther in environmentally important wetlands or iconic conservation areas. There are few locations where private land extends to the river in South Australia, although those that own residential property beyond the Crown land boundary may have permission under the Act to build boat ramps and moorings. The *Native Vegetation Act 1991* and the *Development Act 1993* prevent uncontrolled tree and shrub clearing. River red gums of any size or health state are explicitly protected from clearing (Department of Water and Natural Resources, 2019).

1.4.2 Local land use and demographics

During the 19th and 20th Centuries, farmers cleared large tracts of both the riparian breeding habitats and the Mallee ranges used by parrots for foraging during the non-breeding season (Beardsell, 1985). Many farmers invested in expensive water pumping systems to carry irrigation water from the deeply incised river channel to the higher elevation agriculture areas (Cole et al., 2015). Of the remainder of the Murray River's banks, much has been repurposed to either urban development, privately owned ‘shacks’ and boat moorings, or preserved as conservation reserves or crown lands. Several large country towns including Renmark, Loxton, Barmera, Berri and Waikerie, have expanded along the riverbank, primarily using the river for tourism income and local recreation pursuits and further extending the area of cleared river red gums.

1.4.3 Local climate

Much of the central inland area of South Australia is classified as semi-arid with on average 100 mm more rainfall than the arid desert regions in the winter, and hot and dry summers. Average summer temperatures of 23 °C cause up to 90% moisture loss from the soil and vegetation via evapotranspiration, resulting in little ground surface water storage or percolation to refill groundwater aquifers (MDBA, 2008).

With recurring droughts, the Murray Darling Basin’s annual average rainfall is 454 mm, but this drops to only 260 mm in the Kingston on Murray smaller study area (Figure 5). The effect of increased water acquisition from the upper reaches by eastern state agriculturists and industrialists, has reduced Murray River flow levels to South Australia by more than 30%, from an average pre-Millennium Drought winter period inflow of 2000GL to 700GL by the end of the Millennium Drought in 2010 (MDBA, 2020)(Figure 6).

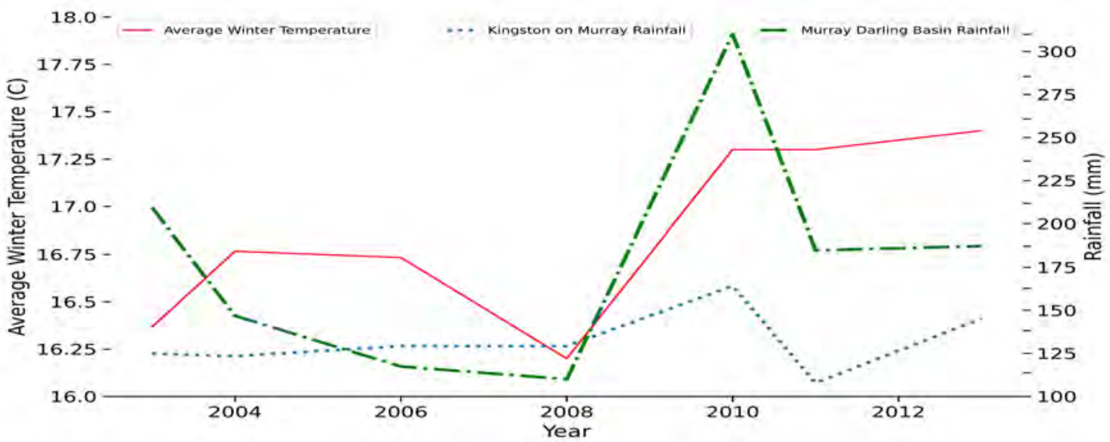


Figure 5: Annual seasonal maximum temperature at Loxton, in South Australia, and total autumn-winter (April to September) rainfall in Murray Darling Basin (high range of semi-arid climate average) and at Kingston on Murray, South Australia (very low semi-arid rainfall total) from 2003 to 2015.

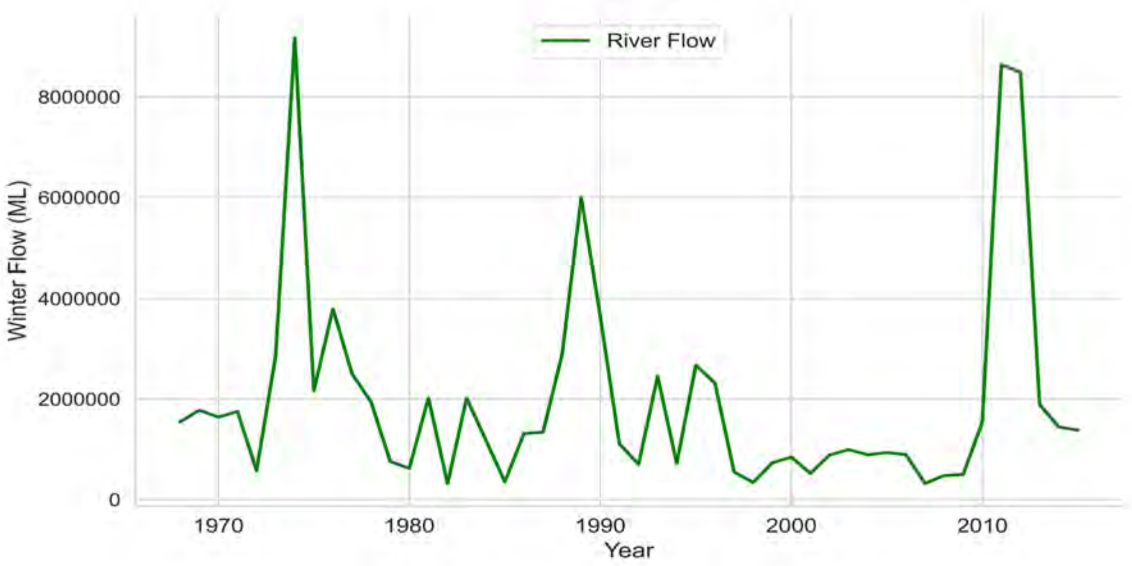


Figure 6: South Australian section of the Murray River monthly inflow volumes (ML) since 1968. (Millennium Drought 2001 – 2009). Peaks at 1975 and 1989 followed large floods in the Murray Darling Basin, increased water regulation started in 1995 with the Murray-Darling Cap. The large peak in 2010/2011 occurred after the Millennium Drought of 2001-2009 broke with increased rainfall across the basin.

1.4.4 Geology and hydrology

The South Australian section of the Murray River passes through a deep, incisive constrained channel after entering the state through the Chowilla floodplain (Colloff, 2014). The underlying limestone, exposed in the river cliffs through the upstream parts of the South Australian Murray, dates back 26 million years to the mid Tertiary period and is a combination of many strata of sedimentary bedrock laid down by repetitive sea incursions as land levels rose and fell. It is this geological history which controls the groundwater levels found in the area (Colloff, 2014).

Local Coonambidgal and Blanchetown Clays line the river channel floor. These overlie the Monoman sand layer. The saline aquifer lies within this layer, connecting directly with the Murray River channel through the banks and channel floor allowing freshwater to recharge the aquifer or saline water to discharge into the river (Doody et al., 2014; MDBA, 2020; Walker et al., 2004).

The reduction in surface water flow, secondary to climate change's decreased rainfall and increased evapotranspiration rates, coupled with the decrease in peak seasonal inflow volumes due to increased abstraction for irrigation requirements, has led to long term natural deterioration in the normally resilient ecosystems along this dryland river system (Colloff & Baldwin, 2010). When large quantities of perennial (long-lived) native vegetation are cleared for short-lived arable crops the important evapotranspiration part of the hydrological cycle is greatly reduced, and, when irrigation to the area is increased to support agriculture, the groundwater aquifer surfaces rise (Barrett-Lennard, 2003). This brings dissolved salt from the breakdown of Monoman sedimentary bedrocks to surface soils and standing water, leading to the deleterious effects of secondary salinization on the eucalypts through their deep tap root systems (Bickford, 2003; Cunningham et al., 2011).

2 Methods

2.1 Datasets

I compiled data from several sources (Table 1) to test the hypotheses on nest tree health selection and the identification of tree response to increasing water availability.

Table 1 : Data sets used

Dataset	Source	Year
Nest site locations	DEWNR & RPRG	2003- 2015
Bird Behaviour data	Expert Panel	2018
Tree species and Health along riverbank	SAMDB DEWNR	2002
Wetland polygons, including Murray River	DEWNR, SA Government	2008
RapidEye Surface Reflectance orthotiles	Planet.com	2003-2015
Landsat Surface reflectance imagery	EarthExplorer.USGS.gov	2003-2010
30cm Digital Elevation Model	DEW	2018
Murray River water gauge data and monthly Flow	Murray-Darling Basin Authority	2003-2015
Climate data: rainfall, temperature	Bureau of Meteorology (BOM)	2003-2015

2.1.1 Nest survey data

The nest-sites dataset collates data from multiple volunteer surveys. Survey frequency and extent varied from annual, full Murray River from the Victoria border to Swan Reach area, to partial reaches in 2014 and 2015 over areas of common parrot presence. The data are presence only, although the temporal nature of the full dataset allows the absence of birds from traditional nest colony sites to be recorded. Nest counts were done using binoculars walking/ boating along the banks of the river. Surveys up to 2011 covered the full length of the river on both banks, with all visible river red gums checked to a distance of approximately 500 m from the banks of the main river and any lagoons or more permanent streams at the time of recording. The surveys in 2012 and 2014 were only partial reaches centred round Markaranka east of Cadell, and 2015 was a partial survey in the Chowilla floodplain. In all surveys, the volunteers used GPS units to identify the tree location in which nests were found. At the start of the survey period in 2003, these units had a recognised horizontal error of up to 30 m in open ground, but would have additional error under tree canopies, leading to potentially large positional inaccuracies in the order of ≥ 60 m (Karaim, Elsheikh & Noureldin, 2018).

2.1.2 Expert opinion questionnaire

I held a meeting with the local regent parrot recovery team volunteers to solicit their knowledge on subtleties of eastern regent parrot behaviour in the state, to compare with that found in the literature for Victorian and New South Wales populations. I compiled the data from the Regent Parrot Recovery Team questionnaire into a spreadsheet in which the most common answer was considered to be 'expert opinion', as a source to add background credibility to any assumptions made about the eastern regent parrot population in the region (Questionnaire, with Responses Table (Appendix 6.10).

2.1.3 Riparian vegetation

The tree-health dataset from the Murray-Darling Basin Authority dates from 2002, prior to the end of the Millennium drought (2006). This layer contained more than 4000 polygons with attributes of the three dominant tree types; river red gum black box and river coobah, and their respective health status. Using an underlay of Google Earth imagery from 2016, the health of trees in many of the delineated areas has changed from that recorded at the time of collection. The dataset did not cover large tracts of the historical river channel, leaving gaps along the length of the river that might have indicated suitable river red gums for potential nest sites.

2.1.4 Local wetlands and rivers

The Murray River and wetland sites layer includes attributes describing the permanence or ephemeral nature of each polygon. This dataset was created between 1986 and 2006 using ground surveys and aerial photography; thus, many polygons of ephemeral water visible on recent satellite imagery are not identified accordingly or are omitted from the data.

2.1.5 Water levels and meteorology

Murray River water gauges measuring water levels, among other variables, can be used to assess nest selection relative to water quality and proximity. I downloaded the average monthly water level data at 3 points: Loveday Swamp, Lock 3 downstream and Overland Corner from the Murray Darling Basin Authority (MDBA) website (livedata.mdba.gov.au/list-view). I selected a 76 km length of river extending from Loxton to Overland corner, which included the wetland areas of Wachtel's Lagoon and Loveday swamp, for closer analysis of bank-fill levels and flooding events in response to Murray Darling Basin rainfall and the effect on total South Australian inflow from upstream water regulation measures. I downloaded the monthly average inflow volume to the Murray River from riverdata.mdba.gov.au/flow-south-australia-calculated.

Figure 7 shows variation in monthly water level for each gauge against the monthly rainfall, with Loveday Pump Station location upstream of Lock 3's weir having a higher average water level than those sites downstream of the lock.

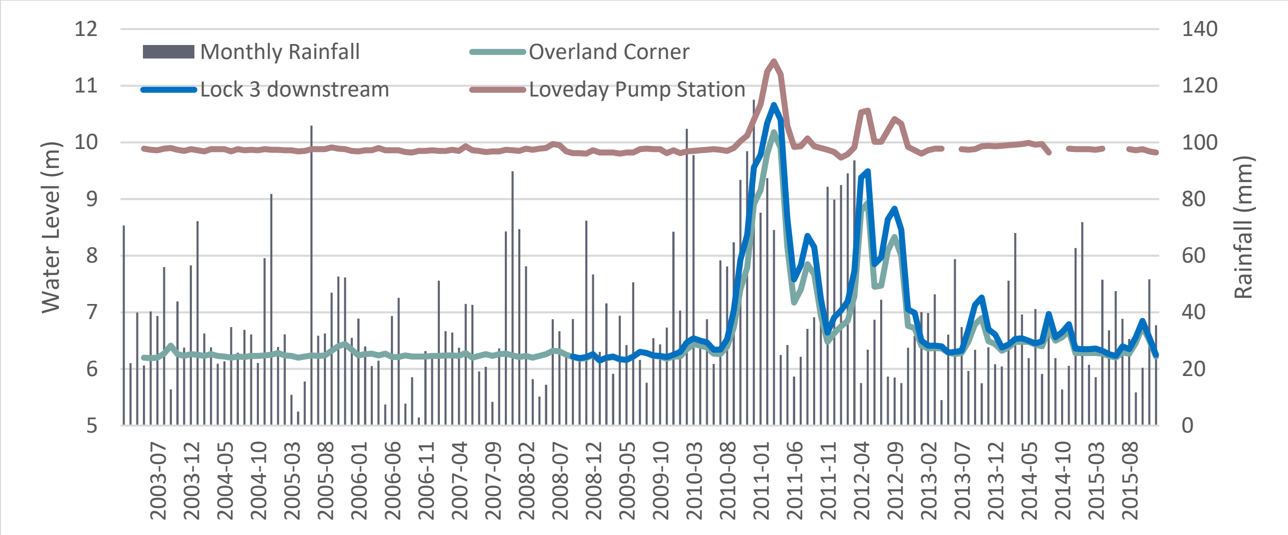


Figure 7: Monthly average river water levels (m) at 3 locations around Lock 3 and corresponding rainfall (mm) for time of reading. Peaks of Murray Darling Basin rainfall do not correspond with rises in South Australian river levels due to the water regulation of the weirs and locks upstream by the MDBA until the drought breaks in January 2010.

The Murray-Darling Basin Authority record of water inflow to South Australia's Murray River, measured downstream of Lock 7 and the Mullaroo Offtake (not including the Lindsay River allowance), is illustrated in Figure 8. Quantities above the red line are above flood inundation flow rates for the South Australian Murray River.

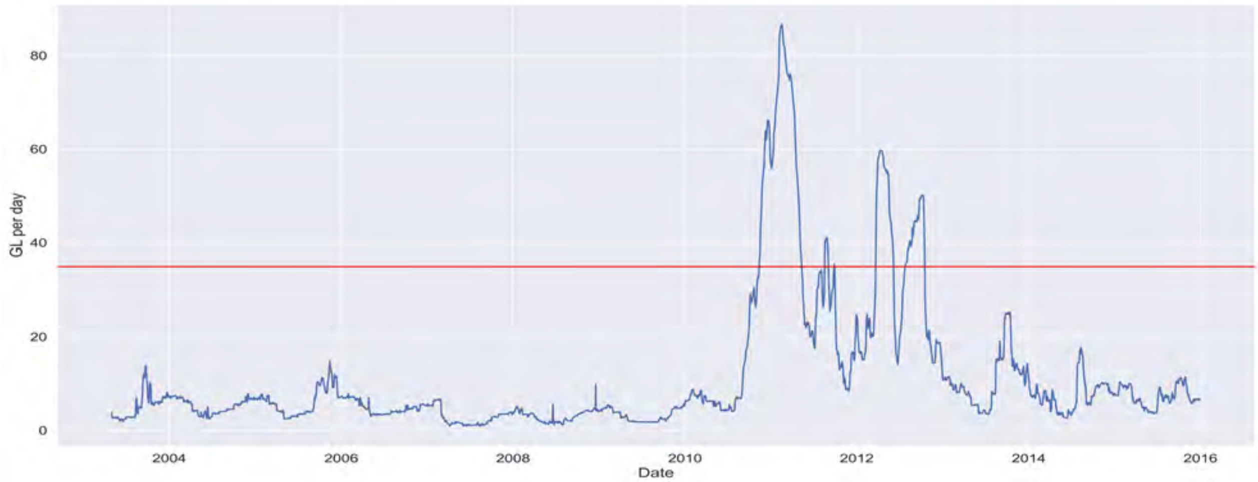


Figure 8: Daily water flow into South Australian section of the Murray River (GL) between May 2003 and January 2016, red line at 35GL/day inundation flow rate

No inundation lasted for longer than 183 days (10 November 2010 to 12 May 2011), although 76 days between the 22 March 2012 and the 5th of June were also above 35 GL/day. Seventy one days between 25 January and 5 April 2011 had flows above the 70 GL/day level to provide long term inundation effects of more stressed river red gum stands in the floodplains.

I collated the monthly average water level for the subsetted area's river water gauge (bom.gov.au/waterdata) from May 2003 to Dec 2015 into Excel spreadsheets that I joined with the feature class of the water gauge locations in ArcGIS Pro using the <Join Table> tool with the common field Location.

2.1.6 Satellite imagery to calculate riparian vegetation health

I downloaded Level 3A Satellite imagery from Rapid Eye (5 m spatial resolution, 5 band multispectral imagery incorporating Blue 440 - 510 nm, green 520 - 590 nm, red 630 - 685 nm, red edge 690 -730 nm, NIR 760 - 850 nm wavelengths). The orthorectified images (Grid cell 5423312 and 5423212), already have radiometric, geometric relief, and atmospheric corrections applied by Planet (Planet Team, 2020).

I downloaded Collection 1, Level 2 Landsat 5 Thematic Mapper (TM) sensor imagery (Row 84, path 96) from the USGS Earth Explorer website, earthexplorer.usgs.gov/ (Earth Resources Observation and Science (EROS) Centre), for the study years prior to launch of the RapidEye satellite. These 30 m spatial resolution surface reflectance images, with 7 multispectral bands, are georectified and radiometrically corrected by the US Geological Survey (USGS) analysts. The TM bands include band 1 (blue) 450 - 520 nm, band 2 (green) 520 - 600 nm, band 3 (red) 630 - 690 nm, band 4 (near infrared (NIR)) 760 - 900 nm.

2.1.7 Airborne LiDAR 30 cm resolution digital elevation model to model flood height extent

I imported 30 cm spatial resolution Airborne LiDAR based DEM, available from the Department of Environment and Water, and clipped the Kingston on Murray subsetted study area from the whole river dataset to reduce geoprocessing times.

2.2 Pre-processing

2.2.1 Nest tree area calculation

I imported all the data into ArcGIS Pro© version 2.5 (ESRI, 2020) and projected them into the GDA (Geocentric Datum of Australia)1994 UTM (Universal Transverse Mercator) Zone 54 coordinate system. I clipped both the vegetation and River and wetland data layers from their original state-wide size to that of the main study area. I combined the individual years of nest site data into one structured spreadsheet of 1139 sightings.

I overlaid the wetland layer with the tree polygons and using the <snap> tool I redrew the 2 layers to reduce overlap and gaps between the two different sets of polygons. A list of the attributes for the water source layer is in Appendix 7. The main Murray River channel was a single polygon entity, with an additional 1193 permanent and ephemeral anabranches, ox bow lakes, and wetland lakes individual polygons. I created polygons identified as ephemeral water in the feature class's voids if they overlay ephemeral water areas on the satellite imagery, to ensure completeness of the layer.

Using the <create feature> geoprocessing tool, I digitised large areas of riverbank land left unidentified by the Department of Environment and Water's vegetation classification, to ensure that any spatial analysis was unbiased by null spaces in the data surface, and confirmed that polygons coincided with the true underlying health of trees in that area. This was a subjective process and, without ground-truthing the data at the time of nest site collection, there will be a component of uncertainty and error introduced into any modelling using this feature class. I included polygons for other vegetation or land use in this feature class, including urban regions, river cliffs (which had no vegetation), horticulture, agriculture and areas that were now dried riverbed regions, but that previously were river features. These dry areas of no trees were invariably surrounded by narrow stands of unhealthy or dead river red gums that had grown there at the time of the permanent water. The final tree health feature class contained 5196 features.

I added two fields to the attribute table to help the geospatial information system software to identify which polygon areas contained river red gum trees, and of which health state. I included the predominant health status of the river red gum in that polygon column, with which I could produce data to test the hypothesis that the eastern regent parrot would select a tree of the healthiest state in that area. I created four status types: *healthy*, *unhealthy*, *drowned* or *dead*. *Healthy* trees were those with at least 90% full leaf crown canopy at the time of surveying, with or without active flowering, or evidence of crown tip growth. *Unhealthy* trees had poor foliage mass, < 90% crown cover, or showed browning of leaves and bare limbs, or had multiple broken off limbs, or split trunks and signs of decay. D*rowned* trees were dead, defoliated trees standing in permanent water, *dead* were those defoliated trees, with no epicormic growth shoots, which were in dry areas (Souter, 2019). I also included a column which simply stated if river red gums were present in the polygon or not. This allowed the software to rapidly select for polygons which contained relevant tree species.

I calculated the Euclidean distance of each nest to the closest water source polygon using the <near> geoprocessing tool, creating another field in the 'nest_tree_intersect' table.

I used the geoprocessing tool <buffer> to clip an area 270 m perpendicular distant from the water source polygon outline for the whole study area, this value derived from the farthest distance inland the observers identified a nest tree. The <intersect> tool combined the clipped out buffered tree status polygons with the nest site data to produce a new polygon feature class with nests and the associated area of the underlying buffered polygon, a total of 1139 rows of data. I calculated the total area for each tree status polygon type and the total available area of the different main classes within the buffered area using ArcGIS Pro (Figure 16). I counted how many nests were found in each tree state, as the 'Observed' data for my later analysis.

I then exported the attribute table to Excel™ and used Spyder© (Raybaut & Contributors, 2020) for analysis using Python™ software modules: NumPy, Pandas, Seaborn, Scipy, xlsxwriter and Matplotlib (McKinney, 2010; Oliphant, 2006; Salvatier, Wiecki & Fonnesbeck, 2016; Van Rossum & Drake, 2019).

Using the <minimum bounding geometry> tool, I estimated the area in the buffered zone which was taken up by nest trees of the different states using a convex hull and sorting by main health status and site-name to ensure groups were created to have the tightest enclosure of each tree. I allocated single trees a maximum boundary polygon of 4 m^2, the largest river red gum on record being 29 m diameter (McIntosh, 2020), and those trees that held more than one nest at a time, or that were returned to in different years were only counted once using this methodology. This method also introduced inaccuracies in area estimation, but the increases in the boundary polygon area are somewhat balanced by the likely under-estimated canopy area maximum of $4m^2$ per individual tree.

I calculated the area of nest tree canopies as a part of the whole river red gum area available, and the whole riverbank zone along the river (Figure 11). I used these data to calculate the proportions of nest trees in each health state compared to the total area of river red gum available along the bank.

2.2.2 Tree health analysis

2.2.2.1 Identifying suitable sub-set study area

The breeding range area would require more than 20 RapidEye satellite images to cover the full extent, leading to analysis complications of multiple, mosaiced images with different collection orbits or constellation satellites, and, hence, different geometric or relief corrections and spectral anomalies leading to decreased validity when comparing images (Martínez-Beltrán et al., 2009; Pettorelli et al., 2005). I therefore selected a smaller area containing many nest trees of varying states for a more detailed analysis. I used 'linear referencing' of the Murray River polygon to identify the location of nests along the length of the river by year (Figure 9). I first used the <eliminate polygon part> tool to remove the small islands within the main river channel, then <polygon to centreline> to create the centre line, with 0 m distance set at Swan Reach. Using the <create routes> tool, I combined the multisegmented centreline into a single line, which I inputted into the <locate features along routes> tool to site the nests along the line by Euclidean distance to the closest point of the centreline.

Figure 9: Distance of survey nest sites along Murray River upstream from Swan Reach, using linear referencing process in ArcGIS Pro. Red box: Kingston on Murray sub-set study area nests

The region between 170 km and 210 km upstream from Swan Reach located around Kingston On Murray had the most consistent nest presence over time to use as a sub-setted study area in which to analyse vegetation health indices and effect of increased water availability. This site also had regions of different water regimes; flooded wetlands, dry historical floodplains, healthy riparian zones by the riverbank and areas of incised river channel downstream with little mature riparian vegetation present. It is surrounded by relatively undisturbed natural riparian vegetation, irrigated horticulture areas, a Ramsar wetland site and tourism locations.

2.2.2.2 Vegetation index

The normalised difference vegetation index (NDVI) is used primarily to differentiate healthy vegetation from unhealthy vegetation, but can be used to identify water and bare-soil pixels in a multispectral image of visible light and near infrared wavelengths bands

$$\mathrm{NDVI} = \frac{\mathrm{NIR - Red}}{\mathrm{NIR + Red}} \qquad (1)$$

Vigorous vegetation with high photosynthetically active foliage biomass will produce a higher NDVI (> 0.3), red pixels in Figure 10b. This includes healthy hydrated eucalypts, fresh verdant spring grass and shrub growth, but also algae in exposed riverbed areas. Low-biomass summer grass or drought-tolerant saltbush for example would have NDVI from 0.2-0.3 (yellow areas in Figure 10b). Bare soil and rock tend to be 0.0 – 0.2, while water-logged soil or water bodies usually give negative values (blue in Figure 10b) unless they contain a lot of turbid material or water plants (Carlson & Ripley, 1997; Pettorelli et al., 2005; Wang et al., 2016).

Riparian vegetation health and vegetation density (leaf area) have also been measured using other indices, including the Structure Insensitive Pigment Index (SIPI) (Penuelas, Baret & Filella, 1995) which is calculated as

$$SIPI = \frac{(NIR - Blue)}{(NIR - Red)} \tag{2}$$

The SIPI calculates the ratio of carotenoids in the leaf material to chlorophyll, higher values indicating stressed vegetation, as the NIR reflectance values will decrease more relative to the red wavelength reflectance when leaves start to die. Large differences in plant vigour between the 2 indices are apparent with regions of minimally stressed vegetation in the SIPI not corresponding to the NDVI vegetation healthy vigour sites (Figure 10).

(a) (b) (c)

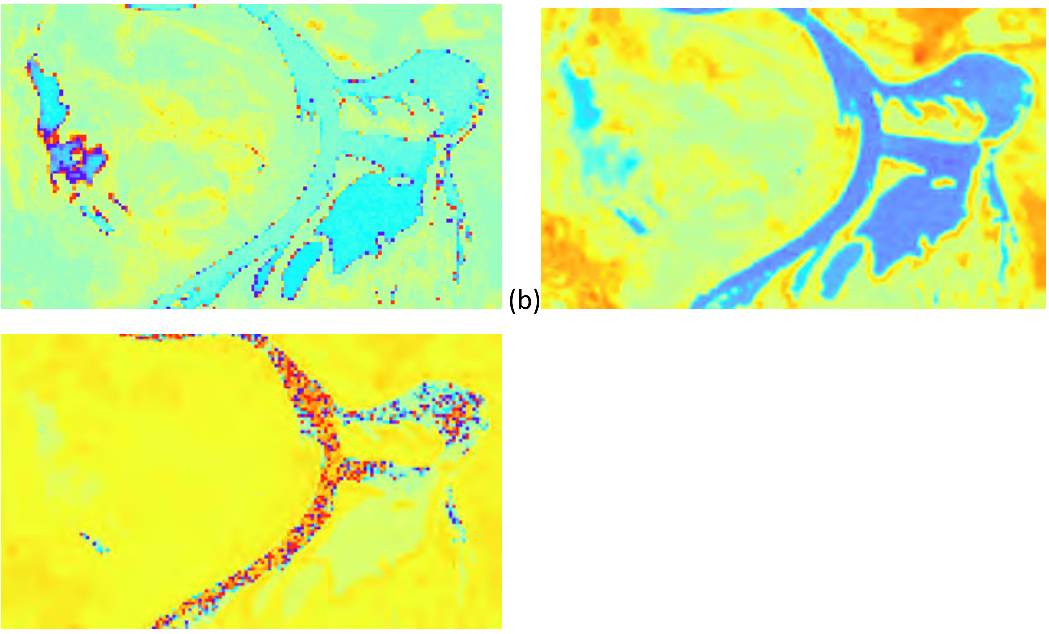


*Figure 10: Comparison of (a) SIPI (red is **least stressed** vegetation), (b) NDVI (red is **most vigorous** vegetation), (c) EVI (Yellow poorly photosynthetic / low biomass vegetation, orange higher photosynthetic potential / vigorous vegetation)*

Another option is the Enhanced Vegetation Index (EVI) (Huete, Huiqing & Van Leeuwen, 1997), created for use with the MODIS satellite. This corrects NDVI where the canopy cover is dense, using coefficients to adjust for atmospheric aerosol scattering (C1 and C2) and soil/canopy background values (L), the ArcGIS Pro constants are based on MODIS data values, but can be adjusted in the raster calculator if very different values are used for the already atmospherically corrected Landsat data used here. Healthy vegetation will be positive values, water and bare rock will be negative.

$$EVI = 2.5 * ((NIR - Red) / ((NIR) + (C1 * Red) - (C2 * Blue) + L)) \quad (3)$$

The EVI image, (Figure 10c), shows a very different image of the same area, with vigorous vegetation having little index difference from areas of lower vigour shrub and non-vegetated areas, and a lot of 'noise' in the permanent water zones, making this index less useful for my research.

The Soil Adjusted Vegetation Index (SAVI) (Huete, 1988) is commonly used in semiarid zones where vegetation cover is thin on the ground, but not typically riparian zones, as it reduces the effects of underlying exposed soil and/or water by including a calculated constant, *L* of the soil exposure factor, to the NDVI equation.

$$SAVI = \left[\frac{NIR - Red}{NIR + Red + L}\right] \times (1 + L) \quad (4)$$

Other vegetation indices which prove useful in similar ecosystems, including the Land Surface Water Index (LSWI) and the Normalised Difference Moisture Index (NDWI), require Shortwave InfraRed bands (SWIR) bands unavailable in the RapidEye constellation (Mancino et al., 2020).

With the availability of free historical imagery from both Landsat 5 and RapidEye and comparing the quality of the calculated vegetation health index output, I selected the NDVI as the most appropriate vegetation index for the purpose of my study.

Using RapidEye's band 3 (red) and band 5 (NIR) from the years between 2009 and 2015, I created NDVI rasters using ArcGIS Pro's NDVI raster function and the scientific output to create a scaled output from -1 to 1. No suitable cloud-free imagery was available for early spring in 2010 from the RapidEye satellite. For the years 2003 to 2010, excluding 2009, I used bands 3 and 4 in the Landsat 5 TM imagery and resampled the NDVI rasters into 5 m pixel size to enable comparison with the RapidEye NDVI outputs.

2.2.2.3 Flood contour polygons

In ArcGIS Pro I enabled the <range> property in the sub-setted digital elevation model, which allows the elevation to be set at any height within the DEM range for visualisation in the map window, enabling visualisation of the lateral extent of water flood over the riverbanks as inflows rose. I also created 30 cm contours to create flood height extents. Using river gauge levels from Overland corner, Loveday pump station and Lock 3 downstream, I compared river height with flood polygons to assess river red gum water access over time and their associated vigour.

2.2.2.4 Evaluation of NDVI outputs

Using <create transects along line> and then <create feature points along lines>, I generated 300 m transects at 15 random sites perpendicular to the Murray River bank to collect annual NDVI values of the riparian zone. Each transect had sampling points at 0, 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100, 120, 150, 180, 220, 260 and 300 m from the origin. The tool <extract multi-values to points> drew the underlying raster cell NDVI values for each year to a table for export to Excel.

2.3 Analysis

2.3.1 Nest hollow tree selection

Using the feature class created by the buffered zone and nest survey intersection, I calculated the expected number of nests of each tree state from the areas of each tree state available and the proportion of the area taken up by trees observed for nesting over the whole study period, (Figure 11).

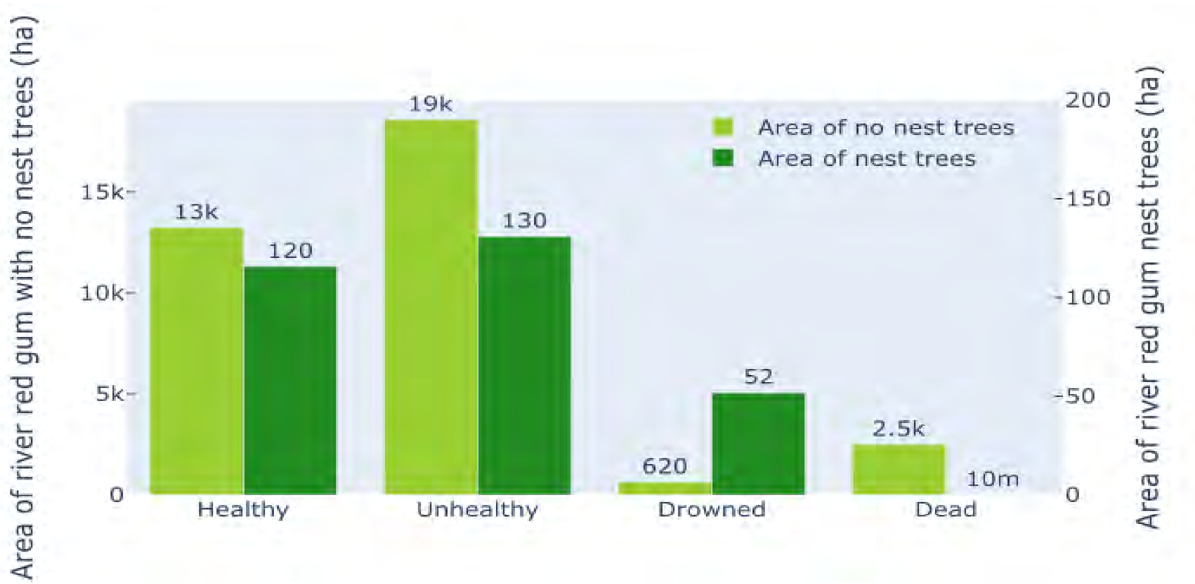


Figure 11: Area of riparian zone river red gums with nest trees and without nest trees (a subset of the whole buffered riparian zone in the study area).

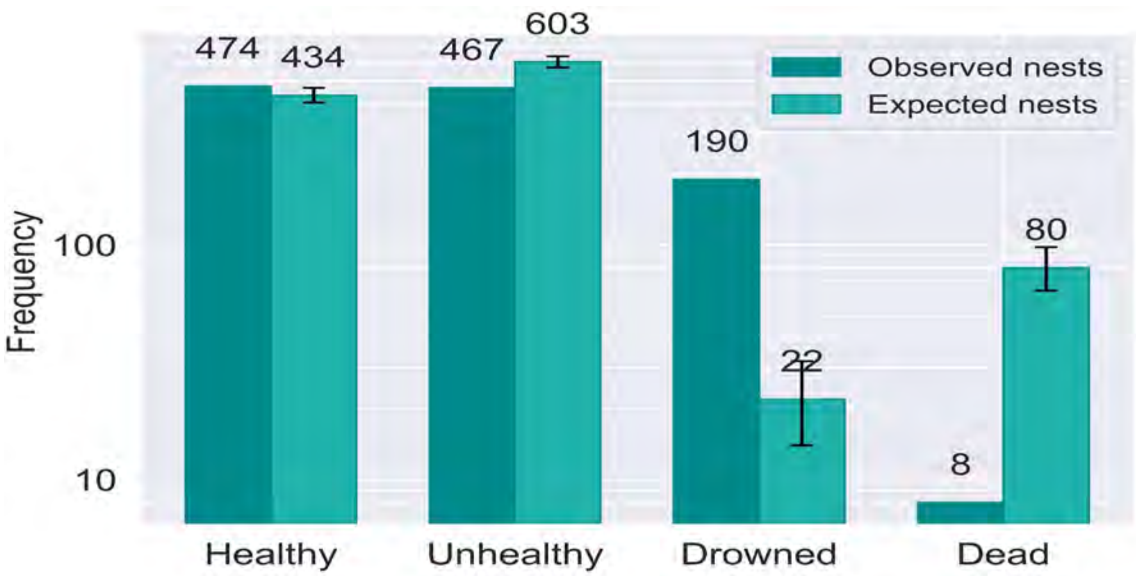


Figure 12: Count of observed nests, and the expected number of nests based on available area of each tree health state

Using the observed nests and the expected nests counts, (Figure 12), in a contingency table, I did a χ^2 test of independence (Equation 5), to test my first hypothesis that eastern regent parrots select healthy trees for their nest site.

$$\chi^2 = \sum \frac{(O-E)^2}{E} \tag{5}$$

where O are the observed results, and E the expected results. No difference in the observed and expected frequencies will produce $\chi^2 = 0$. Degrees of freedom = (number of columns – 1) * (number of rows -1) = 3.

I wrote a script in Spyder, a Python IDE, to run the χ^2 test on the contingency table of calculated expected nest numbers of each type and those observed. The script created 10,000 random iterations of the expected nest count from a multinomial distribution, based on the proportions of area available for each tree type. I used this output to calculate confidence limits for the expected nest count for comparison to the observed counts. See Appendix 6.8 for the python script used.

2.3.2 Tree health

I correlated the NDVI and water levels for each year with the distance from the riverbank to visualise the effect lateral bank recharge, and duration of inundation had on the tree health at the selected sites (Appendix 6.7).

I randomly selected a subset of 15 nests from the 312 found in the smaller study area to investigate the presence of nest loyalty relative to temporal changes in tree canopy health. I charted the values of the NDVI against year calculated for the same location, and the year in which the nests were found identified in each chart (**Error! Reference source not found.**).

3 Results

3.1 Hypothesis 1: Nest tree selection

3.1.1 Nest survey and tree health

3.1.1.1 Temporal changes in nest tree health

Nest survey data for 2003, 2004, 2006, 2008, 2010, 2011 and 2013 cover the full river to Swan Reach, including backwaters in Loch Luna and Murray River National Park north of Loxton. There is insufficient data available on the full river to identify if the swing to healthier trees visible in 2013, 2014 and 2105, after the drought broke and some vegetation recovery occurred, is significant, since the last 2 years of data were partial reach surveys only, and in the downstream areas surveyed, very few drowned trees are available.

There does appear to be a decline in the total number of nests over time across the length of the river (Figure 13), even when excluding the partial survey years. More data from the last 5 years of full river surveys would be necessary to identify any statistically significant population boom as a sequela to the effects of the breaking of the drought on the population.

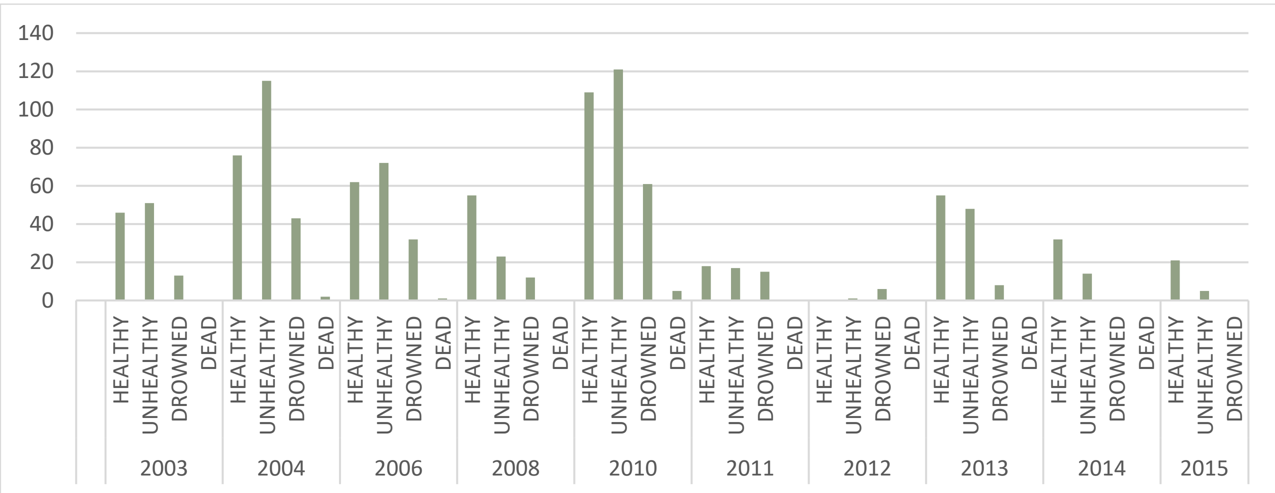


Figure 13: Number of nests counted per year of survey effort, divided into nest tree types in which they were observed (years 2012,2014 and 2015 were only partial reach surveys of the river and may be discounted from the overall trend).

Using the DEW supplied spatial tree health polygon data and the nest observation data, there is little demonstrable change in the proportion of healthier nest trees used by the birds over the whole river length, despite the break of the drought in 2010 (Figure 14).

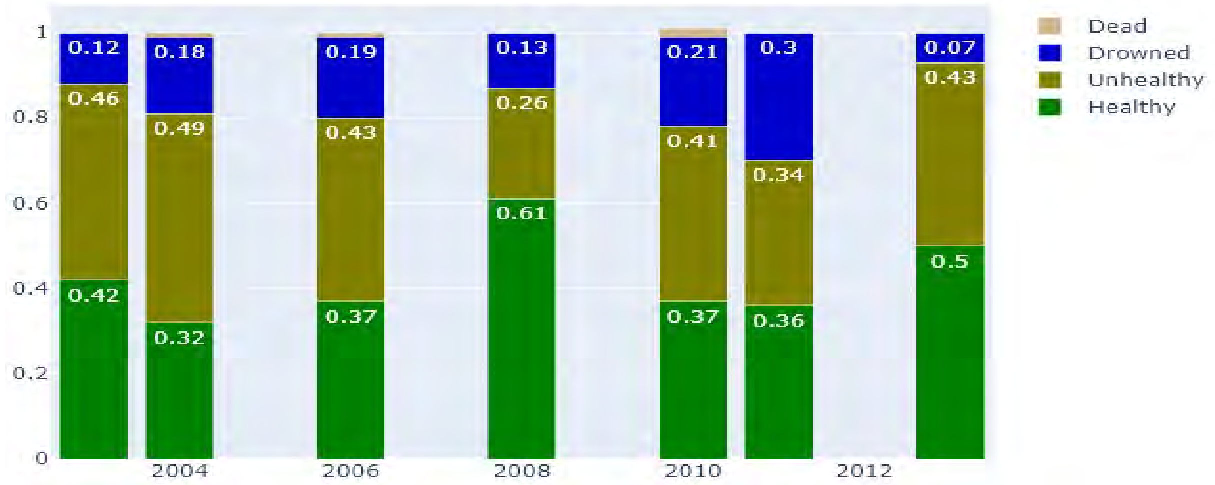


Figure 14: Proportion of nests found in each tree health state selected by eastern regent parrots in study years using spatial polygon dataset from DEW

This seems to differ from the later NDVI analysis (Figure 23), however these results are for the full river nest surveys not just the subset area around Kingston on Murray, which had a high proportion of drowned tree nests.

3.1.1.2 Spatial variation in nest tree health

As the Murray River flows downstream from the Victorian border the proportions of nests found in drowned and less healthy trees visibly decreases, from predominantly drowned tree nests in the Chowilla Floodplain to a high proportion of healthy nest trees at Nickalapko Flat and Morgan (Figure 15).

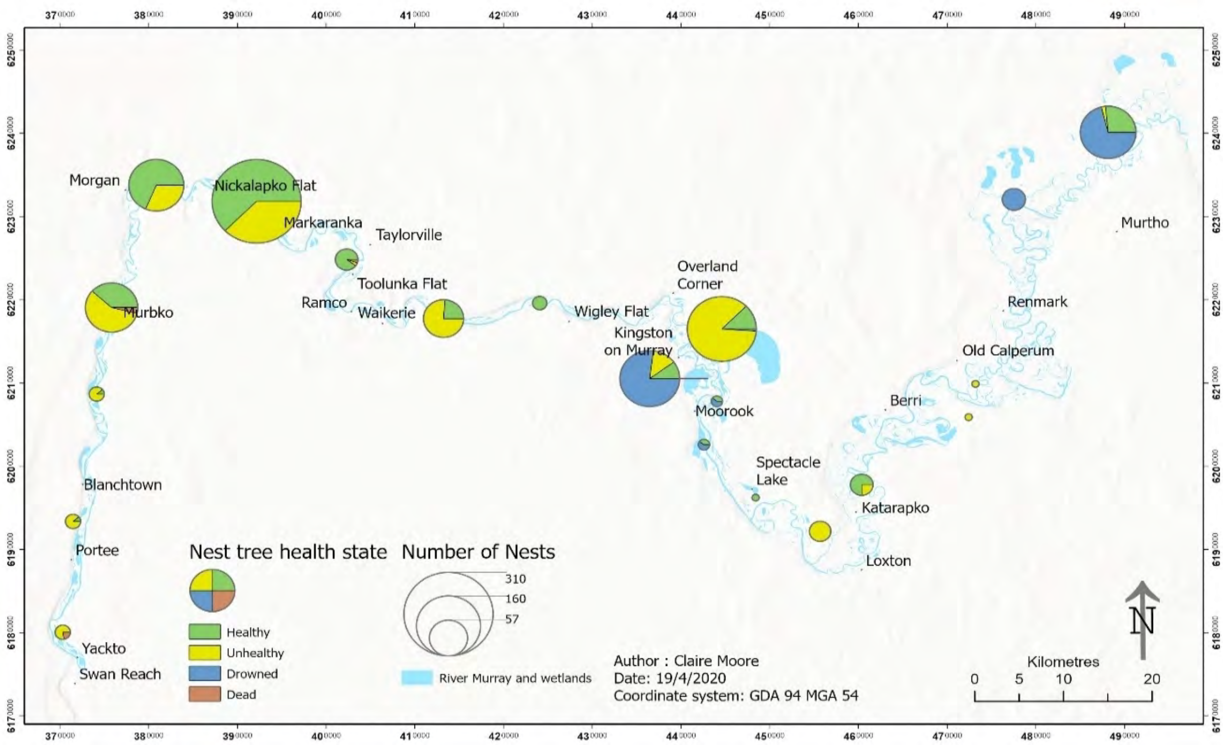


Figure 15: Spatial variation in the distribution of nests and tree health selection between 2003 and 2015, along the South Australian Murray River

3.1.2 Area of river red gum available for nesting

Of the total area within 270 m of the study area's riverbank, only 14% contains river red gums (Figure 16).

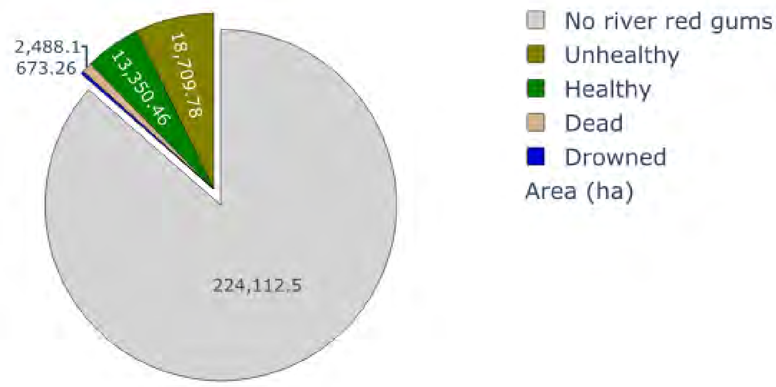


Figure 16: Area (hectares) of river red gum of each health state, and no river red gums within the 270 m buffer zone of the permanent river bank in the study area. (Areas of river red gum presence are expanded further in Figure 18)

The rest of the area is now dominated by anthropogenic influences, including urban development, agriculture and horticulture, regions of *Eucalyptus largiflorens* or dry, treeless areas of the river channel and cliffs, exemplifying the riparian landscape's degradation from its natural *Eucalyptus* woodlands and Mallee scrub (Figure 17).

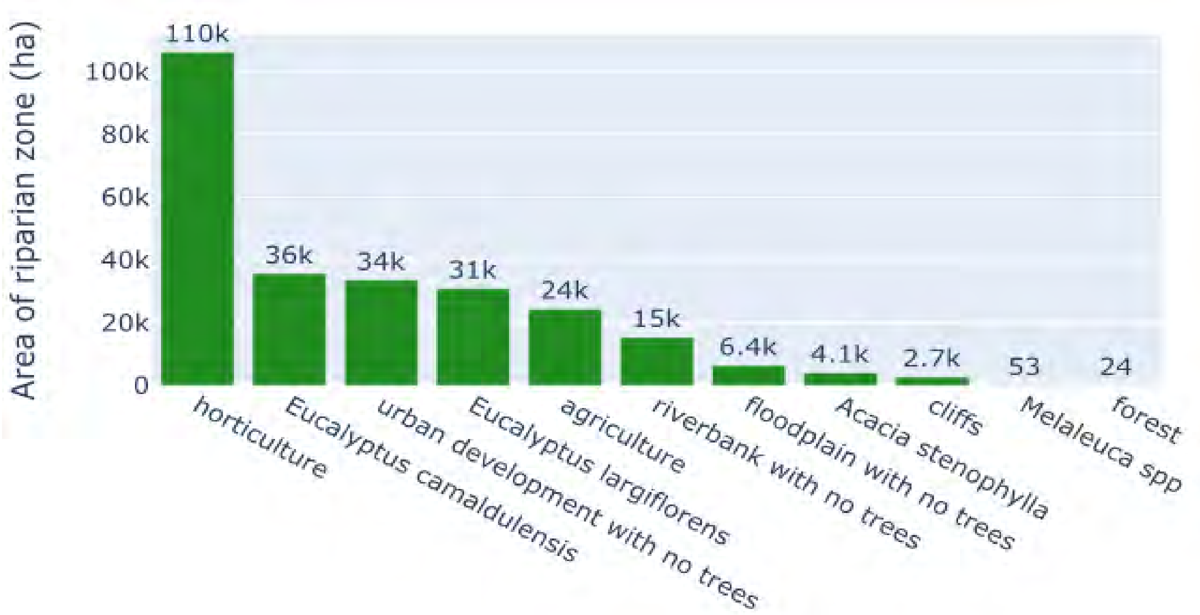


Figure 17: Areas (ha) of different land covers in the riparian zone of the Murray River study area

The total area of river red gums used by nesting eastern regent parrots is less than 298 ha, 1% of the total available river red gum riparian habitat. Of this, 38% of the total area taken up by nests is covered by healthy trees, compared to 44% of the nest tree area being unhealthy trees and 17% Drowned trees (Figure 18).

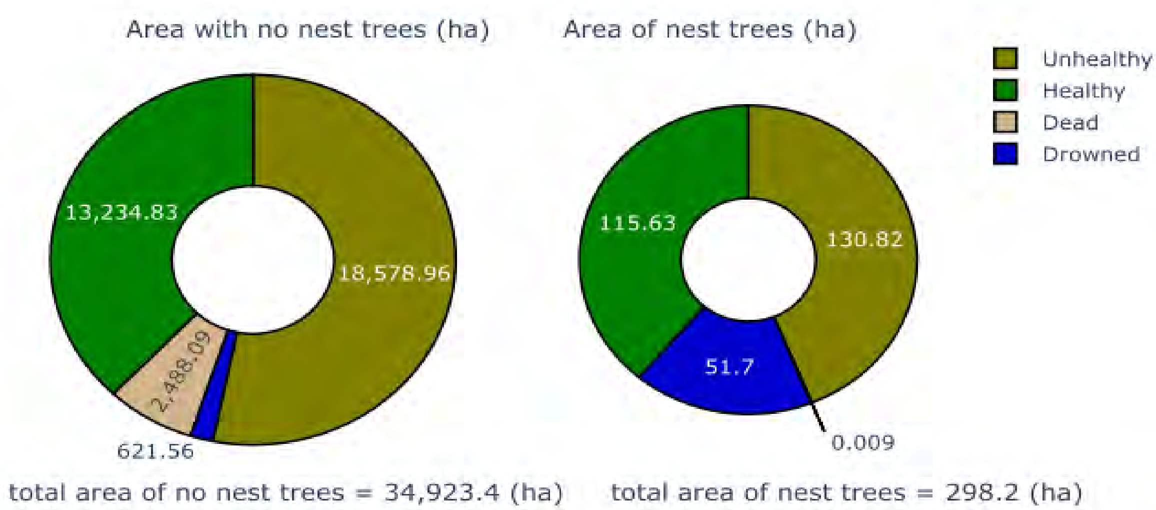


Figure 18: Areas (ha) of tree health type of unused river red gums (left) and those used as nest trees (right).

Of the areas along the riverbank containing river red gum, unhealthy tree zones dominate, but only 0.7% of that area is used by nest trees, a smaller proportion than that of the available healthy and drowned trees used by the regent parrots, implying a selection bias which is investigated in 3.1.3.

3.1.3 Test of Independence of nest tree selection

The χ^2 test demonstrates deviation between expected use and available habitat by tree category ($p < 0.001$).

Observed nest counts for healthy tree choice are higher than expected (outside 97.5% confidence limits). The χ^2 result also implies that more nests are found in drowned trees than expected from the area available. In contrast, observed nests in unhealthy and dead trees are lower than expected for the total area of each state available.

3.2 Hypothesis 2: Tree health in response to changing water availability

3.2.1 Tree vigour relative to Murray River water levels

Annual NDVI along representative transects extending 300 m inland perpendicular to the river and standing water sites (example in Figure 19, and Appendix 6.7), demonstrate the importance of increased river flow volumes to tree health and preservation of the riparian ecosystem for up to 300 m from the bank edge. Drought years (2003, 2005, 2006, 2007 and 2008) had similar NDVIs to 2004 which acts as the mid-drought NDVI baseline. The 2004 results show low positive transect NDVI values with no peaks and troughs of healthier or dead vegetation, indicating widespread vegetation of low photosynthetic activity and biomass associated with poor health of all species of flora present during drought. Beginning in 2010, all transects showed increased NDVI values associated with the increased photosynthetic activity of green, healthy vegetation (Appendix 6.7), This positive effect extends perpendicularly from the riverbank beyond 200 m in sites where inundation of lower elevation banks has occurred. The duration of the improved vegetation vigour is apparent in the NDVI values for the following 2-3 years, with the vegetation remaining healthier than 2004 drought values until beyond the end of the study period. 2013’s anomalous results are due to the presence of saturated soil or surface water just prior to the date of the satellite image.

Using transect 13 in the Loveday Swamp complex (Figure 19) as an example, the lateral bank recharge and inundation effects on local vegetation health can be visualised. At 20 m from the transect start, river red gums are present, with an eastern regent parrot nest sighting in 2010 when the NDVI was < 0.3. The trough at 220 m is the site of an ephemeral backwater creek, hence the negative NDVI after the slight positive lift between 150 and 180 m of bankside trees. The positive effect of increased water access in 2010, caused the main riverbank river red gum vegetation to maintain higher plant vigour than that of 2004 for 80 m inland, before the NDVI values become almost equal again in a dry non-vegetated zone.

a. b.

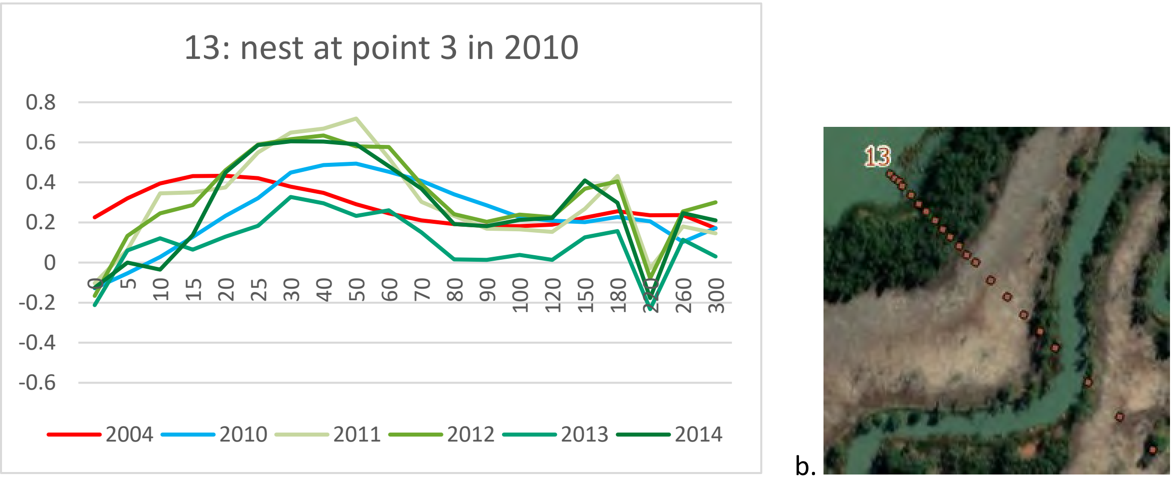


Figure 19: a. Comparison of study years' spring NDVI values (y axis) along 300 m perpendicular transect (x axis) from riverbank, with ephemeral creek at 200 m mark, b. location of transect.

Average NDVI of the transects during the years of the drought ranged from 0.19 to 0.25, demonstrating the tolerance of the local vegetation ecosystem to periods of poor surface water availability. This system's ability to bounce back to vigorous growth and the seed production and germination cycles in response to increased water presence is demonstrated by the high average NDVIs for the transects (0.32) from 2011, 2012 and 2014.

3.2.2 Nest tree proximity to permanent water sources

60% of river red gums used for nesting are within 40 m of the riverbank (Figure 20).

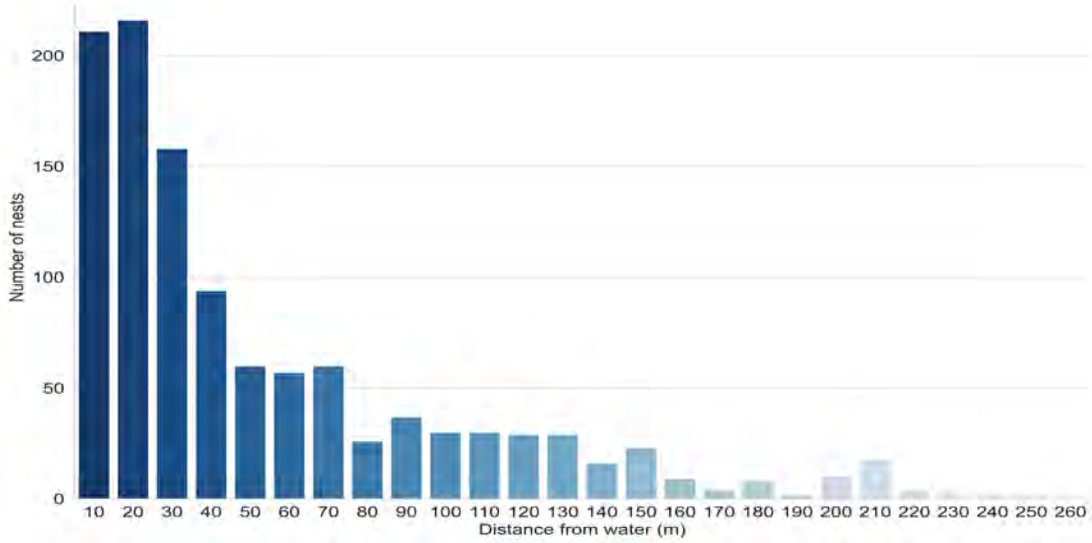
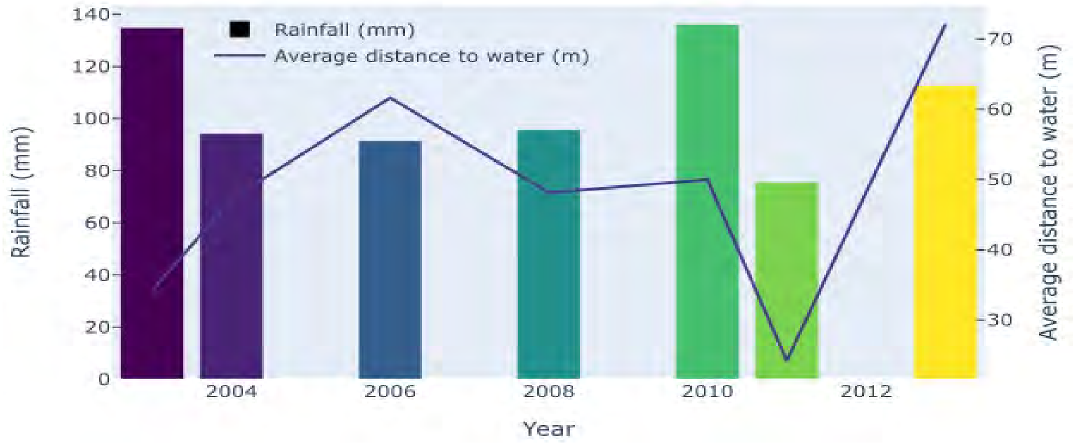


Figure 20: Number of nests found within 10m intervals from nearest permanent water source

Those trees at the greatest distance of 270 m from the river channel are located deep in the curve of Banrock Bend. This feature exhibits repetitive episodes of river channel remodelling which have changed the local topography, creating ox bow lakes and their accompanying banks of river red gum on the inner curve of the bend. These trees retain their health and continue to grow due to the cyclical flooding of the adjacent ox bow lakes as the river fills above 7.6 m height (Appendix 6.6). This stand of river red gums has one of the highest rates of colony loyalty along the river (Appendix 6.3).

Drought (≥ 3 months in which rainfall is < the lowest 10% of records) (Bureau of Meteorology, n.d.) causes river levels to drop, increasing the mean distance of trees to the nearest water source (2004, 2005 and 2006; Figure 21a). The Euclidean distance values calculated are based on the original river polygon outline, which was not altered to allow for drier, lower river level years and thus may have introduced errors. The anomalous value in 2011 is due to the large inflow from the Murray Darling Basin that year as a result of high rainfalls in December 2010 in Queensland and NSW regions (Figure 21b), which caused localised flooding in many areas of the Kingston on Murray river nest sites (Appendix 6.6).



(a)

(b)

Figure 21: Mean nest tree distance to permanent water (m) compared to (a) Murray Darling Basin autumn/winter rainfall total (mm), (b) Winter inflow to SA Murray River (GL)

The proximity of nest trees to water does not appear to correlate closely with either higher rainfall or lower river levels, i.e. birds do not select trees based on the closeness of permanent water. This may imply that the presence and quality of the nest hollow is the main driver and the ability to access water is a secondary factor. Further study is required to confirm these findings, as water proximity is commonly assumed to be one of the strongest nest site attributes for eastern regent parrots in the eastern states (Burbidge, 1985).

3.2.3 Nest tree vigour using NDVI to quantify tree photosynthetic activity and leaf structure vitality / mass

NDVI values for the pixels in which nests were found for each year of the study (Figure 22) indicate that tree health used varied within each year, and between years.

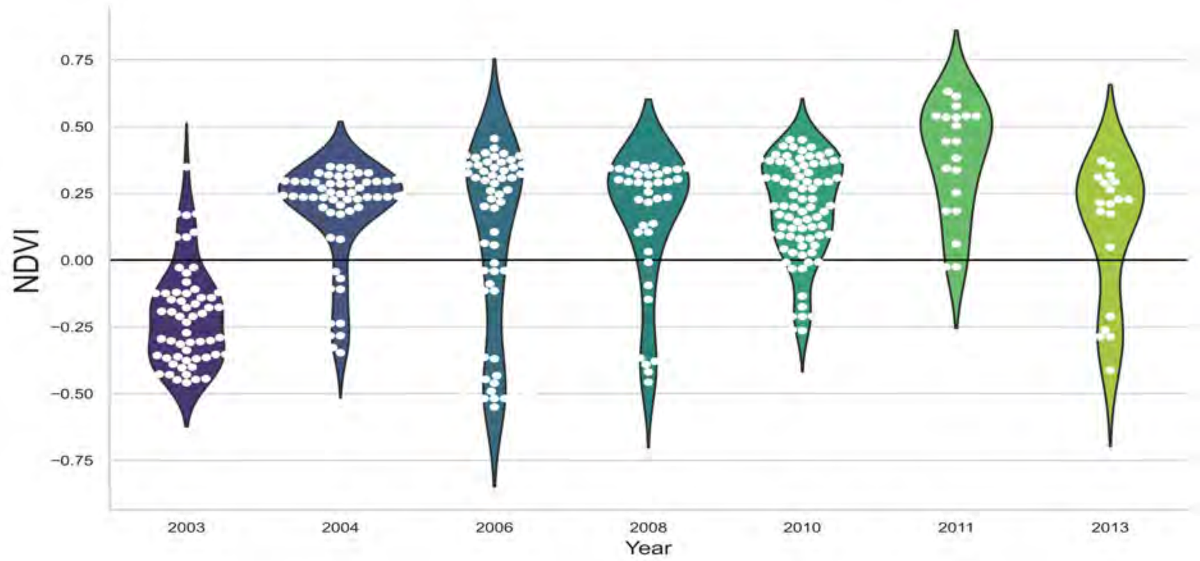


Figure 22: Violin plot of nest tree NDVI in Kingston on Murray study area by survey year showing gradual increase in number of nests found in higher NDVI (Healthier) tree sites

NDVI of trees used in the earlier years are lower on average with an upwards trend towards 2011, ($R^2 = 0.72$) (Figure 23). Nest trees in 2013 have lower overall average NDVI that decreases the R^2 to 0.41 when they are included, suggesting soil saturation after a period of prolonged inundation below the tree canopies, since NDVI values of the same trees rebounded in 2014.

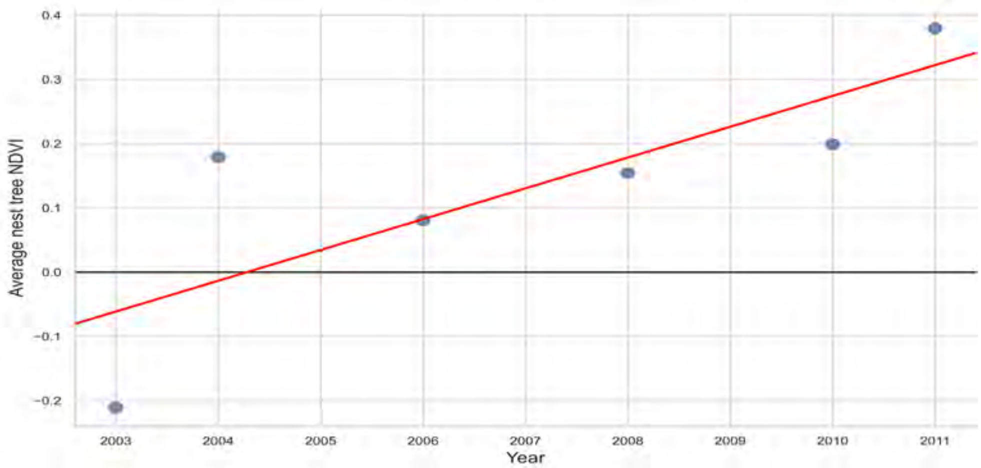


Figure 23: Average NDVIs for nest trees in September of each year, with linear regression line in red, $R^2 = 0.72$.

In 2003, 88% of the nests were in drowned trees, and only 2% in healthy trees with NDVI > 0.3. In 2010 and 2011, > 60% of the nests were in healthy trees of NDVI > 0.3, as the increased rainfall starts to improve tree health. Fewer nests are found in the last years in the sub-setted area, corresponding to a decline in numbers of breeding pairs along the whole Murray River. Those that were present had nested in different sites, possibly with better resources or less human disturbance despite local tree health improvement.

3.2.4 Nest fidelity relative to tree vigour changes

For a random selection of individual nest trees, plots of the NDVI for the same tree over time confirm the pattern of hollow selection (Figure 24). They suggest a temporal shift away from drowned and unhealthy trees in the smaller study site, but no strong relationship is demonstrable in the small dataset available.

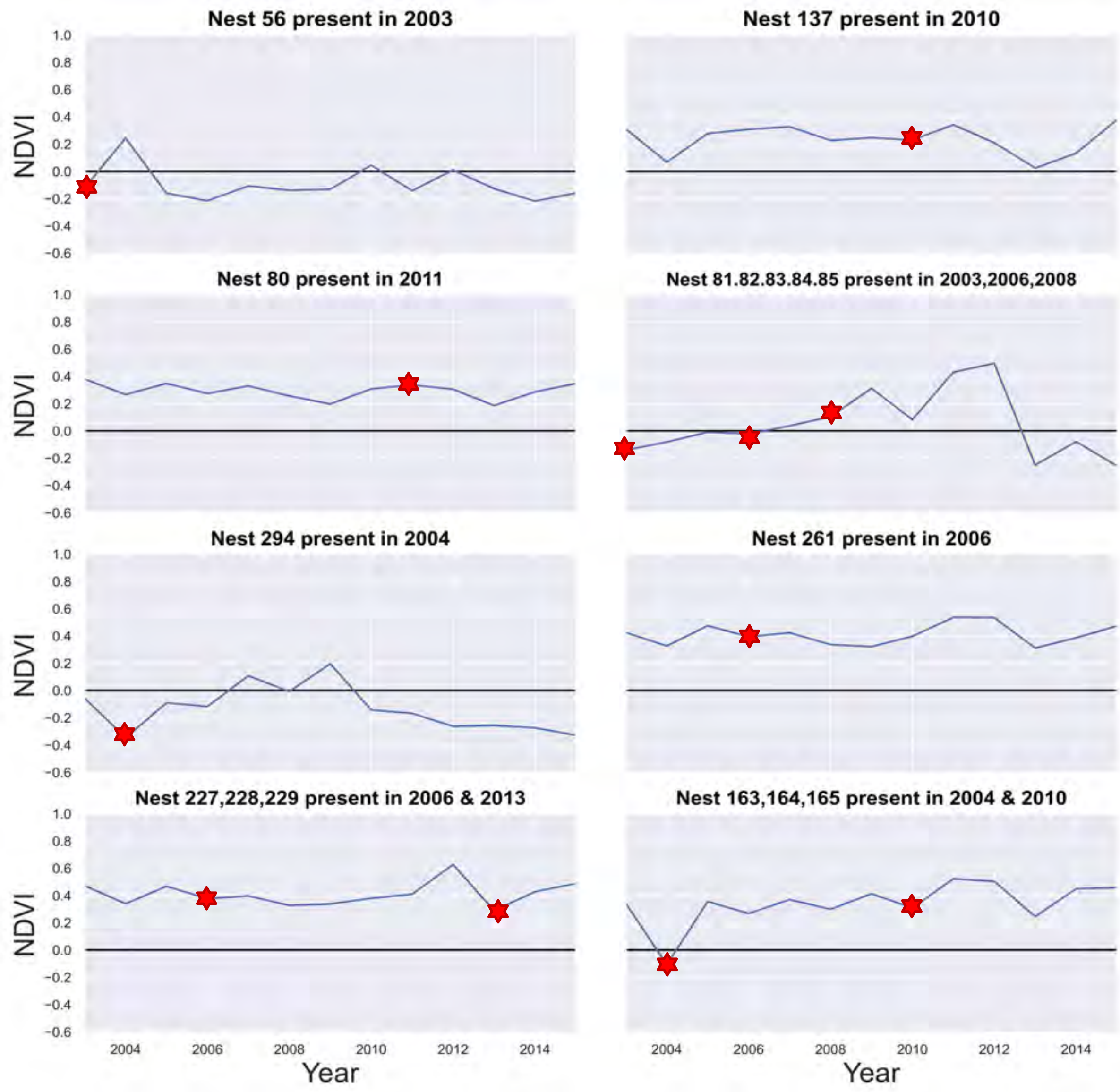


Figure 24:Annual NDVI values for sample of individual nest site pixels, with year of nest presence denoted by ✶. No pattern of nest fidelity or return to tree when it is healthier is visible.

It also appears that trees were not necessarily reused at the peak of their vigour, however, see section 4.1.2 for further interpretation.

4 Discussion

4.1 Nest tree selection

The data support my initial hypothesis that the eastern regent parrot in South Australia selects certain types of river red gum for nest hollows (Figure 12). The parrots select more healthy and drowned trees for nesting than expected due to their comparatively lower availability in the landscape. The selection of unhealthy trees showing poorer canopy cover and leaf fall symptoms is common, but there are 5000 ha more of this tree type available, 30% more than the area containing predominantly healthy trees. In contrast, eastern regent parrots actively avoid dead trees in the South Australian riverbank zones. However, this change towards healthy trees, and away from drowned and unhealthy trees, has only occurred since the Millennium Drought broke in 2010.

The necessity of a safe haven for the fledglings and the nesting parents suggests that tall, mature trees and a high percentage of canopy cover are primary factors in tree selection, but that eastern regent parrots in South Australia consistently chose to nest in dead or drowned trees when there are other healthier tree options available suggests that nesting-habitat affinity is not necessarily fixed.

Successful breeding is a direct result of high-quality nest characteristics in terms of security, proximity to resources, and availability (Cantor et al., 2019; Deng & Liu, 2015; Lewis et al., 2019; Montague-Drake, Lindenmayer & Cunningham, 2009; Renton et al., 2015; Stojanovic et al., 2017). The availability of mature river red gum, not necessarily in healthy trees, nest hollows of adequate size within 260 m of permanent water appeared to be the most influential factors on South Australian nest selection. The selection of river red gum trees with healthy canopy cover in later years of the study is more in keeping with the eastern state regent parrot populations' nest tree selections.

In the eastern states, regent parrots commonly show nest or colony fidelity, as displayed by their return to nest hollows in previously attractive nesting habitat sites (Baker-Gabb & Hurley, 2011). This behaviour, however, has been disputed by Ireland and Ryan-Colton (2016) for the South Australian population, supported by the change in primary colony sites seen during the study period, although it is unknown if these are changes by returning individual breeding pairs or different birds. The eastern regent parrot's size, the potential detrimental effects on normal breeding season behaviour, and the trackers' battery life make it difficult to keep effective location trackers on individual birds for a period covering both breeding and non-breeding season movements, reducing the data available of annual returns to the same area by breeding pairs (Herrod et al., 2013; Ireland & Ryan-Colton, 2016). Data on success of nesting sites is also unavailable to examine the 'win-stay, lose-switch' decision, (Chalfoun & Martin, 2010; Renton et al., 2015), by the parent birds for the annual use of a particular nest hollow, and it is possible that although nest activity is observed, a corresponding successful outcome is not achieved (Cantor et al., 2019).

4.1.1 Qualitative comparison of main nest site areas

Since nesting records began, the annual use of drowned trees, particularly those in the Wachtel's Lagoon and Lake Bonney area (180 km upstream from Swan Reach), has been consistent. In surveys done by Harper in 1989 and Smith 1991 and 2000, between 86% and 94% of nests counted were in the drowned trees around Kingston On Murray. Many of these trees have died as a result of fungal infection and the effects of permanent water logging, and since fallen over into the water (Bickford, 2003). These old trees, many over 300 years old, became permanently inundated after the building of the weirs and locks in the late 1920s/early 1930s. Lock 3's location downstream of the main historical nest colonies in Wachtel's Lagoon, and its subsequent effect on this area's tree population has greatly reduced any possibility of associated nest fidelity, requiring the eastern regent parrots to find nest hollows elsewhere (Schultz, 2006; Smith, 2001). Overland Corner's large proportion of unhealthy nest trees, downstream of Lock 3, in comparison, further demonstrates the influence that Lock 3's flow regulation has on local tree health.

Appendix 6.3 shows the distribution of nests for each year in the Kingston on Murray area. In the Chambers area north of Loveday are several 2003 nests in drowned trees; no birds were found there in subsequent surveys. In the nearby Kingston Backwater, despite stands of healthy river red gum within 500 m, nests are found over several years in denuded, drowned trees that provide little protection for the breeding birds. These trees have been used by eastern regent parrots prior to their permanent flooding and subsequent death after the construction of the river locks in the 1930s (Schultz, 2006). The continued selection of these trees as they became more waterlogged and denuded of canopy foliage suggests some degree of nest fidelity, however the overall number of nests in this stretch of the river had decreased from 55 in 2003 to 5 in 2013, with a 90% decrease in nests in the drowned trees, possibly suggesting a move away from this particular colony site by returning birds, or that colony-loyal members had died during the non-breeding season.

The upstream reach between Loxton and Murtho incorporates the western edge of the wide Chowilla floodplain, one of six Living Murray Icon sites that receives government-regulated environmental flows to redress the effects of drought, reduced river flow from anthropogenic diversions, and increased dryland salinity (Johns et al., 2009). This floodplain is a complex network of anabranches, oxbow lakes, dried riverbeds, and banks with successions of river red gums in varying states of health as the river channel meanders away from these historical locations to its current position. In this area, almost 100% of nest trees were drowned until 2010 when a new colony of 13 nests in healthy trees started at Wiela, 3 km downstream (Appendix 6.4). This colony was observed again when 15 pairs returned in 2015. The drowned trees at Lock 6 consistently had active breeding colonies, with a peak of 16 nests in 2013, but averaging 8 in other study years. Although Nil Nil's colony totalled 2 nests in 2013 and 2015, this number had dropped from the 19 found locally in 2003. No nest sites were counted in the floodplain in 2011 when river flow was high, but this was possibly because of lack of safe access for the ground-based survey team.

This spatial and temporal pattern of nest tree choice is unusual in that the eastern regent parrots appeared to return to previous, less-suitable locations after being at the healthy tree site in 2010. There are large tracts of healthy river red gums close to Nil Nil's drowned trees, suggesting that although apparently healthy trees are available, they might be unsuitable (e.g., too young to have adequately sized tree hollows or lacking in height for safety).

The region between the Wiela colony and the next nests in drowned trees downstream at Gal Gal 6 km upstream of Lock 5 comprises mainly of unhealthy river red gums, with large expanses of *Eucalyptus largiflorens* and intensive agriculture extending along the banks. The lack of dispersal through the healthy river red gums of the Chowilla floodplain suggests that they have few issues with competition for food resources or nest hollows within the colony, and that their choice to group together is instinctual in keeping with their colony breeding status (Matthiopoulos, Harwood & Thomas, 2005).

In lower reaches, west of Overland Corner, there are fewer drowned trees due to flow regulation, but there are also fewer areas of undisturbed river red gums (Appendix 6.2). The 643 nests along the river between Overland Corner and Swan Reach are primarily in healthy trees (56%), with 43% in unhealthy trees. The total area of suitable nest tree area is 7158 ha and 10145 ha, respectively of the 79,750 ha along this length of the river.

The distribution of nests also varies along this stretch of river during this period, with 168 counted in 2004 during the drought, extending downstream to Swan Reach (Appendix 6.5). 192 nests out of the 643 for this region over the study period were identified in 2010 after the Murray Darling Basin's highest rainfall in a decade (136 mm) and a moderately increased spring river inflow volume into South Australia of 7448 GL. Surprisingly, nest numbers did not increase after the increased water availability in 2010, perhaps because these downstream areas had stable water allocations due to effective control of Locks 1, 2 and 3 to maintain riverbank fill at sustainable heights for human enterprises.

4.1.2 Interpretation

The parrots' continued use of drowned trees with no leaf cover, however, does contradict observations of their behaviour in the eastern states (Baker-Gabb & Hurley, 2011; Burbidge, 1985). This trend is slowly changing as the proportion of healthier trees to drowned tree swings in favour of the more stable and fully canopied trees. As discussed above this may be a forced choice as the aging, drowned trees are decaying and falling over, taking their previously favoured hollows into the lagoons and backwaters with them.

The apparent small amount of nest site fidelity in South Australia may also be a result of erroneous assumptions about data accuracy. The collected coordinate data for nest sites showed that nearly half the nest trees in the Kingston On Murray subset were overlapping within 4 m buffer of their location (Figure 25) implying that they were actually within the same tree, since eucalypts demonstrate 'crown shyness', or avoidance of encroaching on each other's canopy (Jacobs, 1955). Using the GIS to model 4 m radii buffers around each observation and reanalysing the data, a new value of nest tree fidelity of 38% is calculated, instead of the previous individual tree coordinate duplication of 17%. This 4 m radius was based on initial tree crown area values, but since GPS units may have errors of 10-30 metres, this overlap may increase the nest fidelity value even more, e.g. in Figure 25 it could be argued that there are 6 nest trees encompassing 22 nest observations, only 2 of which have a single nest recorded there.

Figure 25: Nest tree overlapping multiple 4 m buffer polygons. Nests located within 4m of each other are likely located within the same tree.(ESRI World imagery basemap, DigitalGlobe,GeoEye, i-cubed,USDA FSA,USGS,AEX,Getmapping,Aerogrid,IGN,IGP,swisstopo and GIS User community)

This conclusion is substantiated by the increasing average NDVI for nest trees during the study period, (Figure 23).

4.1.3 Assumptions and uncertainties in the analysis of nest selection

The percentage of nest trees used more than once for the study area was based on a search for nests found at identical coordinates, assuming the global navigation satellite system (GNSS) devices (or handheld global positioning units) had exact location accuracy with no errors, which is unrealistic. Even the newest units available in 2020 document estimate probable errors of 3 m in ideal circumstances, but under trees or in sites of poor satellite geometry this error can be in the range of 30 m or more (Karaim, Elsheikh & Noureldin, 2018). The likelihood that observations were made of birds entering their final nesting hollow, and not when investigating possibilities is also possible, and individuals in breeding pairs could have been counted more than once as a result. Misidentification of the species is also possible; yellow rosellas are not dissimilar and found in the same habitat . Surveys were also done by different team members, with varying expertise, dedication and observational skills over different weeks of the breeding season. Not all years were monitored to the same extent, leading to inconsistencies. The 2011 floods reduced safe access to areas that usually had multiple nests. Although the normal river channel was surveyed, it is possible that the birds had moved farther inland from the original river bank due to lack of dry ground foraging close to their nest tree and were unobserved by surveyors who would only look up to 500 m from the riverbank where possible.

The vegetation polygon data also had potential for large errors and uncertainty associated with the qualitative and quantitative assessment of tree health and predominant species in the individual polygons by the Department of Environment and Water surveyors in 2002-2005. Although the Department of Environment and Water used some classified satellite imagery and ground-truthed their process with personnel using a precursor to the current red gum visual assessment guide (Bickford, 2003; Souter, 2019), these data became outdated as groundwater salinity rose and caused tree diebacks. The digitising process to create a full land cover feature class also required subjective visual assessment of tree health, species, and land use for large tracts of the deeper riparian zone from satellite imagery and Google Earth™ sources. By using the original Department of Environment and Water data, I identified characteristics of each tree species polygon to identify them more accurately in the underlying imagery; however, when compared to contemporaneous Google Earth imagery, this layer had many inaccuracies. Many polygons had mixed populations of tree species and health states and again I had to decide whether to break a smaller polygon into two with mostly healthy trees in one and mostly unhealthy in the other, or to classify the whole polygon based on its dominant species and the health states of any river red gums within that polygon.

4.2 Health assessment of river red gums using satellite imagery and LiDAR

4.2.1 Background of riparian woodlands

Prior to South Australia's Native Vegetation Act 1991, the Development Act (1993) and the Native Conservation Act (1980) were voted into legislation, large stretches of mature river red gum along the South Australian section of the Murray River had been cleared by European agriculturists (Cole et al., 2015). Areas of healthy river red gum are still found in stands along the river length. In the lower reaches, south of Morgan, although proportionately more in comparison to drowned and dead tree areas, the actual availability of mature trees is lower because of high levels of clearing for residential and recreational (Appendix 6.2), and correspondingly nest numbers also decrease markedly after the Murbko colony. The closest patches of natural Mallee woodland and scrub vegetation to the east of this section of the river, that would encompass the eastern regent parrots' summer/autumn range, are separated by large agricultural regions, with few protective movement corridors connecting them, making the more downstream colonies a higher risk selection for nesting season and the summer migration.

Further losses of mature trees along the Murray River are caused by dieback, generally attributed to lack of water in this area (Jensen, 2016). Some areas struggle to retain any healthy river red gum, while other sections seem to have trees which recover rapidly after the increased flow and rainfall. This variation in response has been linked to local differences in irrigation and dam diversions, groundwater availability and soil salinity levels, which may be alleviated by water regulation measures (Cunningham, Griffioen & Mac Nally, 2014; Jensen, 2016).

Riparian zone river red gum stands flower and drop seed in late spring and early summer. Seeds will germinate successfully if they land in bare, moist soil (Jensen, 2016). However, this period coincides with the rapidly growing flush of spring grass, riverbank reeds and ground cover vegetation which all compete for water, soil, and sunlight resources with river red gum saplings (Vivian et al., 2014). Once established in the environment, river red gums having been recorded as flowering and setting seed successfully from 8 years of age, their ability to tolerate sub-optimal water availability is increased (Baldwin et al., 2013; Colloff, 2014; Colloff & Baldwin, 2010). A study by Jensen (2016) reports that river red gum stands in areas to the west of the Murray River show minimal evidence of regeneration and sapling recruitment since 2008. Although, in comparison to the 500 years lifetime of older river red gums, this is a short period of time, if the reduced water availability persists she recommends active management interventions to establish replacement saplings to eventually replace the trees affected by dieback in the region.

The cumulative result of tree loss and the lack of replacement of mature trees in the region has reduced the effective number of current and future river red gum nesting hollows along the Murray River banks. This will have implications for tree cavity requiring fauna populations including brushtail possums, sugar gliders, lizards, barking owls and peregrine falcons, as well as the eastern regent parrot (Lindenmayer, Cunningham & Donnelly, 1997). Other native animals will also be affected by decline in river red gum abundance, e.g. species for whom the eucalypt leaf litter and fallen branches are important food sources for refuge from the heat and predators, including invertebrates, amphibians and reptiles may have to seek alternative habitats (Gonzalez, Scott & Miles, 2011). The stability that healthy river red gum roots provide for the riverbank walls will be lost, increasing riverbank erosion, affecting burrows and dens of bank dwelling species including the eastern water rat (*Hydromys chrysogaster*) and changing river channel flow patterns that may alter fish or invertebrate breeding sites (Bond et al., 2014).

4.2.2 Tree water requirements and riparian ecosystem response to drought

River red gums source most of their water from deep tap roots during drought periods in South Australia, however, superficial tree root access to lateral water supplies from river channel sources and inundation of the trees at least every 3 - 4 years appears to be vital for long term river red gum health (Doody et al., 2014; Johns et al., 2009; Macinnis-Ng et al., 2016; Mensforth et al., 1994; Overton & Jolly, 2004). Without floods, tree vigour deteriorates with leaf fall thinning the canopy and decreasing photosynthetic potential, and, in times of severe heat stress, whole limbs breaking off in an attempt to decrease water requirements. Whilst this process can create new tree hollows for parrot nests in the future, the ongoing health and stability of the tree will deteriorate and its long-term potential as a safe nest haven will be lost (Lindenmayer, Cunningham & Donnelly, 1997).

The decrease in flood frequency and increase in the average daily temperature in the Murray River riparian ecosystems as a result of climate change, potentially causing a radical change in the balance of understory vegetation from those native species upon which native fauna relies. These species, which are adapted to the drought/flood cycle, may be outcompeted by exotic flora species which germinate and reproduce more successfully under the drier climate conditions (Stokes, Ward & Colloff, 2010). It is recognised that floodplain forests and woodlands environments are already vulnerable to anthropogenic clearing and revegetating with food crops or residential development, and the associated influx of non-native flora these bring (Richardson et al., 2007). These 'weed' species may be suitable for short term food resources for the eastern regent parrot, such as the olive and stone fruit orchards in the horticultural areas, but will have a longer reaching effect on the natural riparian zone including the eastern regent parrots' native food preferences of chenopods, bluebush and other native grasses. Being a primarily ground foraging species, the replacement of native shrubs with more open understory vegetation may also leave them more exposed to predators (Baldwin et al., 2013; Colloff & Baldwin, 2010; Vivian et al., 2014).

4.2.3 Water levels

Under the Murray Darling Basin Agreement, South Australia is allocated 1850 GL of water annually from the Murray-Darling river system, an average of approximately 6 GL/day; however, this is only available when not in drought. When in drought, South Australia is entitled to one-third of the total available water to cover critical human supplies, then agriculture and irrigation quotas and river health maintenance in that order. 696 GL of this is the minimum calculated volume required to maintain river flow through the river mouth and prevent the extreme salinity in the lower lakes (Department for Environment and Water, 2020).

Flows of more than 35 to 60 GL/day are required to overflow banks and inundate the South Australian wetlands and low floodplains (Doody et al., 2014; Doody et al., 2015; Johns et al., 2009;

MDBA, 2013), with none occurring between March 2001 and November 2010 (Figure 8). Allocations of water to the South Australian section of the Murray River during this period stayed below 30% for most of the time, with a minimum of 5% of the total in the summer of 2009.

The effect of the 14 locks and weirs built along the Murray in the 1920s and 30s has altered the natural river flow water regime to that of lake-like environments between each weir, changing the aquatic and riparian habitat cycle from episodes of overbank inundation and increased ephemeral lake and creek connectivity followed by dry phases, to that of carefully regulated extended low-level water periods in South Australia (Doody et al., 2014). During drought, the locks are used to maintain river ecosystem health and provide for essential irrigation by maintaining controlled minimum levels of water in the river channel with the assistance of upstream releases from storage damns, such as Lake Victoria just north east of the Victoria Chowilla Floodplain (Colloff, 2014). Weirs can also prevent water reaching parts of the floodplain at certain times to imitate the natural flood/drought cycle previously experienced by natural unregulated flow. Allowing the water to rise just 40 cm behind these locks can lead to large overbank flood extents in the upstream floodplains (Appendix 6.6). The opening of certain weirs redirects river water into dry areas, causing dry creek filling and intermittent flooding, improving local vegetation health and connecting native fish with areas of historical breeding grounds or rich in food resources (Kilsby & Steggles, 2015; MDBA, 2019).

A regular program of environmental flow releases from reservoirs started in 2009 when research showed that at least 79% of river red gum stands in The Living Murray sites were in a stressed condition because of the effect of the changed water regime during the Millennium Drought (Johns et al., 2009). In September 2009 and January 2011 small flows (< 10 GL) were released into the Chowilla Lindsay-Wallpolla reach to specifically protect Southern Bell frog and Barking frog wetland breeding sites, however, little of this water reached the South Australia border to improve local vegetation. Overall South Australia receives few benefits from the upstream environmental flows, since most water is diverted into the New South Wales and Victorian wetlands.

The location of Lock 3, upstream from Overland corner and 431 km from the Murray River mouth, allows regulation of water movement both up and down the river, controlling water levels in the different reaches of the river (Appendix 1). The average drop in water level between upstream Lock 3 and downstream (from available data between September 2008 and Dec 2015) is 3.2 m, (Figure 7), with the lower reach averaging 6.2 m high during the Millennium drought; the contours of river channel and displayed floods show a definite line in river fill value at this location (Appendix 6.6a).

Water levels that do not surpass bank level still have a positive soil saturation effect via percolation of water through the soil layers along the riverbanks, known as lateral bank recharge, and can effectively saturate riparian soils for up to 120 m, replenish groundwater aquifers, and reduce local soil salinity levels (Doody et al., 2014; Overton & Jolly, 2004). The flood polygons from the DEM (Appendix 6.6) show that the river downstream of Lock 3 can increase to 6.9 m before filling in the ephemeral creek backwater sites either side of the main channel and it is not until river height reaches 7.4 m that larger stretches of historical channel ox bow lakes start to fill.

Bank over filling causing inundation of floodplain areas and refilling of disconnected ephemeral water zones, including anabranches, creeks and dried up billabongs in the river's historic path below Lock 3 doesn't occur until river height rises above 8.4 m, and major flooding occurs after water levels reach 9 m (Appendix 6.6a). For the area upstream of Lock 3, the average river height is 9.8 m (Figure 7). Loch Luna and Moorook Game Reserve are permanently flooded swamps maintained by the upstream dam effect of Lock 3. Large scale floodplain inundation occurs when river heights rise above the bank fill level of 10.2 m (Appendix 6.6b). Flows into South Australia stayed above the 35 GL/day rate necessary for overbank flooding (Doody et al., 2014) for fewer than 8% of the days in the study period, with only a further 66 days reaching flow rates of more than 30 GL/day to produce bank fill levels of water (Figure 8).

Despite these brief periods of high flow rates, South Australian flood plain inundation occurred for 7 out of 65 months between July 2010 and December 2015, with rises in river height starting in September 2010 and peaking in February 2011 after heavy Queensland and New South Wales rainfall. River height returned to normal again in November 2011 before peaking at 3 to 4 m above normal in April 2012 for a period of 5 months, when upstream floods again reached South Australia (Figure 6). The ideal period of lying surface water for optimum river red gum health benefits is 60 days, after which the lack of oxygen reaching superficial root areas becomes detrimental to vitality (Doody et al., 2014), however, the longer duration of the 2011 and 2012 flood episodes in this area still had visible positive effects on vegetation vigour for the following 3 years (Appendix 6.7).

4.2.4 Interpretation

My spatial analysis confirms that long-term gains in river red gum health could be achieved along the South Australian Murray River by annual increases in water flow of at least 30 GL/day for at least 30 days during summer to produce lateral bank recharge effects, with an additional flood flow rate of ≥ 35 GL/day for more than 60 days every 2-3 years, in agreement with the findings of Holland et al. (2009) and Doody et al. (2014). The improved health of these keystone mature river red gums in the riparian zone may increase future nest hollow numbers suitable for eastern regent parrots along the South Australian Murray River (Cantor et al., 2019), but also assist in restoration of the associated riparian ecosystem associated with this particular sub-species' presence.

The horizontal extent of the influence on vegetation health of these raised river levels appeared to reach up to 200 m in some locations despite the bank not overflowing, reinforcing the hypothesis that increasing flow from upstream reserves intermittently may be sufficient to ensure maintenance of a vital riparian ecosystem along the river, with the intermittent floods from excess rainfall ensuring the inundation required to enable river red gum seed dispersal and germination. Since the study period ended before the drier winters of 2012, 2013 and 2014 had any detrimental effect on the vegetation vigour, as evidenced by the transect NDVI values of 2014 above those of the drought breaking levels in 2010, we can conclude that there is a prolonged positive effect of at least 2 years on tree health after inundation waters have receded and river levels return to just above mid-drought levels.

The NDVI analysis demonstrated the utility of freely available remotely sensed imagery in identifying areas of healthy vegetation. The positive response of increasing NDVI values after increased water access for both short periods of lateral bank refill in 2010 and again in 2013, and to periods of ground inundation in 2011 and 2012 was clearly identifiable using the annual spring season imagery. The moderate high-water event downstream of Lock 3 between August and November of 2013 caused NDVIs for that area to decrease to below 0 in some sites of what were previously tree canopy regions on dry land. This anomaly occurs because the presence of water in parts of the 5 m^2 image pixel, even if only as moist soil, reduces the NDVI for that area. Water has a much higher relative absorption of NIR wavelengths compared to Red wavelengths, producing a negative, or lower positive NDVI than expected for the overlying partial vegetation cover. An alternative hypothesis is the imagery was taken straight after a heavy rain event, but a second cloud free image 4 weeks later showed similar lower NDVI results for the same area implying the ground itself is saturated. In ephemeral lake beds after flood waters recede, or riverbank locations as river levels drop, the moist ground surface supports transient abundant growth of intensely photosynthetic algae and water loving plants, producing very high NDVI values in the previously negative NDVI pixels until the exposed soil dries up again and they die. These sites can be easily distinguished from tree pixels by the GIS software when overlaid on the underlying base imagery or masked out by a higher water level polygon overlying the NDVI raster layer.

The randomly located transects supported the reliability of NDVI values in identifying regions of water influx and regression, invigoration and deterioration of vegetation health, or sites where annual fluctuations are most apparent (Appendix 6.7). Sites where the convex bend of the river has a large sandbank, transect 4 and 7, show considerable variability in site of active vegetation growth dependent on the most recent river level. Areas beside ephemeral water locations, transect 6 and 11, show a response to water influx the next growing season, which wanes as water levels regress, returning to lower NDVI levels of vegetation photosynthesis. Sites along the river which have active horticulture irrigation influences will tend to have healthier local riverbank vegetation during agricultural irrigation season, but not spring when the imagery was obtained (Appendix 6.7, transect 12) due to lateral recharge from the agricultural watering.

4.2.5 Error and uncertainty in NDVI index of tree health

Although NDVI image analysis is a well-recognised method of quantifying vegetation vigour, it does have inherent generalisations and potential errors associated with its use.

The spatial resolution of the underlying satellite images introduces inaccuracies, with an assumption of single vegetation species fully covering the whole pixel, unlikely for river red gum in a 30 m by 30 m pixel (Goetz, 2006; Huylenbroeck et al., 2020; Zhangyan et al., 2005). The intensity of the different reflected electromagnetic wavelengths received by the onboard sensors from the field of view, and the average values for each band width within that area are converted to a digital number for that pixel. Pixels containing different ground covers, e.g. water, bare soil and vegetation types of varying photosynthetic activity, called mixels, will have an NDVI value based on the average reflectance values of all the different land covers, and not necessarily show the actual index value for the main vegetation therein (Jensen, 2014; Michez et al., 2017; Zhangyan et al., 2005). Artificially higher NDVI values can occur if the tree's canopy is broken or defoliated, allowing the satellite sensors to pick up the spring flush of underlying ground cover and understory through the bare crown, or conversely lower NDVIs will be produced if water-saturated ground underneath is visible through a partial canopy. NDVI values for the same location and land cover can vary considerably over time for several reasons including time of data collection relative to recent rainfall, temperature and wind conditions (Olmos-Trujillo et al., 2020; Pettorelli et al., 2005; Wang et al., 2016).

Comparing resampled Landsat 30 m spatial resolution imagery (Red band of 0.63 – 0.69 µm and NIR band of 0.77 – 0.90 µm, radiometric resolution 8 bit) with RapidEye 5 m spatial resolution and radiometric resolution 12 bit (red band 0.63 – 0.685 µm and NIR 0.76 – 0.85 µm) will produce inconsistencies in NDVI values, and reduce the statistical credibility of comparing 'like with like' (Martínez-Beltrán et al., 2009; Teillet, 1997). The use of different RapidEye satellites from the 5 satellite constellation for each year's image, drifting of satellite orbits (Deng & Di, 2001), on-board clock and sensor calibration inaccuracies introduce systematic sensor type errors (Mancino et al., 2020). Data collection errors associated with the differing times of day of image recording, viewing angle of sensor, cloud cover, and sun angles, underlying soil type, slope topography and aspect, which all affect the Bi-directional Reflectance Distribution Function (BRDF) of the vegetation type under study, will also combine to reduce NDVI temporal comparison validity although to a lesser degree (Burgess, Lewis & Muller, 1995; Mancino et al., 2020; Martínez-Beltrán et al., 2009).

Riparian vegetation diversity has also been identified by combining multispectral imagery with co-registered Light and Distance Ranging (LiDAR) techniques to aid in quantifying tree canopy cover and its photosynthetic capability (Arroyo et al., 2010; Goetz, 2006; Huylenbroeck et al., 2020; Michez et al., 2017; Shendryk et al., 2016). Using 3D point clouds to map the structural complexity of the riparian zone vegetation, an analyst can identify large tree canopies by their elevation above the ground, and extract just the overlying NDVI pixels for those locations. This would remove high NDVI pixels of shrub and spring ground cover growth from the analysis and increase the accuracy of average nest tree NDVI values for the study area. The method of simply comparing NDVI values to assess tree health and suitability for nest cavity use appears effective in this study. The addition of airborne LiDAR data would have improved differentiation of tree pixels from ground shrubs increasing the accuracy of detection of suitable nest trees but was outside the budget of the study.

Without simultaneous ground observations of the study area to confirm the validity of any vegetation index raster outputs, accuracy cannot be assessed. However, the actual degree of exact health is not the most relevant part of this study, but rather the visible vegetation health response to additional water, which this method does demonstrate well.

5 Conclusions

This study confirms that South Australian eastern regent parrots will select to nest in healthy river red gum trees over other tree states and that the availability of healthy trees increases in response to increased Murray River water flows. Combining nest survey point data with elevation data and remotely sensed data in a geospatial information system I was able identify the relationships between nest trees, rising water levels and river red gum vigour. With this information it is possible to locate areas of changing parrot use over time and assess the influences of tree health on nest colony selection.

The continuing decline of the eastern regent parrot population in South Australia is apparent from the nest survey data collected by the Regent Parrot Recovery Team during the study period. The end of the Millennium drought in 2009/2010 and the associated increase in Murray River water and riparian corridor tree health does not appear to have had a positive effect on the number of breeding pairs in the state, although nests are now more often found in healthier canopied trees, in keeping with the eastern state bird populations.

The Murray-Darling Basin Authority has regulatory management of local river levels by releasing stored water from upstream reservoirs into the main channel, however these are often timed to improve agricultural demand and not necessarily for the benefit of the Riverland ecosystem. Extra water allocations to protected wetland sites, which includes the Chowilla Floodplain and its downstream extension to Renmark, do not necessarily trickle downstream to less recognised Ramsar sites such as the Banrock Station Wetland Complex in the sub-setted study area. Consideration must also be given to the effect a sudden return to ‘natural’ flood regimes by engineered environmental flows in this region of the Murray River will have on the now established drier ecosystems created by the reduced inundation cycles (Baldwin et al., 2013; Bond et al., 2014; Stokes, Ward & Colloff, 2010). Studies show that inundation causes dispersal of both exotic and native seeds, microbial populations, natural organic matter sediment, and nitrogen rich agricultural fertiliser pollutants, leading to eutrophication related harmful algal blooms, fish mortality events and dead zones, and cause increased turbidity of water systems that may all have adverse effects on both the terrestrial and aquatic ecosystems in the area and downstream (Kilsby & Steggles, 2015; Talbot et al., 2018). These artificial changes in flow patterns through pumped flooding and temporary diversions to disconnected wetlands can cause disruptions in flow velocity of river channels, altering fish behaviours or their entrapment in floodplain zones, while also potentially diverting water away from stable wetland zones causing their degradation (Pittock, Finlayson & Howitt, 2013).

Despite the conservation status of the Wetland sites, and the many species dependent on a healthy river and vegetation ecosystem, the state and federal government priorities appear to be anthropocentric towards agriculture and urban development. The Basin Plan (Commonwealth of Australia, 2012) created a framework to manage distribution of the available Murray Darling Basin water efficiently and effectively to maintain, or restore if necessary, Riverland natural environment health, societal needs, manage groundwater aquifers, and ensure water quality. Recent findings published on the Commonwealth Environmental Water Office's success managing the Basin Plan suggest that despite the investment in engineering infrastructure based on modelling studies, the plan has been successful in increasing annual water through environmental flows to only 2% of the targeted floodplain targets (Chen et al., 2020; Pittock, 2020).

The ongoing destruction of the riparian river red gum, and native vegetation Mallee areas makes the South Australian Riverland zone even more inhospitable for the eastern regent parrot and, since fewer breeding birds remain, their philopatric offspring will also decrease in number. This self-perpetuating cycle could eventually lead to total local extinction of the eastern regent parrot in South Australia unless efforts to restore the important parts of their econiche are rapidly increased. A combination of federal and local government environmental management strategies is needed to deliver the flow volumes into the South Australian Murray River required to sustain the iconic wetlands and their associated river red gum woodlands. The cooperation between states is still not balanced for the welfare of all parts of the Murray-Darling Basin and ensuring environmental flows of enough frequency and duration to the South Australian region appears to be a constant battle, especially during times of water shortage.

5.1 Future Research

There remain many unknowns in the breeding site selection drive of the eastern regent parrot in South Australia. Although known to live up to 20 years in the wild, the ability to trace the individual movements of different colonies between breeding seasons, and during, is difficult due to the difficulty finding them outside breeding time to safely catch and place tracking units on them which don't interfere with their cavity dwelling habits and behaviour. Zoos SA and the Department of

Environment and Water are currently following several birds trapped and tagged in late Winter/early Spring 2019, but the data is not yet available.

The longer generational effect on population numbers after the increased average rainfall in the last decade has not been fully realised. The increased health of the mature river red gum along the riverbanks of historical nesting colony sites may still have a positive effect on nest fecundity and colony numbers but data needs to be collected. More detailed information on Riverland feeding patterns during breeding season would help identify why certain sites are more popular with nesting birds than some with healthier trees.

Using GIS web apps including Survey 123™ or even just Quick Capture™, location of sightings, tree type, time of day, number seen, interactive behaviours, food resources present, and images can be uploaded to a web map for easy access by researchers. Restrictions on who can download the phone app would allow some quality control of expertise and response accuracy, but still open up the survey process to considerably more observers than currently active regent parrot recovery team members, increasing the data obtained through-out the year. Bayesian models could include a degree of uncertainty associated with such variable data quality, as seen in the Koala Count (Sequeira et al., 2014), to create a regent parrot distribution model for the whole of the year.

Using the ArcGIS Pro Spacetime cube tool, spatiotemporal modelling of the annual NDVI raster layers creates an emerging hotspot grid highlighting the location of regularly increasing NDVI values and those where NDVI is decreasing or remains low. This process would provide environmental managers a map showing sites which still respond positively to the increased water access and would benefit from additional flow allowances diverted to their section of the river channel. Locations which had no increased NDVI after the higher water levels of 2010 onwards would need more intensive restoration to recover.

The importance of corridors for the population to move between breeding and summer sites has also not been well researched, but integrating citizen science, remote sensing satellite imagery, airborne LiDAR and ground surveys during the post breeding period would improve the knowledge database and produce some predictors for movement corridor suitability. This information could inform landowners and the Department of Environment and Water in the most useful sites to restore to optimise safety for the regent parrots as they move between the Riverland and Mallee.

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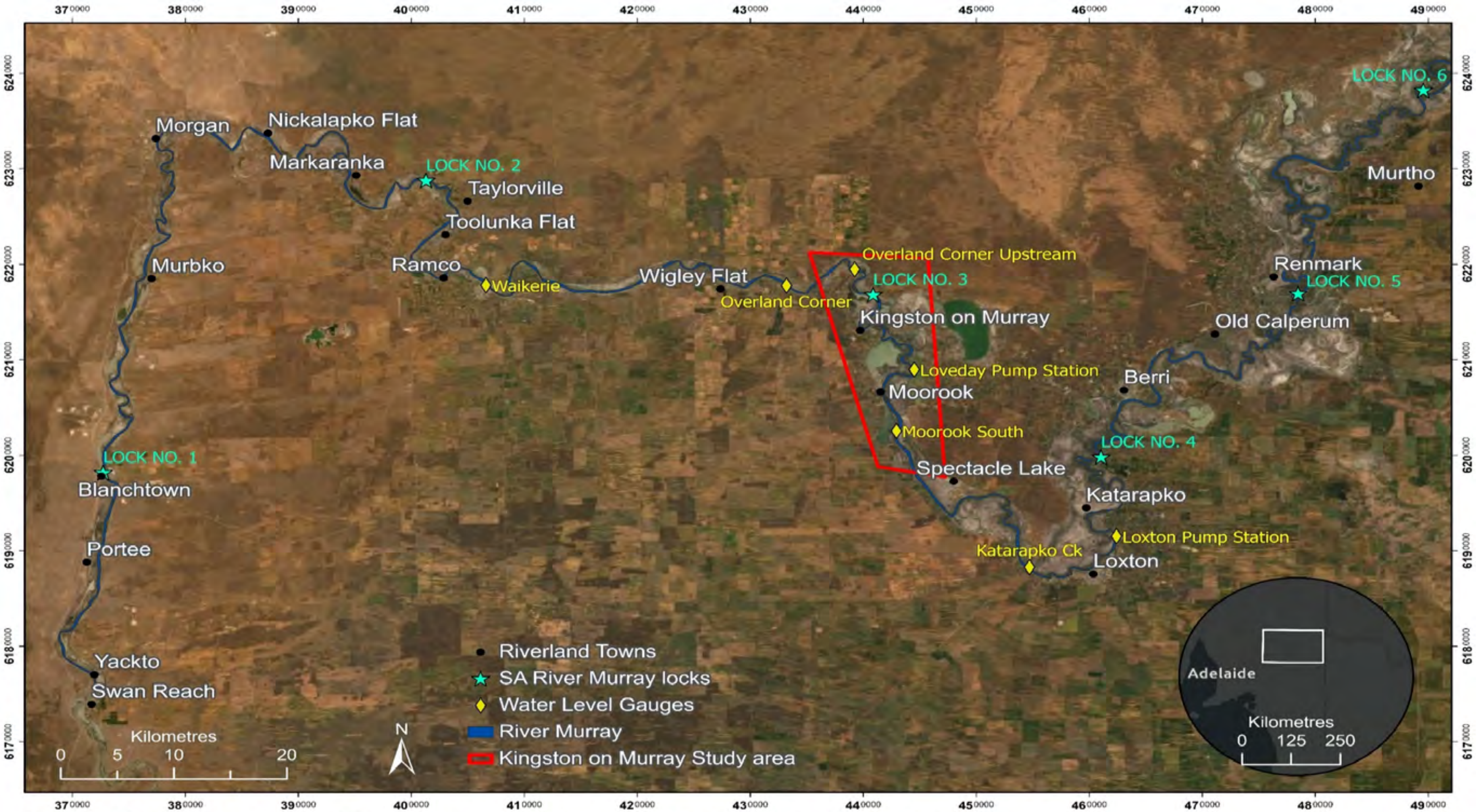
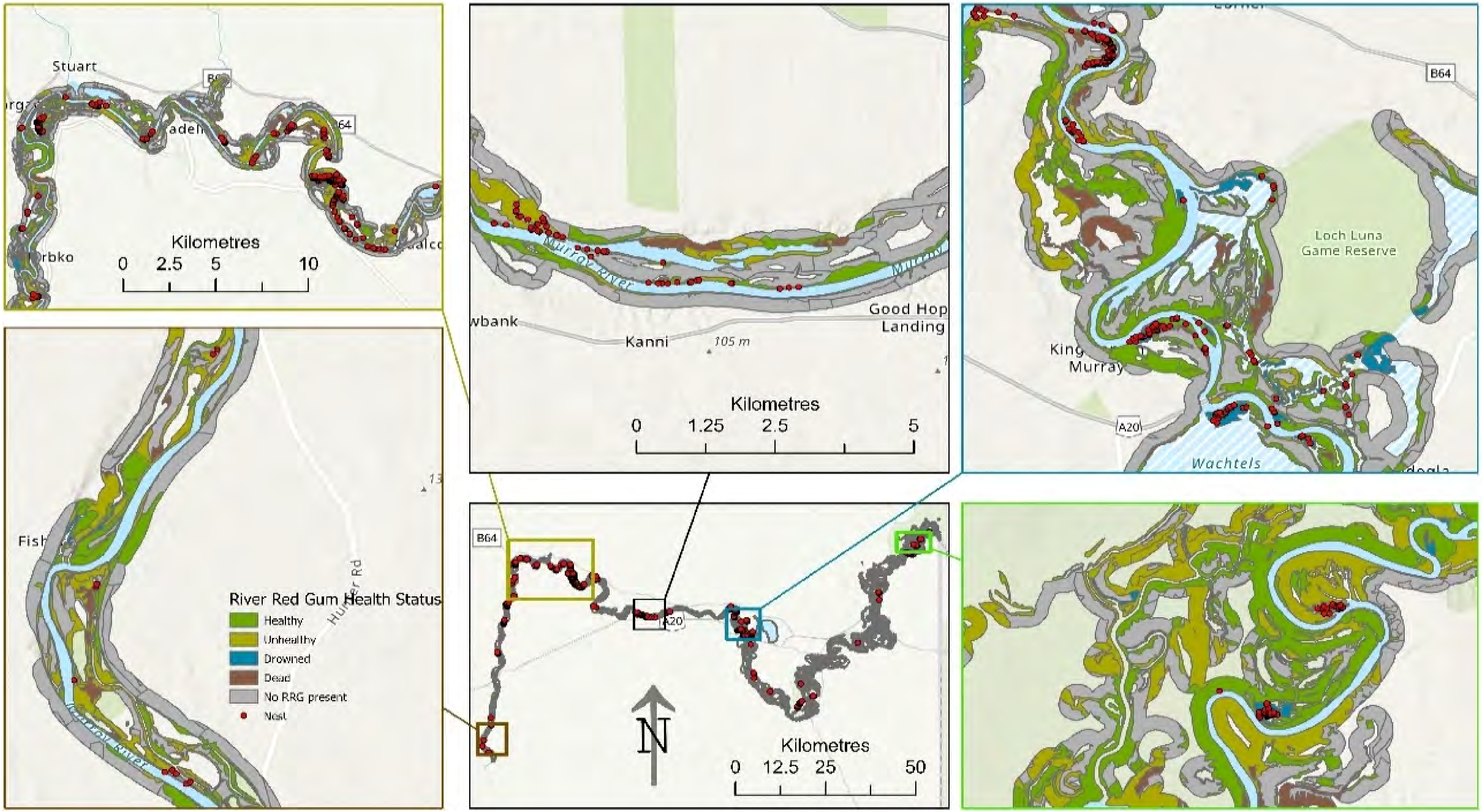
6 Appendices

6.1 Map of study area with locations of locks and water gauges

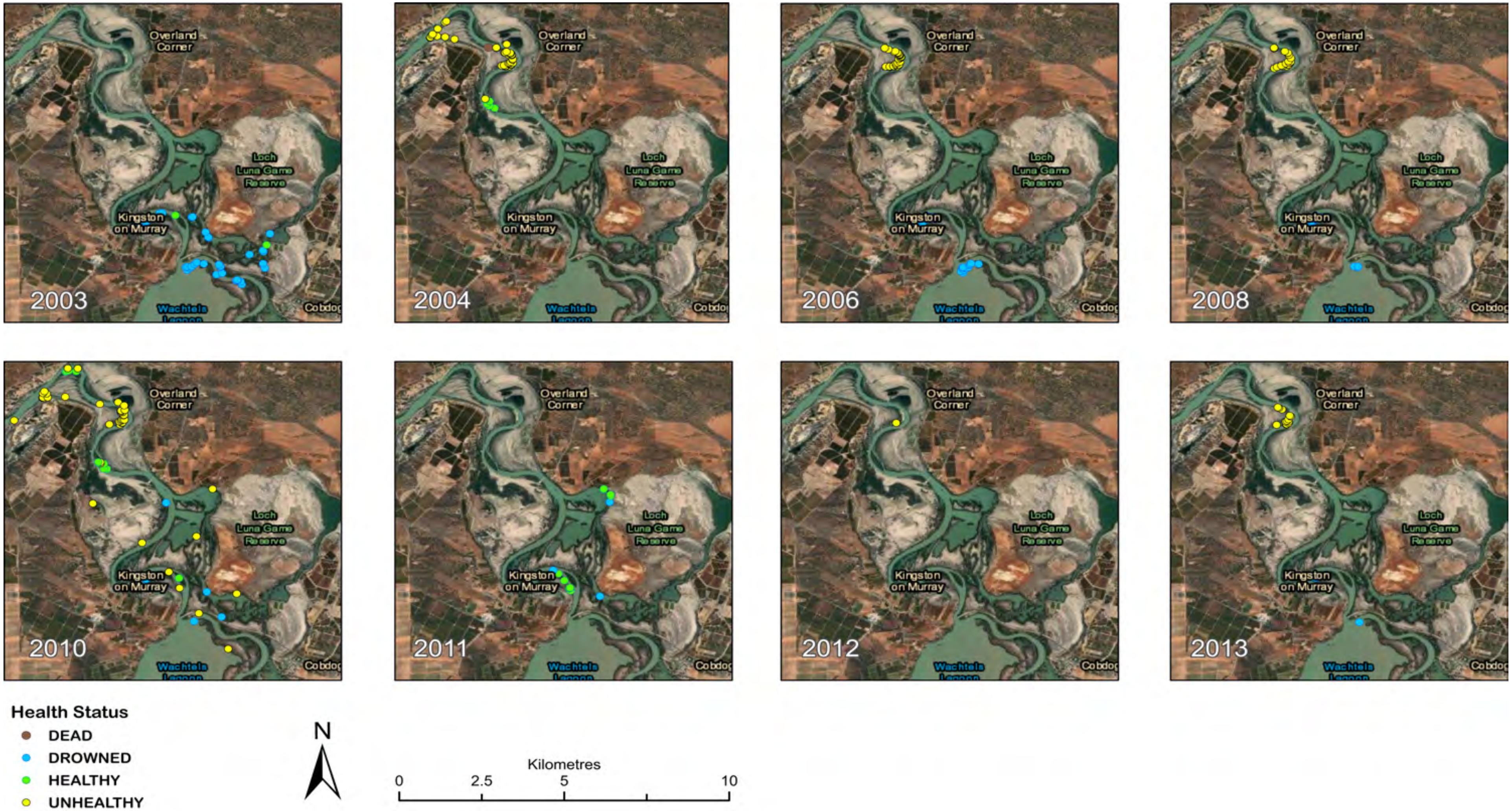


Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

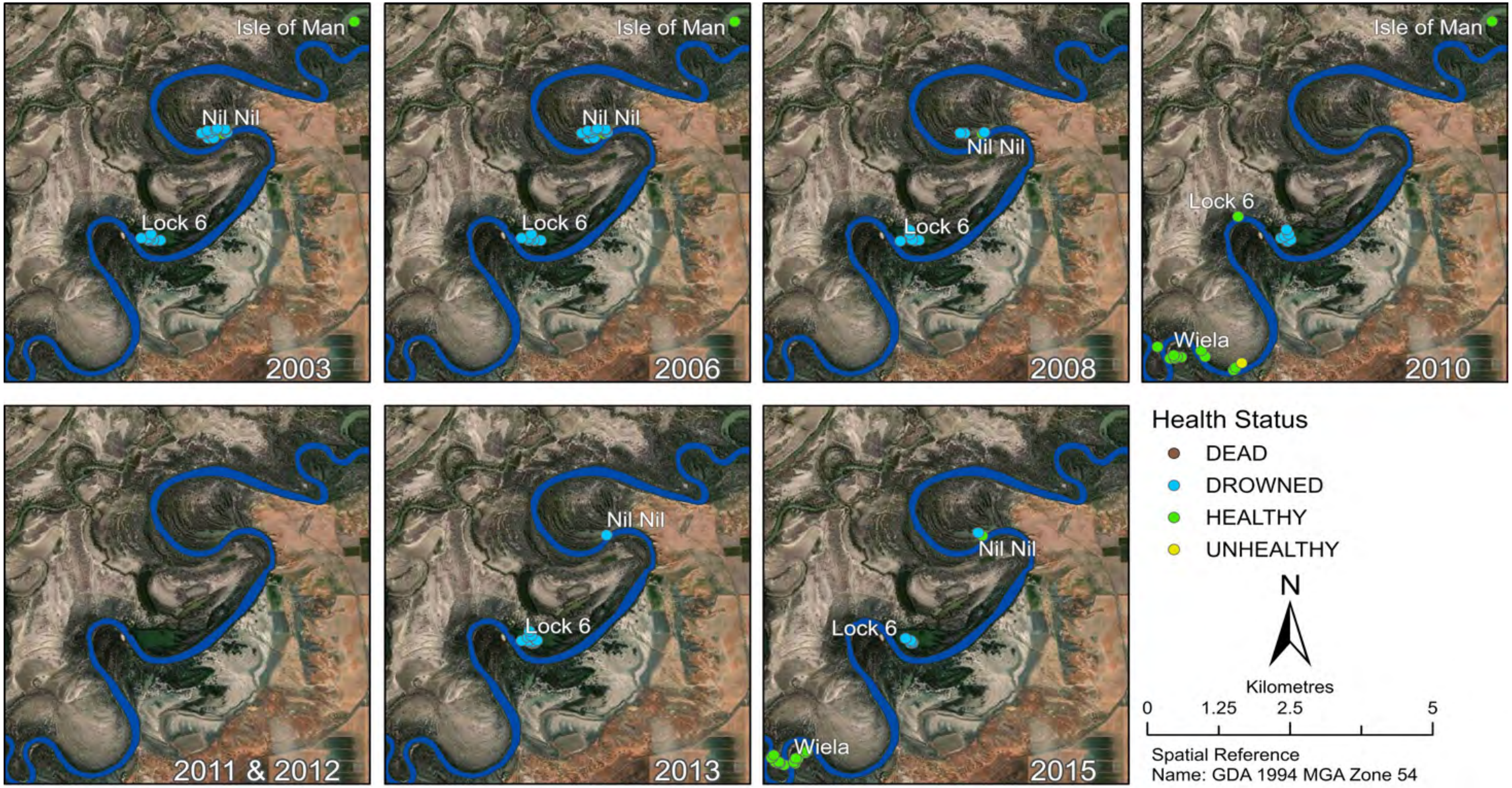
6.2 River red gum presence and health status at major nest site colonies along South Australian Murray River



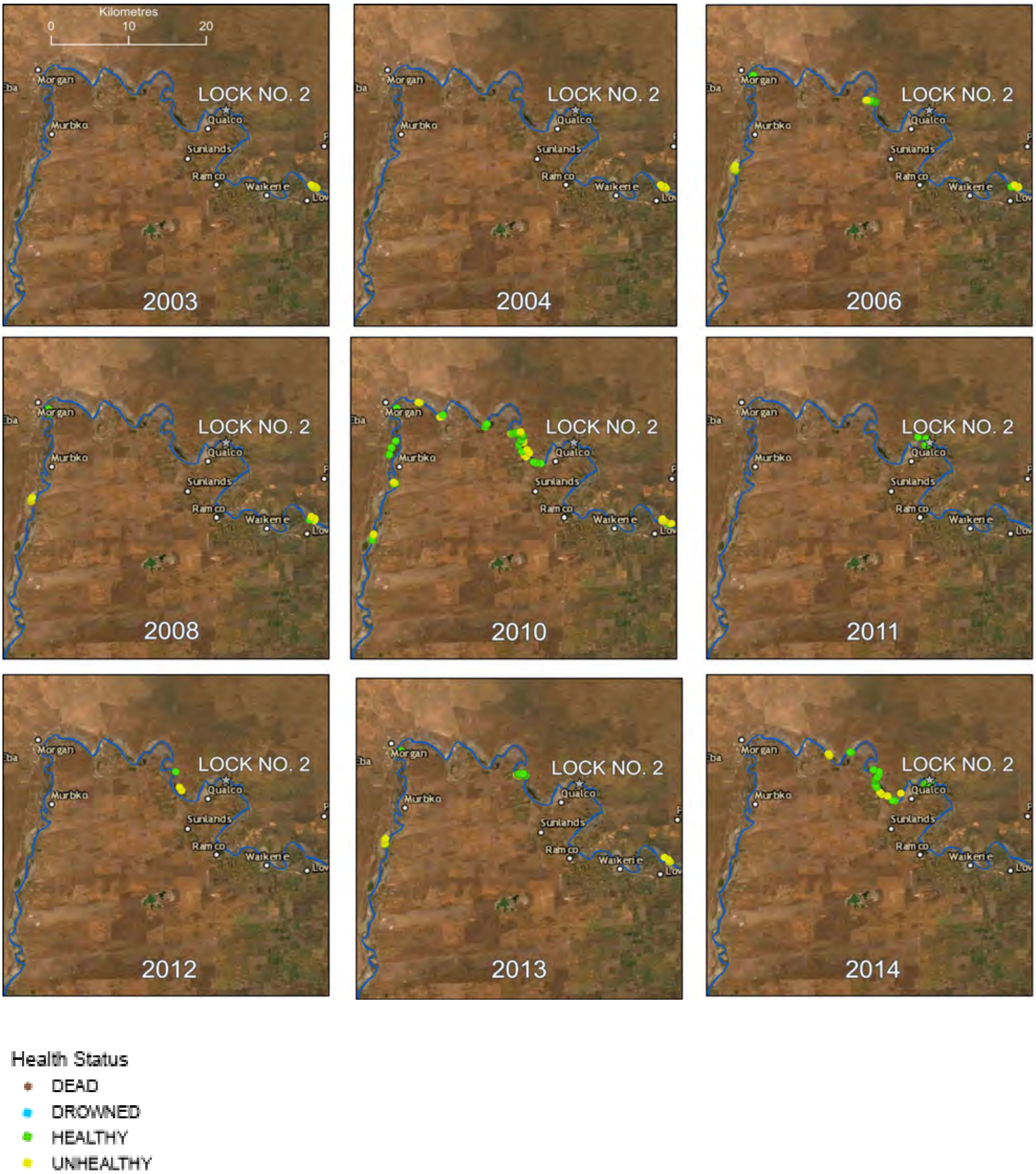
6.3 Nests in Kingston on Murray area during each survey year



6.4 Nest sites in the Chowilla Floodplain in survey years



6.5 Nest locations downstream of Overland Corner in survey years

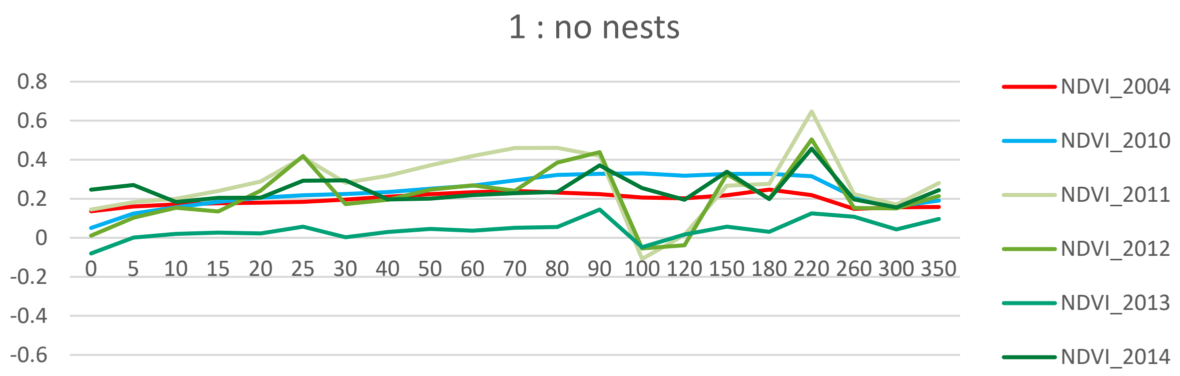


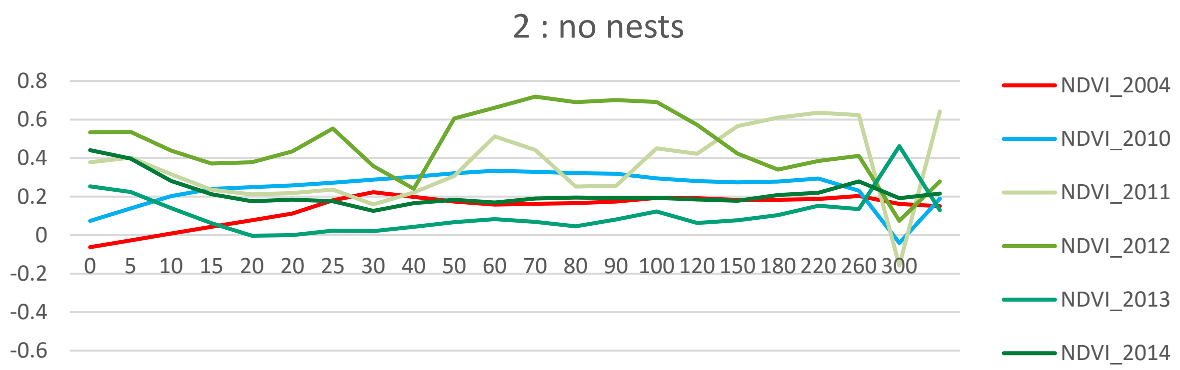
6.6 Annual peak flood polygons for (a) below Lock 3 and (b) at the Loveday Swamp pump station

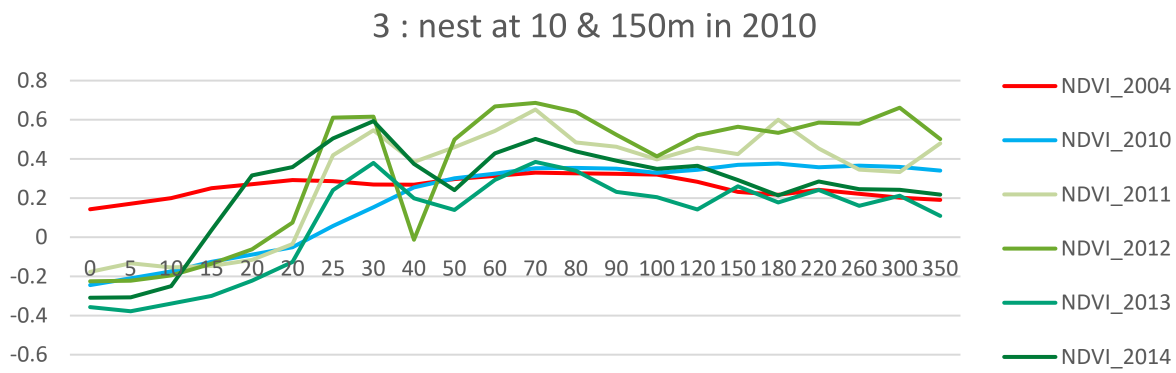
(a) Lock 3

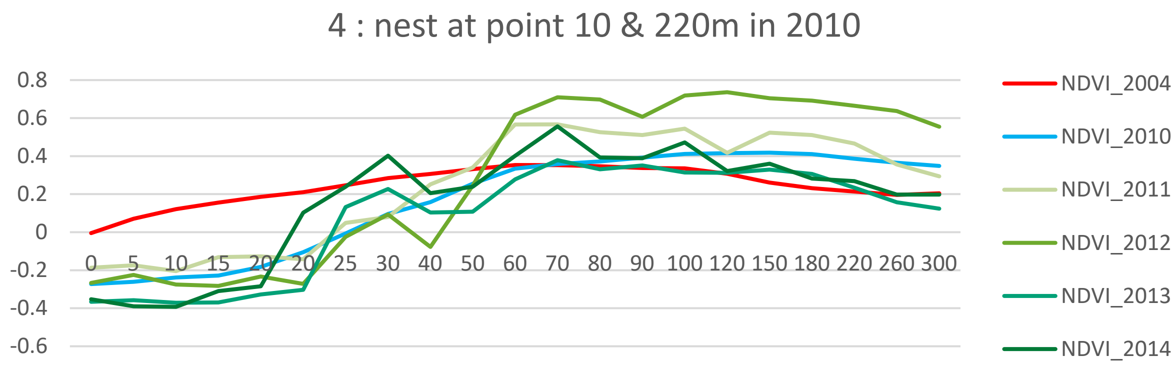
(b) Loveday Swamp Pump Station

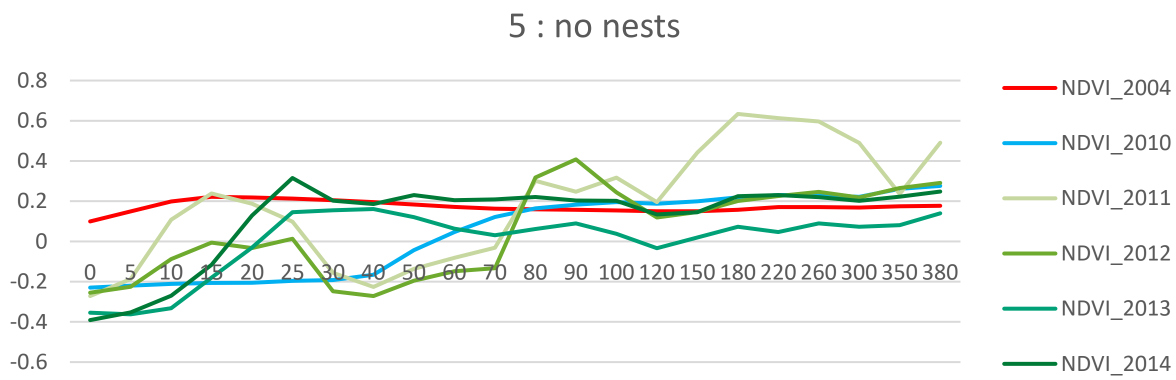
6.7 NDVI values along transects at random locations in Kingston on Murray study area

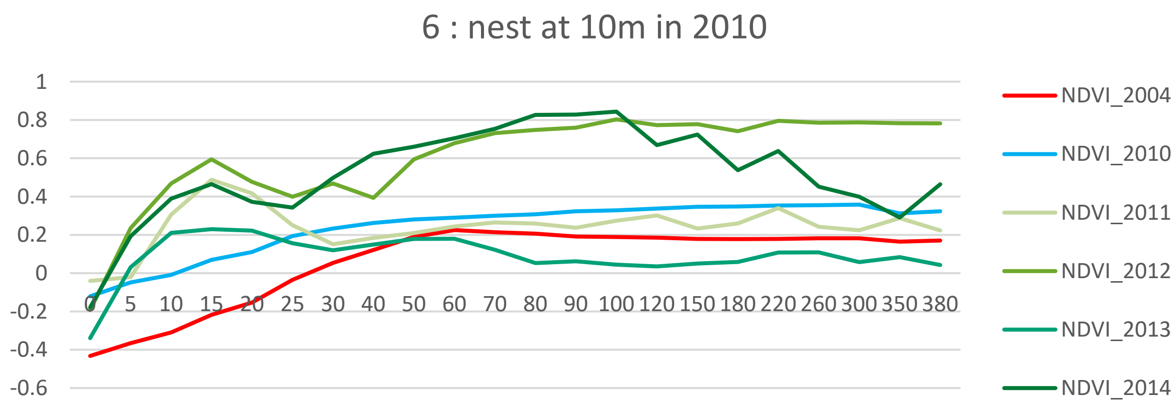


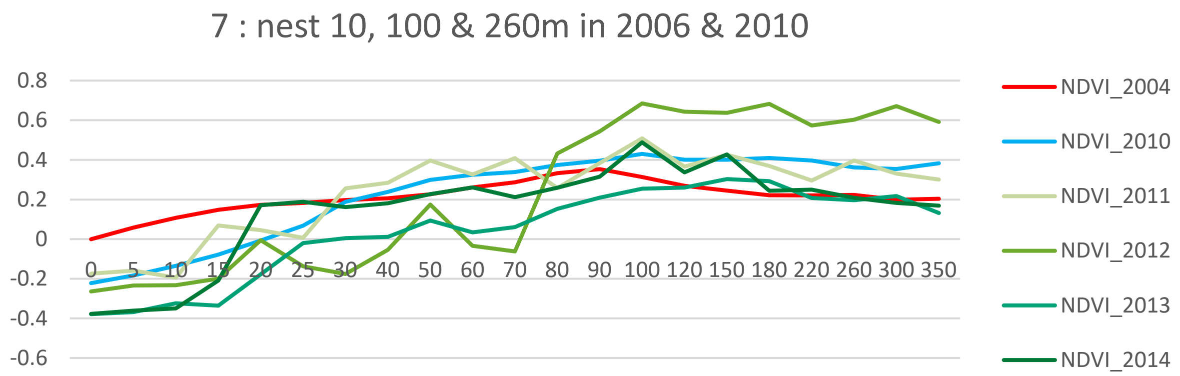


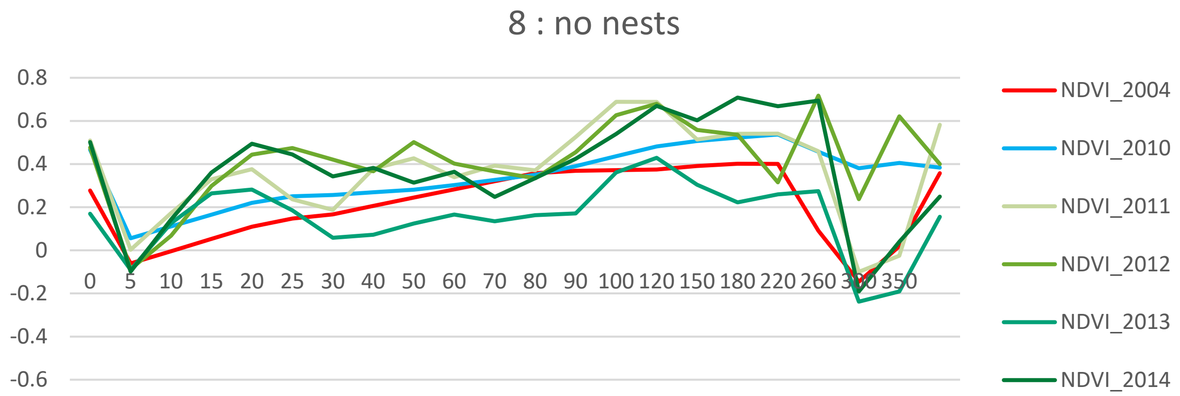

3 : nest at 10 & 150m in 2010
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0 5 10 15 20 20 25 30 40 50 60 70 80 90 100 120 150 180 220 260 300 350
NDVI_2004
NDVI_2010
NDVI_2011
NDVI_2012
NDVI_2013
NDVI_2014

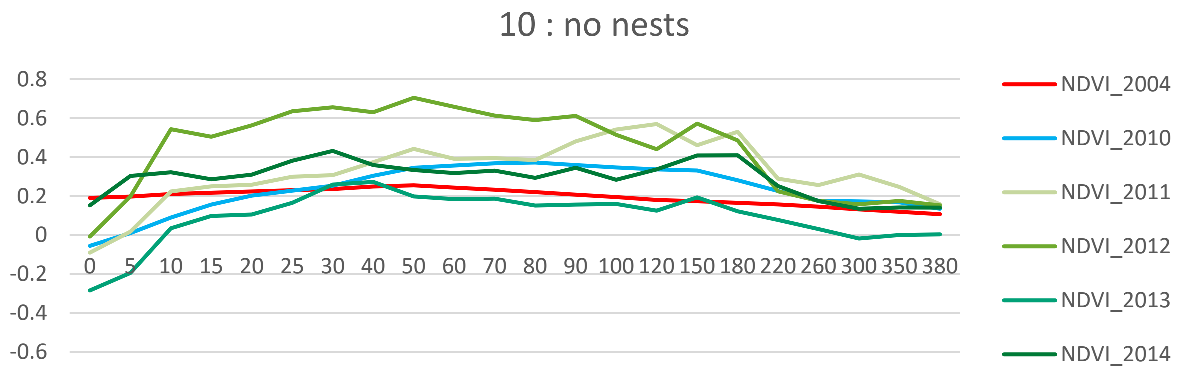

4 : nest at point 10 & 220m in 2010
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0 5 10 15 20 20 25 30 40 50 60 70 80 90 100 120 150 180 220 260 300
NDVI_2004
NDVI_2010
NDVI_2011
NDVI_2012
NDVI_2013
NDVI_2014

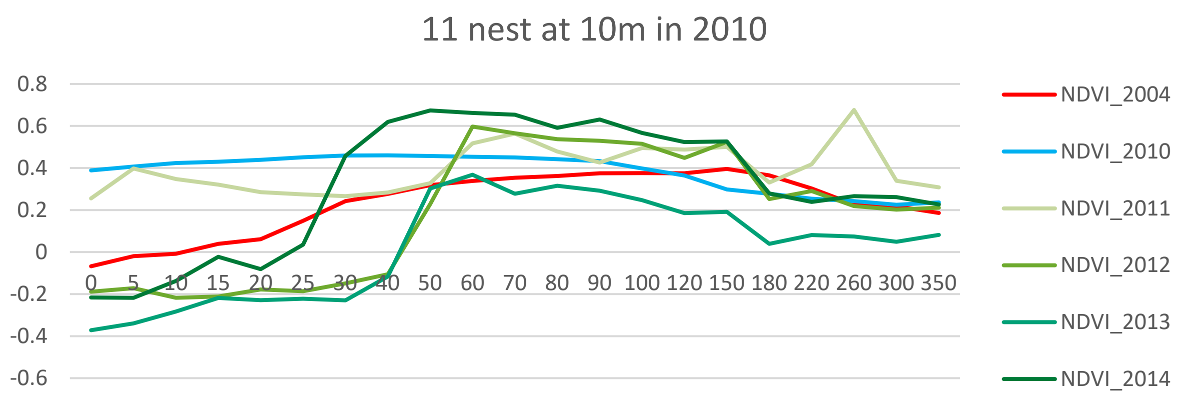

5 : no nests
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0 5 10 15 20 25 30 40 50 60 70 80 90 100 120 150 180 220 260 300 350 380
NDVI_2004
NDVI_2010
NDVI_2011
NDVI_2012
NDVI_2013
NDVI_2014

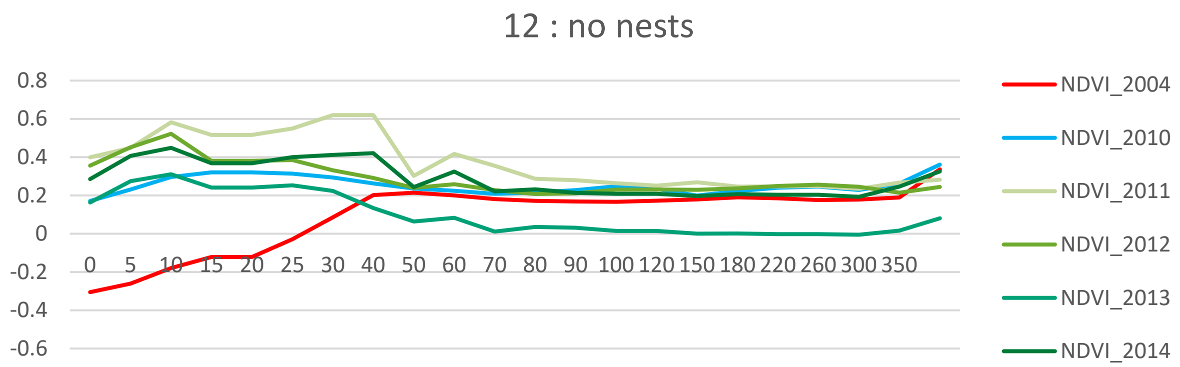

6 : nest at 10m in 2010
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0 5 10 15 20 25 30 40 50 60 70 80 90 100 120 150 180 220 260 300 350 380
NDVI_2004
NDVI_2010
NDVI_2011
NDVI_2012
NDVI_2013
NDVI_2014

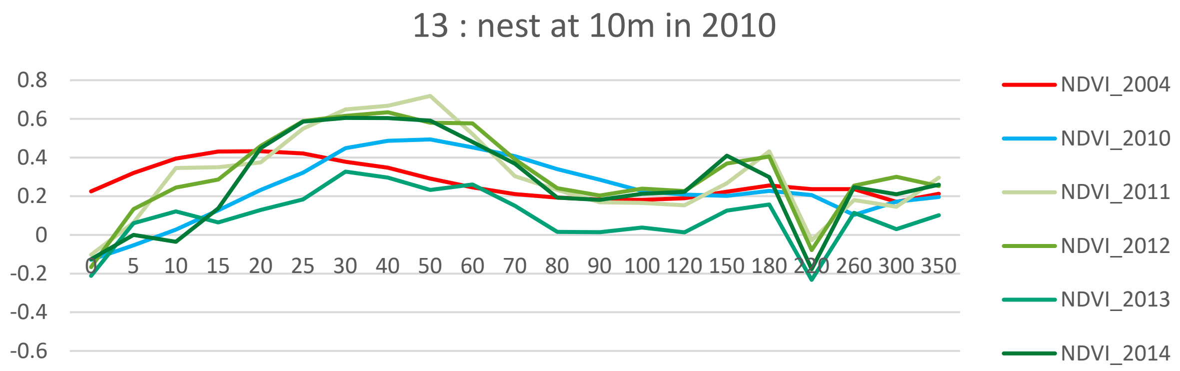

7 : nest 10, 100 & 260m in 2006 & 2010
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0 5 10 15 20 25 30 40 50 60 70 80 90 100 120 150 180 220 260 300 350
NDVI_2004
NDVI_2010
NDVI_2011
NDVI_2012
NDVI_2013
NDVI_2014

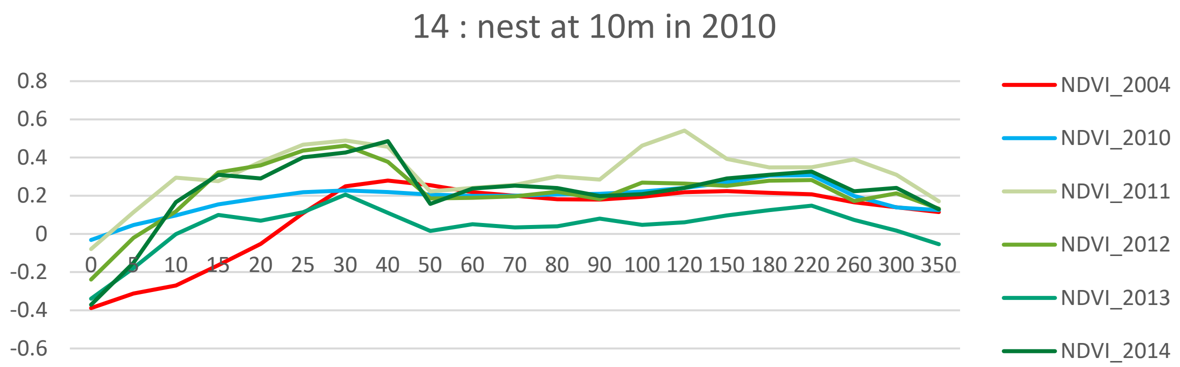

8 : no nests
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0 5 10 15 20 25 30 40 50 60 70 80 90 100 120 150 180 220 260 300 350
NDVI_2004
NDVI_2010
NDVI_2011
NDVI_2012
NDVI_2013
NDVI_2014

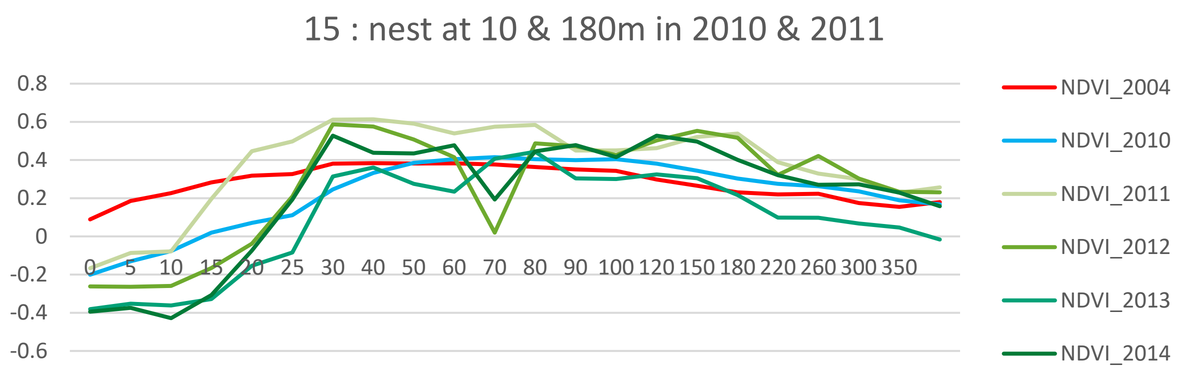

10 : no nests
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0 5 10 15 20 25 30 40 50 60 70 80 90 100 120 150 180 220 260 300 350 380
NDVI_2004
NDVI_2010
NDVI_2011
NDVI_2012
NDVI_2013
NDVI_2014


11 nest at 10m in 2010
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0 5 10 15 20 25 30 40 50 60 70 80 90 100 120 150 180 220 260 300 350
NDVI_2004
NDVI_2010
NDVI_2011
NDVI_2012
NDVI_2013
NDVI_2014


12 : no nests
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0 5 10 15 20 25 30 40 50 60 70 80 90 100 120 150 180 220 260 300 350
NDVI_2004
NDVI_2010
NDVI_2011
NDVI_2012
NDVI_2013
NDVI_2014


13 : nest at 10m in 2010
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0 5 10 15 20 25 30 40 50 60 70 80 90 100 120 150 180 220 260 300 350
NDVI_2004
NDVI_2010
NDVI_2011
NDVI_2012
NDVI_2013
NDVI_2014


14 : nest at 10m in 2010
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0 5 10 15 20 25 30 40 50 60 70 80 90 100 120 150 180 220 260 300 350
NDVI_2004
NDVI_2010
NDVI_2011
NDVI_2012
NDVI_2013
NDVI_2014


15 : nest at 10 & 180m in 2010 & 2011
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0 5 10 15 20 25 30 40 50 60 70 80 90 100 120 150 180 220 260 300 350
NDVI_2004
NDVI_2010
NDVI_2011
NDVI_2012
NDVI_2013
NDVI_2014

6.8 Python script for Chi Squared Test of Independence

```
#%%
#import modules
import pandas as pd
import seaborn as sns
import numpy as np
from scipy import stats
from scipy.stats import chi2_contingency
import xlsxwriter as xlsx
import matplotlib.pyplot as plt
import matplotlib.ticker
from matplotlib.ticker import ScalarFormatter

#datasets
nests = [8,190,474,467]
nestsdf = pd.DataFrame(np.array([nests]))
nest_arr = np.array([nests])
proportion = np.array([0.0698, 0.0189, 0.3815, 0.5298])
f_exp = [80,22,434,603]
f_expdf = pd.DataFrame(np.array([f_exp]))
f_exp_arr = np.array([f_exp])
states = ['Dead','Drowned','Healthy', 'Unhealthy']
table = [nests,f_exp]
tabledf = pd.DataFrame(table, index = ['Nest count', 'Expected count'], columns = ['Dead','Drowned','Healthy', 'Unhealthy'])
print(tabledf)
significance = 0.05
p = 1- significance

#Chi squared test on calculated expected values
chisq,pval,dof,exp = stats.chi2_contingency(tabledf)
critical = stats.chi2.ppf(p,dof)
print('Chi Squared value =', chisq)
print('p value =', pval)
print('degrees of freedom=', dof)
print('Critical value =', stats.chi2.ppf(p,dof))

print('chi squared =%.6f, critical value=%.6f\n' % (chisq, critical))

if chisq > critical:
   print("""At %.2f level of significance, we reject the null hypotheses and accept H1. They are not independent.""" %
(significance))
else:
   print("""At %.2f level of significance, we accept the null hypotheses. They are independent.""" % (significance))

##or compare p value and level of significance

print('p-value=%.6f, significance=%.2f\n' % (pval, significance))
if pval < significance:
   print("""At %.2f level of significance, we reject the null hypotheses and accept H1. They are not independent.""" %
(significance))
else:
   print("""At %.2f level of significance, we accept the null hypotheses. They are independent.""" % (significance))

#create array of random iterations of 10,000 possible EXPECTED nest,based on proportion of area available of each type
iters = 10000
for i in range(iters):
   data_nests = pd.DataFrame(np.random.multinomial(n= 1139, pvals = [0.0698, 0.0189, 0.3815, 0.5298],size =
10000),columns = ['Dead','Drowned','Healthy', 'Unhealthy'])
```

```
pd.DataFrame.head(data_nests)
#print(data_nests)
#data_nests.to_excel('Exp_nests_nos.xlsx')


#chi squared test of independence on data from random iterations of possible nest numbers
obsx2 = np.sum((nest_arr - f_exp_arr)**2/f_exp_arr)  #observed nests count sum of sqaures
simx2v2 = (f_exp_arr - data_nests)**2/f_exp_arr
for j in range (iters):
   simx2 = np.sum((f_exp_arr - data_nests)**2/f_exp_arr) # expected nest count sum of squares

sim_more_obs = np.where(simx2 > obsx2) #how many ofthe expected tree type sum sq are greater than the observed sum squares
pr_sumChisqobs = np.divide(len(sim_more_obs),iters) # probability null hypothesis of no difference should be rejected
print(pr_sumChisqobs)

#calculate median, and upand lower 95% CI
avail_med = data_nests.median(axis = 0)
avail_quantiles =data_nests.quantile([0.025,0.975])
avail_std = pd.DataFrame.std(data_nests).round(1)
LQ_exp = [63,13,403,570]
UQ_exp = [96,31,467,636]

med_arr = avail_med.to_numpy()
med_arr = med_arr.reshape(1,-1)
meddf = pd.DataFrame(med_arr,index = ['Median'],columns = ['Dead','Drowned','Healthy','Unhealthy'])
avail_quantiles = avail_quantiles.append(meddf)
yerrs = [[16,8,30,33],[18,10,33,33]]

tabledf_tx = tabledf.T
tabledf_tx['LQ_exp'] = LQ_exp
tabledf_tx['UQ_exp'] = UQ_exp
tabledf_tx['Std'] = avail_std

#%%
#Plot
#style
sns.set_style('darkgrid')
ind = np.arange(len(nests))  #the x locations on the axes for each tree type
width = 0.35 # bar width

fig, ax = plt.subplots()
ax.set_yscale('log') # logarithmic y axis scale
ax.yaxis.set_major_formatter(matplotlib.ticker.ScalarFormatter())

plt.grid(True,which='both',axis ='y')

obsnests = ax.bar(ind - width/2, table[0], width, yerr= 0,color = 'C2',edgecolor = 'forestgreen', label = 'Observed nests')
avail_nests = ax.bar(ind + width/2, table[1], width, yerr = yerrs,capsize = 4, color = 'C5', edgecolor ='sienna', label = 'Expected nests')

#add text for title, custom x-axis tick labels, y axis
ax.set_ylabel("Frequency")
ax.set_title("Observed and Expected Nest Frequencies by Tree Health")
ax.set_xticks(ind)
ax.set_xticklabels(states)
ax.legend()

fig.tight_layout()
plt.show()
```

6.9 Attributes included in the Water source dataset from Department of Environment and Water 2006

OBJECTID
FeatureCode
SUBCODE
Region
WETLANDID
AUS_WETNR
AUS_WETNR_OLD
NAME
COMPLEX
WetlandType
WaterRegime
WetlandSystem
AusDir_no
WATERCOURSE
InternationalStatus
NationalStatus
GroundTruth
Project
CaptureSource
CaptureMethod
FeatureSource
FEATURERELDATE
ATTRIBUTERELDATE
HorizontalAccuracy
MINSCALE MAXSCALE
Shape_Length Shape_Area

6.10 Expert opinion questionnaire and response table

Questions for Experts

I've put in (a)-(e) type options but realise that my arbitrary choice of values may not be in agreement with what you think, so please mark the sliding bar below and put in a number of your own choosing if you'd prefer. Any questions for which you have no experience or opinion please leave blank, I won't mind and it won't affect the outcome.

Feel free to add notes/ change questions wording or offer an alternative more relevant question as well, any and all information will be useful for the overall picture

1. **Nesting Tree species:** How positive are you that in South Australia are *Eucalyptus camaldulensis* (Red River Gums) are the only tree used for nesting?
   a) 100%
   b) 80-99%
   c) <80%

   0% 50% 100%

2. **Nesting tree health:** What percentage of live versus dead trees do you think are used
   a) >80%
   b) 50-79%
   c) 20-49%
   d) <20%
   e) is this a preference or 'hobson's choice' for other reasons of food,water availability?

   0% 50% 100%

3. **Nesting tree proximity to water:** How close must the nesting tree be to a stable water source, either river or billabong/waterhole(m)?
   a) <10 m
   b) 10-25m
   c) 26-50m
   d) 51-100m
   e) >100m

   0.0m >100m

4. **Nesting Tree size**: What is the average diameter/width of the tree at breast height (DBH)?
   a) <0.5m
   b) 0.5 - 1.0m
   c) 1.1 – 1.5m
   d) 1.51 – 2.0m
   e) >2.0m
   f) Please suggest a value?

   0.0m 1.0m >2.0m

5. **Nesting Tree size:** What is the average height of the tree? (*Is this a more accurate measurement of tree utility as a nest site or impossible to accurately gauge so irrelevant?*)
   a) <15m
   b) 15 - 20m
   c) 20.1 – 25m
   d) 25.1 – 30m
   e) 30.1 – 40m

f) >40m

10m 25m 40m

6. **(a)Nest fidelity**: What percentage of nests are used repetitively (e.g. every year/2-3years)?
   a) <25%
   b) 25-50%
   c) 51-75%
   d) >75%

0% 50% 100%

6(b): same question for **percentage of trees** used again, even if a different hollow is used?

7. **Number of nests in same tree:** Are multiple nests only found in trees above a certain size?
   a) Yes if tree > 2.0m diam
   b) Yes if tree 1.5 – 2.0m diam
   c) Yes if tree 1.0 - 1.5m diam
   d) No, size appears unimportant, location is more relevant?
   e) No size is unimportant, no obvious reason for more than 1 nest per tree is observed

Diam BH 0.5m >2.0m

8. **Colony size:** What percentage of colonies of birds (> 4 individuals of 2 parents and offspring) are found in areas of assumed optimum location characteristics? (*live,suitable sized RRG, within 25m of water, in previously recognised suitable location*),

0% 100%

8(b) or is there no recognisable predilection for colony creation (? Familial links keep the colony going, or historically site was possibly of highly optimal characteristics but has deteriorated since?) Yes/No

9. **Proximity to mallee feeding sites:** How close are the most accepted optimal **mallee** resources for the foraging male birds?
   a) < 1km
   b) 1.0 – 5km
   c) 5 – 15km
   d) >15km

0.0km >15km

10. **Proximity to alternative suitable foraging sites:** How close are other optional food sources used instead of more distant mallee? (includes almonds and fruit orchards, unripe wheat crops, vineyards or horticultural enterprises)

0.0km 10km 20km

11. **Minimum Area of suitable individual foraging sites for breeding season:** What would be the recognised minimum total area of foraging site for Regent Parrots? Are they willing to stop at any site size from $2m^2$ or will the only forage on larger sites. (Use whatever units you prefer in a note if that is easier)

1m^2 50m^2 100m^2 200m^2(2ha)

12. Corridors connecting nesting sites to forage locations: Are there suitable vegetation corridors linking nesting sites with foraging areas? (*suitability: approx. 10-15m wide, relatively unbroken or interconnected with <100m open ground between cover?) note which you estimate would be the maximum distance between unconnected forage sites they would be willing to fly across as well if you have an opinion)*

YES/NO Distance of open ground they would fly across to food?

13. Suitable connective corridors characteristics

Relative importance	**essential**	**good**	**preferable**	**not necessary**
a) Continuity of corridors canopy cover	☐	☐	☐	☐
b) Presence of many single trees in open ground	☐	☐	☐	☐
c) At least 10m wide corridor	☐	☐	☐	☐
d) Linking large areas of good vegetation	☐	☐	☐	☐

14. Percentage of suitable foraging sites in surrounding limit of daily flight area (20km radius): What do you think is the minimum proportion of suitable forage compared to grazing or human development within the local area to make Regent Parrots choose a nesting site?

Don't know or ?

<10% 50%

100%

15. Proximity of human development: What do you think is the closest distance that birds will nest to an active human development (farm/residence/industry/tourism site)?

0.0km 5.0km 10.0km

16. Effect of human urban development compared to agricultural/horticultural environs: How detrimental to using an otherwise 'perfect' nesting site do you think human developments are, for example within 1km or 5km?

<0.5km away

No effect will not nest

1-5km away

No effect will not nest

17. Success of breeding season: Are previously successful sites more likely to be used by the Regent Parrot again if nothing has apparently changed? YES/NO

18. Locations of most apparent successful breeding: circle and/or write % success beside each if recognised

a) Wilperna	s) Ball Island
b) Isle of Man	t) Island Reach
c) Nil Nil	u) Yarra Point/Reach/View
d) Lock 6	v) Tooluka Flat
e) Gal Gal	w) Hogwash
f) Whirlpool	x) Markaranka & Markaranka Backwater/Flat

g) Congalena	y) Taylor Flat and TF west
h) Katarapko	z) Morgan Cons Park
i) Beldora	aa) North West Bend
j) Kaiser South/North	bb) H Boord Res Bend
k) Watchels Lagoon	cc) NW Bend Lagoon
l) Kingston Backwater	dd) Murbko Flat
m) Kingston Upstream	ee) McBean Pound North
n) Thurk Island	ff) Wombat Hollow
o) Chambers 1,2,3,4	gg) Portee
p) Sugarloaf	hh) Yarramundi
q) Underpass	ii) Yackto Creek and River
r) Banrock Bend	jj) Yackto Lagoon
	kk) Schillers Flat/Nigra lagoon

19. **River water level effects on choice of breeding sites:** Are nesting sites more prevalent when the RRG is within 10m of running water? (OR during drought when river levels are very low, are fewer nests in total found along the SA River Murray? And how low stops birds breeding that year?)

    Y/N ____

20. **Is there a notable pattern in changing characteristics of yearly nesting locations perceived by expert: Y/N**

    What do you think is the reason? Climate/too few breeding pairs left/ increased competition from other spp?

21. **State of the population:** Do you think the Regent Parrot population is

	Increasing	decreasing	stable?
a) In its endemic range	☐	☐	☐
b) South Australia	☐	☐	☐

22. **Causes of decline:** 0% 50.0% 100.0%

    a) Breeding Habitat loss ____________
    b) Foraging Habitat loss ____________
    c) Climate change effects ____________
    d) Tree death/removal ____________
    e) Allee effects ____________
    f) Interspecies Competition ____________
    g) Predation lizards/ferals ____________
    h) Hunting/poisoning ____________

23. **Which do you feel are the most effective Regent Parrot population protection methods?** (OR place the following protection methodologies in order of importance, starting with most effective, and give each a percentage score of efficacy)

    a) River Bank protection sites
    b) Ban on clearing of fallen RRG along riverbank to protect nest hollows
    c) Habitat protection of Mallee scrub within foraging distance
    d) Vegetation corridors from river to mallee
    e) Community involvement in recording sightings
    f) Farmer incentives to provide suitable habitat patches for foraging or corridors along fence lines

g) Feral species predator control
h) Bans on hunting/poisoning
i) Horticulturist education about the lack of damage caused by ground foraging Regent parrots and the actual benefits they may provide
j) Government control on Murray River water levels to sustain lower reaches flora and fauna
k) Other protection measures?

Expert opinion responses table

Responder position	1: tree spp positive	2 :trees live%	3 prox to water(m)	4 tree DBH	5 tree height	6 nest fidelity%	7: multiple nests and size	8: Colonies in optimum location%	9: prox to mallee (km)	10 prox to alt forage (m)	11 min plot size for forage(m^2)	12:corridor,dist open ground	13: needs for corridors	14: % forage cover local area
DEWR	80-99	50-79	<300m[a]	1.5-2	15-20	<10	Y if >1.5m	<10%, but clump pref.	5-15km	<5km	10	10-15m corr, but <300m apart ok	+ , *	?
Banrock St	80-99	>80	26-50	1.5-2	20-40+	50	Y if >1.5m	50	1-5km	<10km	10+	y	%,*,**,+	<40%
RPRT	100	15	50 but some >350m	>1m	10-40m	10	?	70	<1km depens on site	<1km	varies small to large	more navigation tool, use landmarks ,happy cross open ground	%,*,**,+	?
RPRT	100	100	90	>0.5	10-40m	75	Y >0.75m	100	<1km depens on site	<5km	varies v small ^	y	+, *	90
Landcare	100	>80	100-200	1-2m	15-40+	51-75	?	no obv prediliction	<1-15km	0-5km	?	Yes,not enough, will fly across 2km?	**,*', +	?

Corridor preferences

**	between forage,
*	>10m wide
+	continuity
%	good canopy cover

15 (m)(dist to house)	16 (m) urban develop	17: site success effect	19: river water level	20 : change in location character	21: pop numbers 1:endemic range, 2:SA	habitat loss (nesting and forage mallee)	climate change	tree death/ removal	allee effect	competition	predation	hunting
50-100	0	poss	prob???	poss human control/ but gen ecosys health	1.:stable, 2:decline	40%	10	10	25	25	10	40
100	0	y	y	n	1 stable,2 decline	30-75%	<25	<40	<40	<75	<15	<10
1500	75% avoid site if <0.5km	?	no observed effect	?	1?2, decline	50-80	75	100	?	25	10	75
0	no effect	y	y	n	1:increase,2:dec	80	??	0	?	90	5	?
1-2km	50% won't if <0.5km	y	? Validity of question	y veg change,tree health, competition spp ingress	1:dec-stable, 2. decline	50-75	60	10		75	50	75

23: protection methods and order of importance									
(1) Horticulturist educ	(2)Gov control on water level	(3)Mallee protection	(3)veg corridors	(3)farmer incentive to provide habitat					
hort	veg corridors	habt prot malle foraging	farmer incentives	Gov water control	protection vs hunting etc	Community involve	Bank protection sites	Feral spp control	ban on clearing dead trees and hunting.poison
hort	gov water control	bank protection sites	mallee habitat prot	community involve	farmer incentives				
hort	gov water control	gen community education	(a)-(f)					feral spp and ban on hunting not imp	
veg corridors	hort eductaion	farmer incentives	mallee habitat protetion	competitor spp control	cont cntrol hunting/poisoning				