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SA Arid Lands

Coolibah (*Eucalyptus coolabah* Blakely & Jacobs) of the Diamantina and Warburton River systems in north-eastern South Australia

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Natural Resources Management Board

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Cover images:

Coolibah at Goyder Lagoon waterhole April 2014; coolibah at Goyder Lagoon waterhole May 2015

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1 Background

This study is a component of a larger multidisciplinary project to; identify the biophysical processes influencing ecosystem health; sustain biodiversity; and inform environmental water requirements within the Diamantina River system in far north-east South Australia.

The project was funded by the Australian Government with the intent to *"maintain ecosystem function and increase ecosystem resilience to climate change; and increase and improve the management of biodiverse carbon stores across the country"*. The funds were awarded to the South Australian Arid Lands Natural Resources Management Board (SAAL NRM Board) and co-administered with the South Australian Department of Environment, Water and Natural Resources (DEWNR)

Evidence of detailed autecological studies of Australian floodplain perennial species of arid zone environments is limited in the literature. There have been two studies of *Eucalyptus coolabah* in the far north-east of South Australia. The first examined the basic demography of *Eucalyptus coolabah* in the lower reaches of the Cooper near the Birdsville track. The second examined the water sources accessed by *Eucalyptus coolabah* at sites on the floodplain of the Diamantina and Neales Rivers. Both authors refer to the dearth of knowledge regarding the ecology of this species (Costelloe et al., 2008, Roberts, 1993).

2 Coolibah - Keystone species

This autecological report forms an adjunct to the related synecological report of the riparian vegetation communities of the study region (Gillen 2017). Findings from that study, in relation to the role Coolibah plays in the structure and functioning of the plant community, serve as a fitting introduction to this report, summarising the significance of the species in the Diamantina/Warburton River system;

> *"The riverine corridor of the Diamantina represents a significant mesic zone of transition or ecotone between the aquatic and proximal more xeric vegetation communities associated with river channel and lateral floodplains respectively. Ecologically ecotones are generally considered to be zones of high biodiversity driven, in the instance of the Diamantina River, by the bilateral flow of nutrients and water between channel and floodplain. Regular flood pulses down the river channel sustain the vegetated corridor concomitantly recharging local groundwater systems, where possible, upon which the long lived Coolibahs depend for moisture during natural periods of drought. During times of major floods, driven by monsoonal and La Nina influences high in the Queensland catchment, floodwaters break free of the channel confine, flowing through the ecotonal Coolibah corridor and out across adjacent floodplains transporting and depositing debris, seeds and associated nutrients. As the floodwaters draw down over time and recede back into the channel, nutrients, resulting from the biological pulse of activity across the floodplains are drawn back into the channel recharging the associated trophic systems of the aquatic ecosystem.*
>
> *The regularity and hence reliability of the hydrological regime of the Diamantina is the main driver of the persistence of Coolibah riverine woodlands and the broader albeit sparser distribution of the species across the associated floodplain landscape. The dominance of Coolibah has a major role in contributing to and supporting the biodiversity of the system and as such could be viewed as a keystone species influencing directly and indirectly biotic and abiotic processes supporting a broad range of associated taxa. Disrupting the naturally functioning hydrological regime by major, upstream, water extractions, irrigation activities, diversions or off stream storage, would have major detrimental ramifications for Coolibah which would cascade through associated and dependent trophic levels.*
>
> *The recruitment of Coolibah, a long-lived perennial, is very dependent upon major, uncommon extensive flood events. Coolibah seed is dispersed widely during these events both longitudinally down the system and laterally across the adjacent floodplain. These extreme and uncommon flood events are strongly correlated with a clustered sequence of 'flood years' driven by the La Nina cycle of the ENSO system. The sequence of wet years flooding the region and saturating the soil profile facilitates the dispersal, germination, establishment and persistence of new cohorts of Coolibah.*
>
> *Once established, mature Coolibah ameliorate climatic and soil conditions immediately below their canopies (Figure 1) It has been established for a number of Australian phreatophytes, including Eucalypt species, exhibiting dimorphic root structure that tap roots via, a process of hydraulic lift, bring groundwater at depth to the upper soil profile making moisture available to the lateral root system (Brooksbank et al., 2011, Dawson and Pate, 1996, Holland et al., 2006, McLean, 2014, Stephen et al., 1998). So potentially for the phreatophytic Coolibah, tapping into groundwater at depth and via hydraulic lift during dry conditions, the tree could raise moisture to the upper soil profile where it would become accessible not only to its shallower lateral root system but also provide moisture and associated nutrients to a range of soil biota and other plant species. This potential mechanism of hydraulic lift in relation to Coolibah needs to be verified. Coolibah thus serves as a facilitator providing ameliorated climatic and suitable abiotic and biotic conditions and thus extending habitat for a range of taxa in an otherwise harsh and stressful environment."*

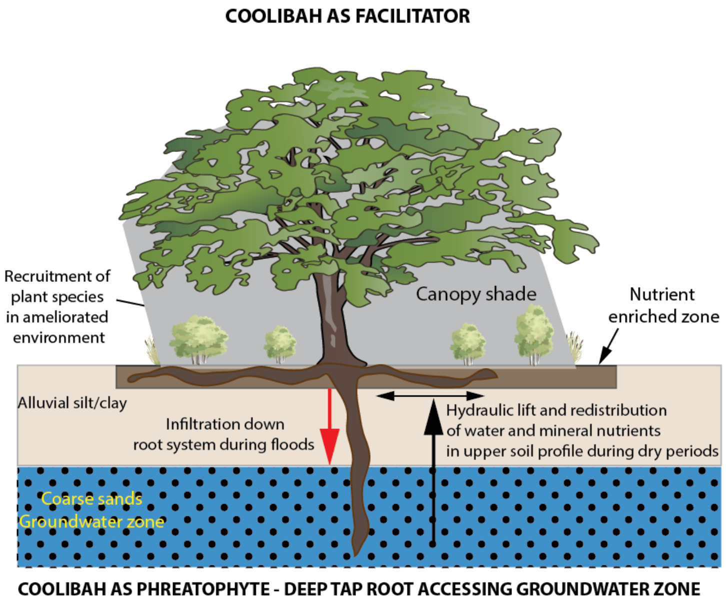


Figure 1 Coolibah as a keystone species; facilitator; and bioengineer

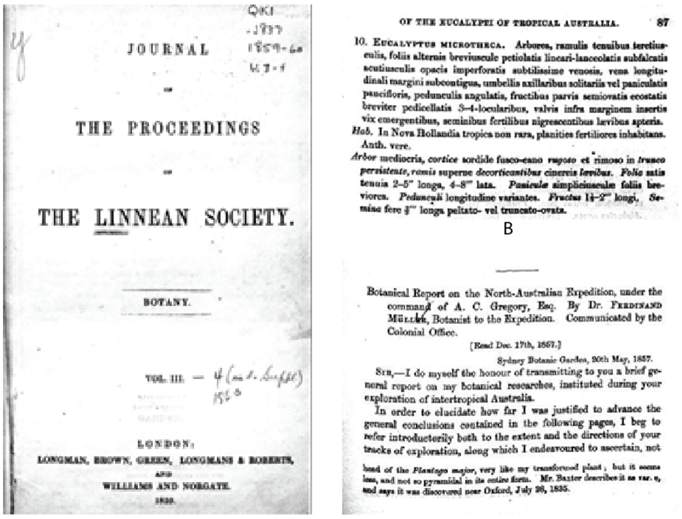
3 Taxonomic history

The genus *Eucalyptus* includes approximately 900 species and subspecies (Brooker and Kleinig, 2004). As a genus it is ubiquitously spread across a wide range of environments and climatic conditions throughout Australia.

3.1 *Eucalyptus microtheca* vs *Eucalyptus coolabah*

As so very aptly and succinctly stated *"There is still much confusion as to the correct name of the iconic Coolabah"* (sic) (Wrigley and Fagg, 2012). The confusion lies in the compounded problem over time of variation in both scientific and common nomenclature when dealing with the species.

During the North Australian Expedition, 1855-56, under the command of A C Gregory, the expedition's botanist, Ferdinand von Mueller, collected a specimen of a eucalypt from the Victoria River in the Northern Territory. Subsequently Mueller officially described and named what became the type specimen of *Eucalyptus microtheca* F.Muell, (Figure 2). *Eucalyptus* is a combination of the Greek, *'eu'* = well and '*kalyptos*' = 'covered' referring to the cap (operculum; can be single or double) covering the floral buds; *microtheca,* again a combination of the Greek, '*micro*' = small and '*theke*' = container; referring to the small fruit of the species, amongst the smallest in the genus. (Wrigley and Fagg, 2012)



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OF
THE LINNEAN SOCIETY.

BOTANY.

VOL. III.

LONDON:
LONGMAN, BROWN, GREEN, LONGMANS & ROBERTS,
AND
WILLIAMS AND NORGATE.
1859.

OF THE EUCALYPTI OF TROPICAL AUSTRALIA. 87

10. Eucalyptus microtheca. Arborea, ramulis tenuibus teretiusculis, foliis alternis breviuscule petiolatis lineari-lanceolatis subfalcatis acutiusculis opacis imperforatis subtilissime venosis, vena longitudinali margini subcontigua, umbellis axillaribus solitariis vel paniculatis paucifloris, pedunculis angulatis, fructibus parvis semiovatis ecostatis breviter pedicellatis 3–4-locularibus, valvis infra marginem insertis vix emergentibus, seminibus fertilibus nigrescentibus lævibus apteris.
Hab. In Nova Hollandia tropica non rara, planities fertiliores inhabitans. Anth. vere.
Arbor mediocris, *cortice* sordide fusco-cano *rugoso* et rimoso in *trunco persistente, ramis* superne *decorticantibus cinereis lævibus. Folia* satis tenuia 2–5" longa, 4–8‴ lata. *Paniculæ* simpliciusculæ foliis breviores. *Pedunculi* longitudine variantes. *Fructus* 1½–2‴ longi. *Semina* fere ½‴ longa peltato- vel truncato-ovata.

B

Botanical Report on the North-Australian Expedition, under the command of A. C. Gregory, Esq. By Dr. Ferdinand Müller, Botanist to the Expedition. Communicated by the Colonial Office.

[Read Dec. 17th, 1857.]

Sydney Botanic Garden, 20th May, 1857.

Sir,—I do myself the honour of transmitting to you a brief general report on my botanical researches, instituted during your exploration of intertropical Australia.

In order to elucidate how far I was justified to advance the general conclusions contained in the following pages, I beg to refer introductorily both to the extent and the directions of your tracks of exploration, along which I endeavoured to ascertain, not

head of the *Plantago major*, very like my transformed plant; but it seems less, and not so pyramidal in its entire form. Mr. Baxter describes it as var. ε, and says it was discovered near Oxford, July 26, 1835.

A

C

Figure 2 Ferdinand von Mueller's description of *Eucalyptus microtheca*

In his published *Eucalyptographia*, Mueller provides the following aboriginal names for the species;

> :"…its aboriginal name in the Riverina is "Tangoon", on the Murchison-River "Callaille" and "Yathoo"; in Western Queensland the name, given by the autochthones to this tree, is "Coolybah".(Mueller, 1879-84)

Mueller further describes the distribution of the species as following;

> "From the vicinity of the Murchison-River northward as far as Cambridge-Gulf and the lower Victoria River, widely though not gregariously distributed through the interior of Australia, reaching the Darling and Lachlan Rivers southward and the Flinders-River north-eastward (F. v. M.), occurring in Dampier's Archipelagus (*Gazelle*-expedition), occupying as well hilly as flat ground and even dry sandy places". (ibid)

Unbeknown to Mueller at the time was that his classification comprising a single species across a very broad geographic distribution included a group of closely related taxa (referred to later as the Coolibah or 'microtheca group'), subsequently split into separate species and associated varieties and sub-species. This taxonomic separation commenced in 1934 with the first comprehensive revision of the *Eucalyptus* by W F Blakely who recognised that Mueller's previous '*E. microtheca*' was restricted to the far north of the continent and the previous suspected southern distribution of the species was in fact a separate but closely related new species *Eucalyptus coolabah* Blakely and Jacobs, sp. nov. [species nova = new species]. Blakely described the difference between the old and new species as follows;

> "It differs from *E. coolabah* mainly in the smaller buds, more turbinate fruits [shape of an inverted cone] with their relatively smaller and shorter valves, in the persistent Box-like bark throughout, in contradistinction to that of *E. coolabah* which is a half-barked species…" (Blakely, 1934) (Figure 4)

The new species was aptly named from a type specimen from the Bogan River, near the small township of Coolabah in western New South Wales. (Slee et al., 2006)

Blakely further recognised the variation in *Eucalyptus coolabah* through the creation of two additional varieties; *E. coolabah* var. *arida* ("aparra", Type specimen from the Cooper Creek. Kopperamanna, South Australia) and *E. coolabah* var. *rhodoclada* ("red-branched Coolabah") (ibid)

In a further revision of *Eucalyptus coolabah*, Hill and Johnson (1990) considered *E. coolabah* var. *rhodoclada* to be a separate species (included within *E. victrix*) and distinguished the following three subspecies;

- *Eucalyptus coolabah* subsp. *coolabah*
- *E. coolabah* subsp. *arida;* and a new subspecies
- *E coolabah* subsp. *excerata*

Figure 3 shows the distribution of these three subspecies and recognises the intergrades present between the subspecies particularly at their margins of distribution.

As can be seen from Figure 3, *E. coolabah* subsp. *arida* is the dominant subspecies to be found in the Diamantina study region in South Australia. The type specimen for the subspecies was collected from Kopperamanna on the Cooper Creek by Herbert Basedow, 17 November 1919 (Hill and Johnson, 1994). In their review of the Coolibah group, Hill and Johnson described the group as being "*ecologically highly specialised, all taxa occurring in habitats that are seasonally wetter than the surrounding country*"; and state that the group is "*one of the widest-ranging eucalypt groups in Australia*…."(ibid). The authors also clarify, that due to the original spelling and use of 'coolabah' in the original description by Blakely, that this spelling has been retained conventionally for the scientific epithet even though the spelling 'Coolibah' has now been adopted for common nomenclature.

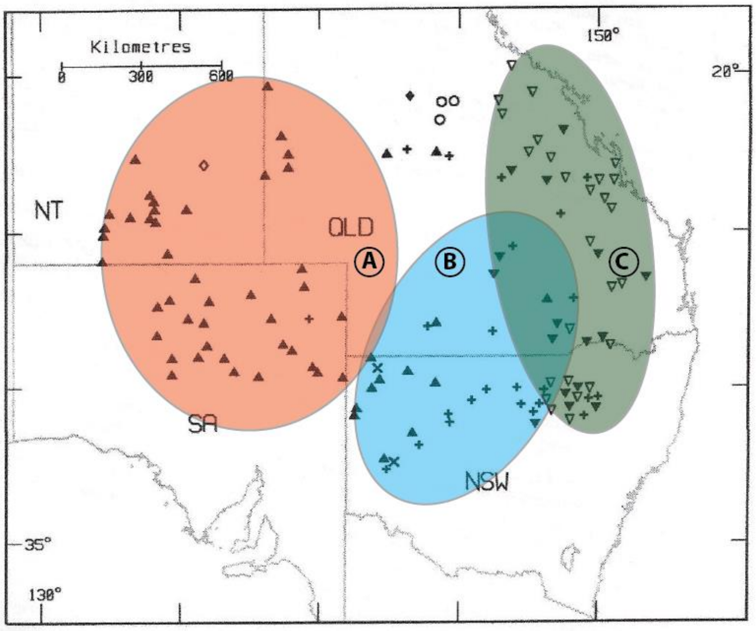


Fig. 12. Distribution of *E. coolabah* subsp. *coolabah* (plus), subsp. *excerata* (inverted open triangle), subsp. *arida* (triangle), subspp. *arida–excerata* intergrades (circle), subspp. *coolabah–excerata* intergrades (inverted solid triangle), subspp. *arida–coolabah* intergrades (cross), *E. coolabah* subsp. *arida–E. victrix* intergrades (open diamond), *E. coolabah* subsp. *arida–E. microtheca* intergrades (solid diamond).

Ⓐ Predominantly *E. coolabah* subsp. *arida*
Ⓑ Predominantly *E. coolabah* subsp. *coolabah*
Ⓒ Predominantly *E. coolabah* subsp. *excerata*

Figure 3 Distribution of *Eucalyptus coolabah* subspecies: (Hill and Johnson, 1994)

Pryor and Johnson (1971) in their classification of the eucalypts developed the following hierarchy in their division of the genus *Eucalyptus* down to the level of subspecies, namely; subgenus, section, series, subseries, superspecies, species and subspecies. At the level of subgenus, the two major subgenera of the eight proposed by Pryor and Johnson (ibid) namely *Monocalyptus* (species with one operculum) and *Symphomyrtus* (species with two opercula) dominate in terms of numbers of species. As a species *Eucalyptus coolabah* is included within *Symphomyrtus*.

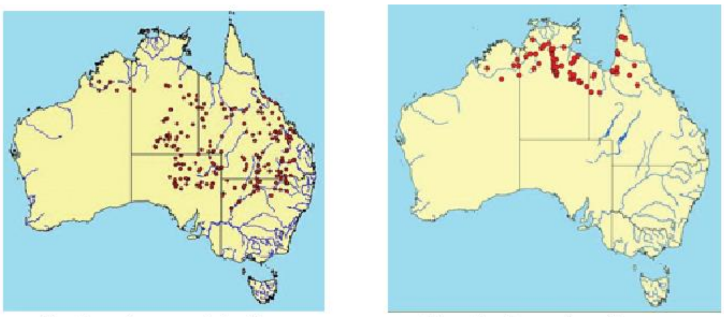
More recently the standard reference to the eucalypts, *EUCLID: Eucalypts of Australia* states;

> *"In the classification of Brooker (2000) [who identified 13 subgenera] Eucalyptus coolabah belongs in Eucalyptus subgenus Symphomyrtus section Adnataria (the boxes) because the buds have two opercula, ovules are in four rows, seeds are flattened-ovoid, cotyledons are reniform, and anthers are rigid on the staminal filaments. Within section Adnataria, E. coolabah belongs to a subgroup of box species with mostly tropical distribution, series Aquilonares subseries Protrusae, having inflorescences terminal on the branchlets, adult leaves very densely reticulate and fruit that are small, fragile and mostly have exserted valves. The number of species in this taxonomic series is contentious" (Slee et al., 2006)*

This somewhat tortuous time travel through the taxonomic development and history of the Coolibah taxonomic group serves to clarify why the nomenclature encountered in the literature can be so confusing. For many years following Blakely's description of *Eucalyptus coolabah* in 1934 the binomial *Eucalyptus microtheca* continued to be broadly used.

To further emphasize the taxonomic uncertainty referred to by Slee et al above, within South Australia, even though the majority of herbarium specimens are currently recognised as *E. coolabah* subsp. *arida,* Nicolle (2013) states;

> *"Through extensive field observations, I have found the characters that these authors [Johnson & Hill, 1990] used to distinguish the subspecies to be highly variable and often environmentally-determined. Therefore, these subspecies of E. coolabah are not recognised here. [Native Eucalypts of South Australia]"*

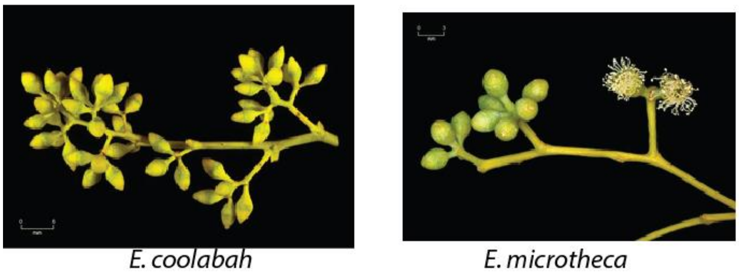


Euclayptus coolabah Distribution

Eucalyptus microtheca Distribution

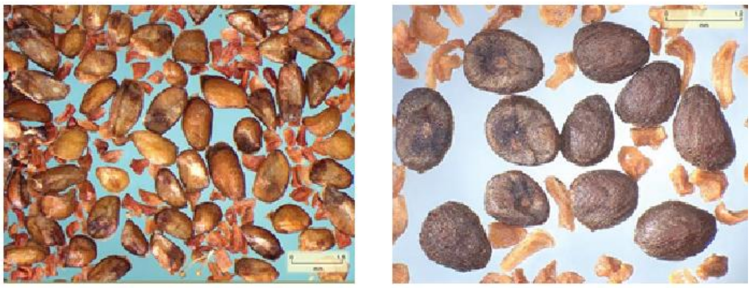
E. coolabah Fruit

E. microtheca Fruit



E. coolabah Buds

E. microtheca Buds



E. coolabah Seed

E. microtheca Seed

Figure 4 Comparison of *Eucalyptus coolabah* with *E. microtheca* (Slee et al., 2006)

Belonging to *Eucalyptus*, subgenus *Symphomyrtus*, section *Adnataria*, includes Coolibah in what is colloquially referred to as the “Box Group” of Eucalypts. According to Boland et al;

> *“The name ‘box’ was applied by the early settlers who saw a resemblance between the hard, interlocked timber of the European box (Buxus sempervirens L.) and that of grey box (Eucalyptus moluccana).” (1984 (4th edn))*

The term “Box” now relates to the nature of the physical appearance of the bark of this group of trees; generally the bark is rough, composed of short tightly held fibres, often presenting as flaky or tessellated in appearance. The appearance of bark varies considerably (Figure 5).

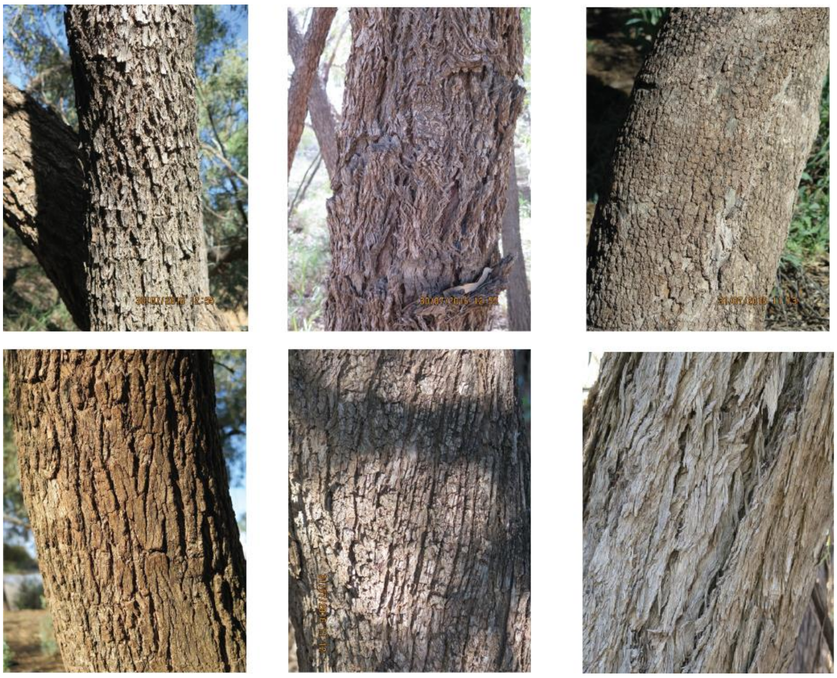


Figure 5 Variation in Bark of E. *coolabah* in Diamantina study area

4 Coolibah characteristics

The majority of *Eucalyptus* species in Australia belong to two sub-genera; *Symphomyrtus* (approximately 370 species) and *Monocalyptus* (approx. 120 species). As stated earlier *Eucalyptus coolabah*, Coolibah, is included in the *Symphomyrtus*. Noble (1989) in his review of the ecological traits of these two sub-genera hypothesized that members of *Symphomyrtus* possessed characteristics that would seem to render them more adapted to the habitats of arid dryland river systems than those of *Monocalyptus*. These stated characteristics included *inter alia;* greater flood or waterlogging tolerance; greater salinity tolerance; greater ability to exert stomatal control; faster seed germination; and more rapid growth rates in the seedling stage. In support of this argument; namely an increased capacity of the sub-genus to cope with harsher states of stress, Noble also referred to the observation of Florence (1981)who found that *Symphomyrtus* species extended further into the drier areas of Australia than *Monocalyptus*.

As a species, Coolibah expresses a great degree of intra-specific variation genetically across its wide range of distribution influencing both physiology and physiognomy and resulting plasticity in growth forms. Hence the morphology of the tree reveals significant variability according to the nature of the environment in which it grows. Examples of this morphologically variability within the study area are depicted in Figure 6; the more typical form encountered across the xeric floodplains being more compact in form in stark contrast to the massive form exhibited growing in mesic conditions along the Diamantina Channel.

Figure 6 Left, Coolibah, D Split Waterhole; Right, Coolibah, Cooper Creek crossing Birdsville Track

Coolibah as a typical phreatophyte; a drought avoiding perennial; exhibits the typical dimorphic root structure (Figure 7) characteristic of this group of arid-zone tree species (Dawson and Pate, 1996, O'Grady et al., 2006a, O'Grady et al., 2006b, Whitehead and Beadle, 2004, Jones et al., 1997). The tree possesses the ability, as do many other eucalypts, to rapidly extend a tap root from seedling stage, directly seeking more reliable sources of soil moisture upon which to draw and support establishment and persistence of the individual. For a phreatophyte this deep rooting ability to tap into groundwater at depth is crucial in supporting and maintaining physiologic functioning through extended periods of drought (Costelloe et al., 2008, Doody et al., 2009, Holland et al., 2006). In addition, the trees exhibit an extensive, widely spreading lateral root system which can quickly respond to local periods of rainfall of minor inundation events from flooding, drawing upon moisture in the upper levels of the soil profile.

Figure 7 Coolibah root structure; in vicinity of Yammakirra Waterhole

The leaves of Coolibah are typically characteristic of eucalypts in general being; sclerophyllous in presentation; falcate or lanceolate in shape in adult leaf form; hanging pendulously, almost vertically to minimize effect of direct sunlight and maximize efficient water use by protecting leaf stomata as much as possible. Coolibah leaves develop through several stages following germination (heterophylly) expressing subtly differing form, shape, size and colour as they develop and progress from seedling, through juvenile, intermediate and adult stages of leaf form.

Another distinguishing characteristic feature of *Eucalyptus coolabah* is that whilst its trunk is rough-barked its upper branches are smooth and whitish whereas for similar appearing species such as *E. microtheca* and *E. largiflorens*, rough bark persists on their upper branches (Brooker and Kleinig, 2004, Nicolle, 2013, Slee et al., 2006).

4.1 Uses

In contrast to original indigenous peoples who lives were integral with the life history of Coolibah (see Ethnography Section) , European settlers found it initially challenging to find a use for this unique tree. Maiden (1889) reporting in "*The useful native plants of Australia: including Tasmania*", was most disparaging or perhaps lacking in vision when stating that "*it is neither very much used or valued*". However from this initial lowly pessimistic view of the potential of the species, appreciation and associated utilization did naturally develop.

Blakely (1934) considered the timber to be "very hard and durable both in and out of the ground, it also makes good fuel". The actual density of the timber is impressive being claimed to be around 1150 kg/m3 (Boland et al., 1984 (4th edn)). Ultimately the sheer strength and durability of the timber was recognized broadly by those living within landscapes dominated by the species who found it most useful for the construction of exceptionally durable fences and yards (Figure 8). The more innovative bush improvisers amongst them managed to fashion a wide range of products that required strength and durability including;

bearings, bushings, bolts, shafts, frames and wheels parts for heavy vehicles (Little, 1983).

Figure 8 Pastoral industry uses of Coolibah

Such is the contemporary fame and iconic significance of this species that a quantity of Coolibah timber was recently incorporated into the fabric of a ceremonial horse drawn coach for Queen Elizabeth II (Greg Campbell, Managing Director, S. Kidman and Co, pers. Comm. 2016)

As is often the case with Australian plant species the potential of Coolibah for a variety of purposes has been recognized in a number of other countries. Due to its tolerance of salt, flood, drought and extreme temperatures, it is used across a range of environmental situations in projects of land reclamation and restoration, production of fuel wood and pulpwood, and is being investigated as a potential source of anti-microbials and antioxidants (Deans, 2002). The species is currently extensively exploited in a range of middle eastern and African countries including; Sudan, Kenya, Tanzania, Nigeria, Egypt, Pakistan, Iraq and Iran (Anekonda et al., 1999, Callaghan et al., 1989, Ghaffar et al., 2015, Johansson and Tuomela, 1996, Li, 1998, Li, 1999b, Li, 1999a, Maghsoodlou et al., 2015, Marcar et al., 1995, Morabito et al., 1996)

5 Genetics

5.1 Introduction

> *"Effective in-situ gene-pool conservation will depend on understanding the patterns and distribution of genetic variation, breeding systems, the impact of inbreeding, gene flow, and the nature of selective forces acting upon populations." (Potts and Wiltshire, 1997)*

> *"The extent and distribution of genetic variation within a species are of fundamental importance to its evolutionary potential and determine its chances of survival. Assessments of genetic variation are therefore of key importance to the development of effective conservation strategies." (Newton et al., 1999)*

Australia's Biodiversity Conservation Strategy 2010-2030, defines Biodiversity very succinctly as "*the variety of all life forms*" comprising three levels;

genetic diversity – the variety of genetic information contained in individual plants, animals and micro-organisms

species diversity – the variety of species

ecosystem diversity – the variety of habitats, ecological communities and ecological processes.

As depicted in Figure 9, genetics operating at the most basic level of ecosystem structure, composition and function, underlies the variability of species, populations and ecosystems (Balkenhol et al., 2016).

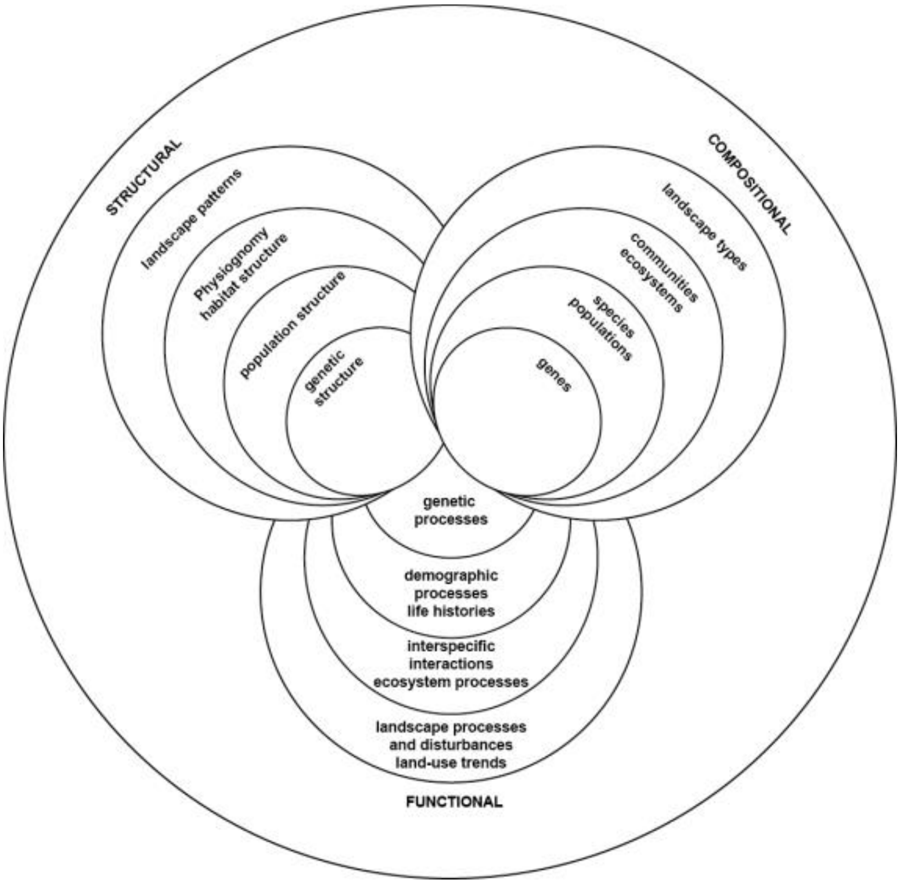


Figure 9 Levels of biodiversity; adapted from Noss (1990)

Coolibah as a species plays a highly significant role in directly influencing ecosystem structure, composition and function of the riparian community of the Diamantina/Warburton River system (Gillen, 2017). In this capacity Coolibah is performing as a keystone species, a biodiversity indicator and a potentially valuable surrogate for monitoring the biodiversity health of the river system. In light of its keystone role and the above statement by Newton et al., it is sensible to assess the nature and status of genetic variation of Coolibah across its range.

Genetic variability is critical for the ability of a species to adapt to environmental change particularly in light of the potential impact of climate change upon the hydrological regimes of the Diamantina system in the future. It has been suggested that genotypic diversity may enhance ecosystem resilience in response to environmental disturbance or stress. (Reusch et al., 2005)

> *"Genetic diversity defines the evolutionary potential of species and is consequently of prime importance for the long-term preservation of biodiversity in changing environments." (Gugerli et al., 2008)*

The genetic variability of a species such as Coolibah can be expressed as variation in the nucleotides, genes, chromosomes or genomes at the level of individual or population across its range at a particular point in time. The genetic variability of the species is driven by processes of mutation, selection, gene flow and drift influenced by landscape attributes and functions.

Understanding the genetic variability of Coolibah, across the range of the species, provides an insight into the intertwined nature of ecological and evolutionary processes that have and continue to determine the current state of population genetic dynamics.

5.2 Methodology

2015 Sampling Program

In collaboration with colleagues at the Research School of Biology, Australian National University, survey methodology and protocols were developed for the collection and in-field storage of samples for the two phases of field work; Phase 1 - 2015 and Phase 2 - 2016. Phase 2 was developed in response to the findings from Phase 1.

Phase 1: Aims included;

- insight into the structure of genetic variability of Coolibah across multiple river catchments within the Lake Eyre Basin; and
- insight into the nature of genetic variability down the Diamantina/Warburton system.

The distribution of samples sites is depicted in Figure 11. Samples from the Finke River were provided by Dr Justin Costelloe. Samples from the Mulligan River, Eyre Creek and Field River were collected during a botanical survey of a portion of the Simpson Desert in July 2015; these samples were not included in subsequent DNA Analysis. The remainder of samples were collected during April-May 2015. Samples consisted of mature Coolibah leaves from mature individuals. One to two leaves were collected from each tree and stored in a permeable paper bag with silica gel to facilitate drying and reduce the potential development of mould. For all sites on the Diamantina/Warburton system, where possible, leaves were collected from 30 trees located along the river channel (mesic environment) and from 30 trees on the periphery of the adjacent floodplain (xeric environment); resulting in a total of 60 samples at each waterhole. From all other river systems sampled leaf material was collected from 30 individuals along the river channel. Whilst collecting leaves from individual trees, in all cases every attempt was made to leave at least 30 metres between trees to reduce the potential of sampling closely related individuals.

All leaf samples have been lodged with the Ecogenomics and Bioinformatics Lab (EBL), Australian National University (ANU). The cost of analysing all samples collected being prohibitively high, a subset of 90 samples, from trees located only along river channels, was selected for analysis which comprised the following;

- Diamantina/Warburton River system
    - Tinnie Landing Waterhole (WH) - 30 samples
    - Yelpawaralinna WH - 5 samples
    - Goyder Lagoon - 5 samples
    - Tepamimi WH - 5 samples

    - Andrewilla WH - 5 samples
    - Yammakirra WH - 5 samples
    - Double Bluff WH - 5 samples
- Cooper Creek - 5 samples
- Bulloo River - 5 samples
- Paroo River - 5 samples
- Warrego River - 5 samples
- Darling River - 5 samples

DNA from all 90 samples was extracted by the Ecogenomics and Bioinformatics Lab (EBL) at ANU. The resulting material was genotyped for approximately 20,000 Single-Nucleotide-Polymorphisms (SNP's) using Genotyping-by Sequencing (GBS; see (Elshire et al., 2011) for greater detail), a method of reduced representation genome sequencing for simultaneous discovery and genotyping of SNP's (Pers. Comm., Niccy Aitken, EBL, ANU). The large amount of resulting sequence data obtained was then analysed to obtain informative SNP's which were subsequently included in a multivariate classification analysis to determine relatedness among individuals and geographic sites.

Results

The resulting dendrogram (Figure 10), provides an preliminary indication of the structuring of genetic variability of the Coolibah population both across the rivers of the Lake Eyre Basin and down the Diamantina/Warburton river system. Group 2 broadly includes samples from all rivers excluding the Diamantina/Warburton system. Groups 1 and 3 broadly represent the genetic variability of Coolibah down the length of the Diamantina/Warburton system. Group 1 is comprised of all samples from the most southern site on the Warburton system, Tinnie Landing Waterhole. Group 2 broadly includes the remaining samples from all Diamantina/Warburton River sites. However, within Groups 2 and 3 there is a slight mixing of a few samples between the groups.

Hence, the analysis whilst roughly presenting a broad geographic structuring in genetic variability also reveals a strong clustering at a local level, representing closely genetically related individuals which suggest other factors influencing the genetic variability across all samples analysed. Interestingly the lone single member 'group' to the far upper left (circled) of the dendrogram represents a sample collected from the Darling River at Bourke, New South Wales. The most probable explanation for this outlier is that it was mistakenly collected from a sympatric species, *Eucalyptus largiflorens*, which closely resembles *E. coolabah* in the field in the Murray Darling Basin.

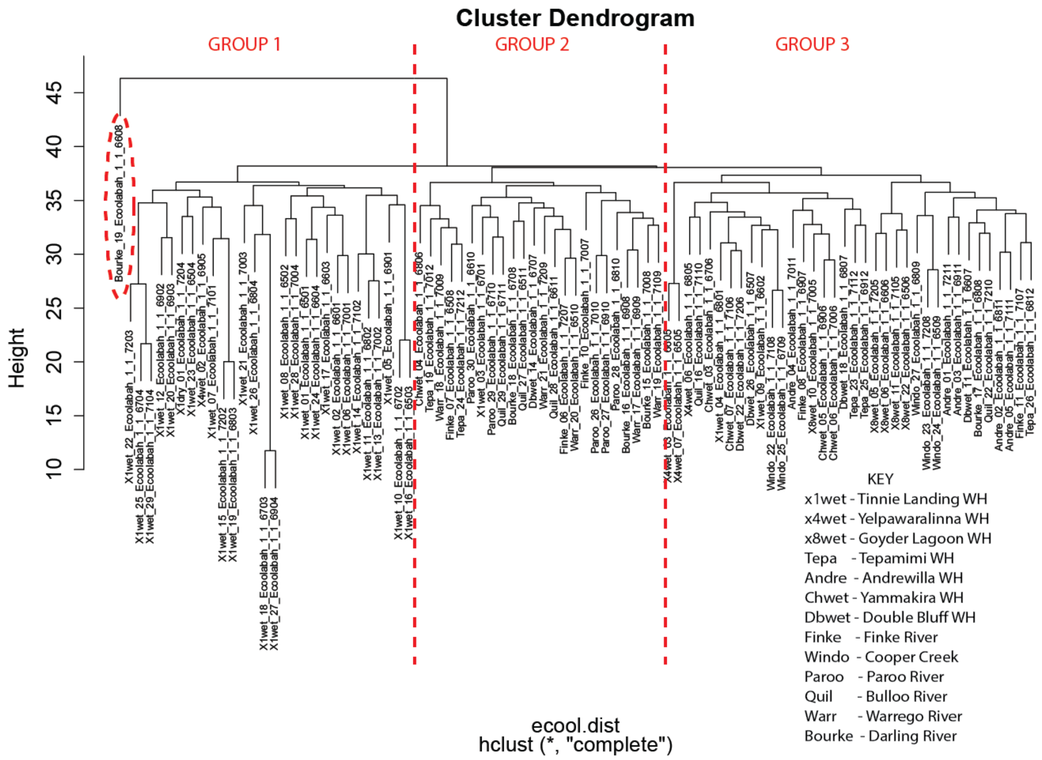


Figure 10 Dendrogram depicting relatedness between individuals and sites

2016 Sampling Program

The results from Phase 1 determined the design of Phase 2 which aimed to investigate in greater detail a range of potential additional factors influencing genomes at a local level and more broadly within the region.

The intent was as follows;

- Diamantina/Warburton System
    - investigate the potential influence of environmental gradients upon genetic composition and variability within the system.
    - investigate at the local site level the genetic composition and relatedness between differently aged cohorts.
- Cooper Creek River system
    - investigate the level of genetic relatedness between Coolibah populations representing two river systems of relatively close geographic proximity (the Cooper and Diamantina systems)
    - investigate the level of genetic relatedness between differently aged and flood related cohorts of Coolibah.

5.3 Sampling design Diamantina/Warburton River System

As Figure 11 shows, six sites were selected for sampling, three representing the far north of the system; Double Bluff, D Split and Andrewilla Waterholes in the north; and three in the far south; Cowarie crossing, Mia Mia and Tinnie Landing. It would be expected at this broader regional level that the northern population, receiving more regular flooding pulses would differ genetically from the southern population which experiences less regular flooding and potentially increased saline conditions. It would also be expected that the geographically extended virtually monospecific lignum (*Duma florulenta*) swamp (Goyder's Lagoon) that separates the northern and southern populations would impede gene flow further reinforcing genetic separation. Goyder's Lagoon represents a major zone of transition between the Diamantina River to the north and Warburton River to the south. The swamp is virtually devoid of Coolibah trees, in contrast to the heavily wooded Coolibah riverine corridors that mark the passage of both Diamantina and Warburton Rivers.

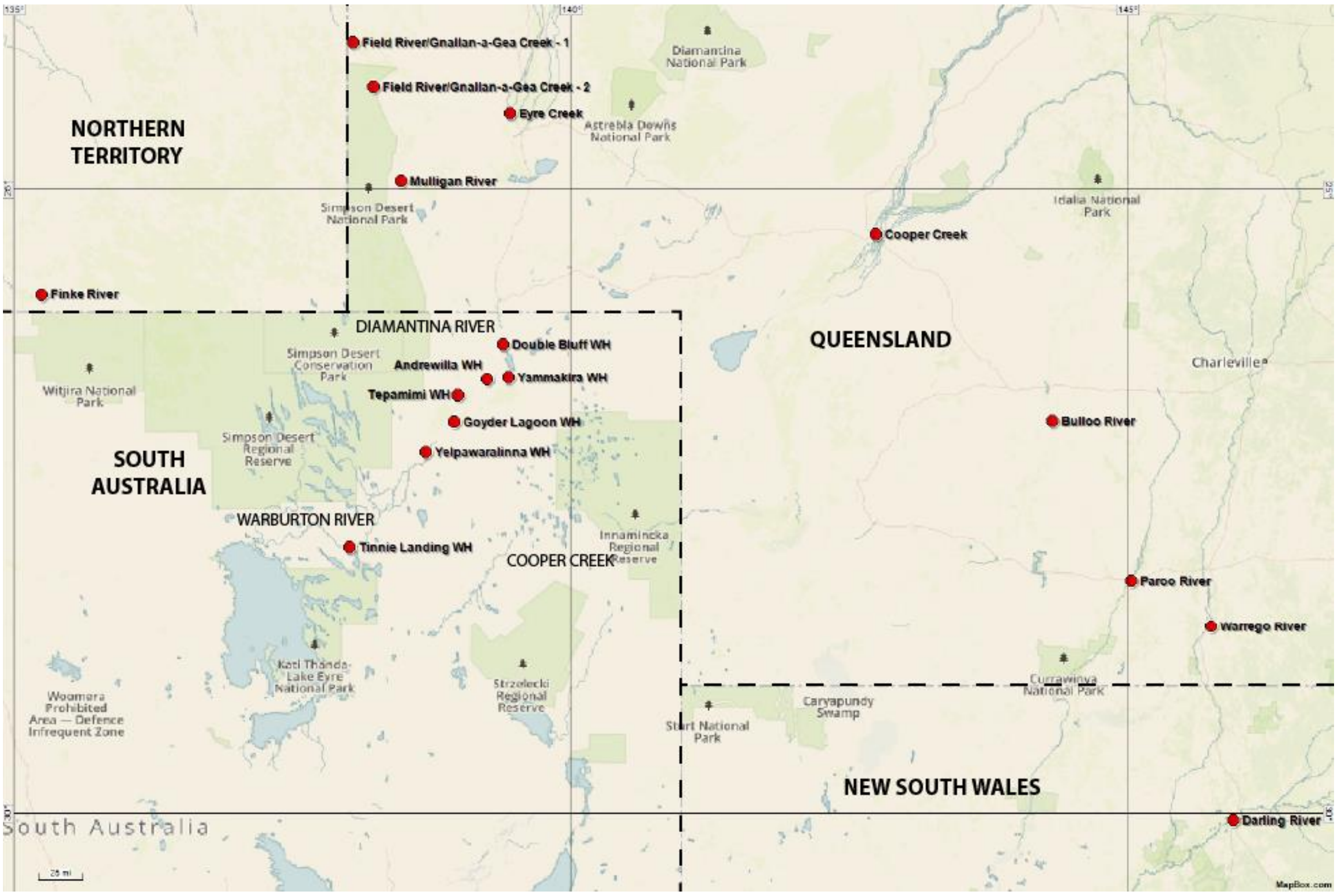


Figure 11 Location of leaf sampling sites during 2015

The sampling structure adopted at the local level of each site is depicted in Figure 12. A total of 60 individuals was sampled at each of the six sites; 30 individuals from each of the identified mesic (river channel bank) and xeric (adjacent floodplain) communities representing a lateral gradient of increasing water stress. To investigate genetic relatedness between differently aged individuals the 30 individuals in each of the mesic and xeric communities were further sub-divided into two classes, 'large' and 'small', based on trunk girth as a surrogate for age as shown in Figure 12.

Figure 12 Example of sampling structure at site level; Cowarie Crossing 2016

5.4 Sampling design Cooper Creek System

Samples were collected from mature individuals at the six sites depicted in Figure 13, namely;

- Group A
  - Lake Apanburra – Northwest branch, Cooper Creek – 15 samples
  - Hamilton Creek – Northwest branch, Cooper Creek – 15 samples
  - Christmas Creek – Northwest branch, Cooper Creek – 30 samples
  - Narie Waterhole – Main branch, Cooper Creek – 30 samples
  - Cooper Creek Crossing – Main branch, Cooper Creek – 30 samples
- Group B
  - Coongie Lakes District site – 3 x 15 samples

Group A samples were collected with the intent of investigating the relatedness of Coolibah populations from two river systems in relatively close geographical proximity. During the extreme flooding events of the 1970's satellite images revealed how proximate the flood waters of the Diamantina and Cooper were in the vicinity of Lake Apanburra and Christmas Creek. The samples associated with the Coongie Lakes District site, Group B, were collected opportunistically en route to Lake Apanburra. At this site there was clear evidence of three cohorts of Coolibah of markedly differing ages. Each of these cohorts was clearly associated with separate flooding events. Samples were collected to determine the genetic relatedness or otherwise of the cohorts.

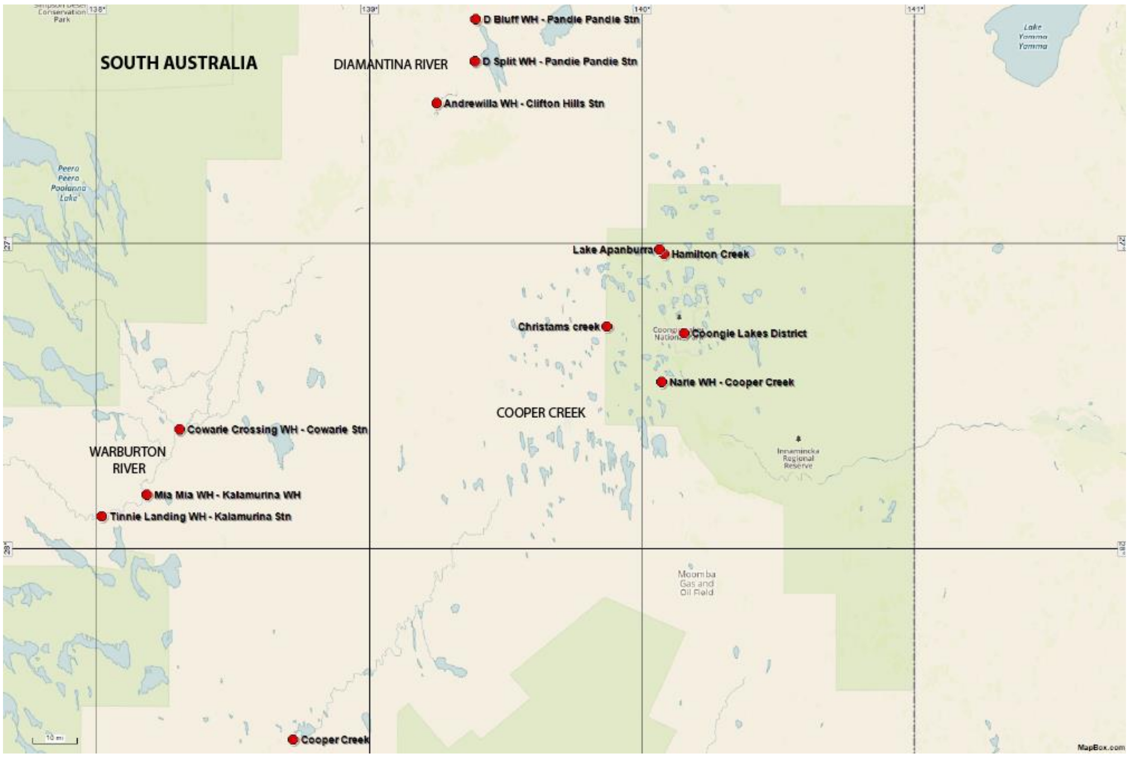


Figure 13 Location of sampling sites during 2016

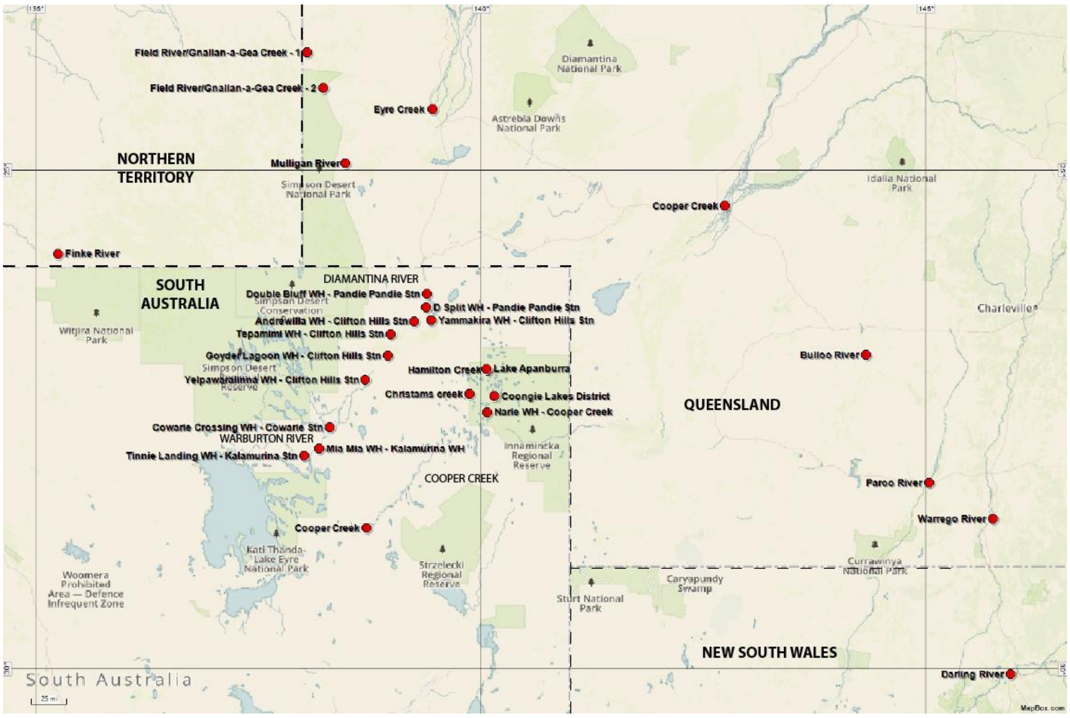


Figure 14 All sampling sites, 2015-16

All samples collected during Phase 2 have been lodged with the Ecogenomics and Bioinformatics Lab (EBL) at ANU. DNA has recently been extracted from all samples from all sites however due to current demands within ANU the sequencing and multivariate classification of all samples has been delayed.

5.5 Discussion

> *"There is strong circumstantial evidence that gene flow in eucalyptus is more a function of pollen than of seed dispersal." (Potts and Wiltshire, 1997)*
>
> *"Seed dispersal in the genus appears to be extremely limited." (ibid)*

Throughout the study area clusters of a variety of Coolibah cohorts can be distinguished marking the outer edge of previous floods which have extended to varying degrees across the adjacent floodplain. Most conspicuous, as the ^{14}C dating potentially reveals is the cohort relating to the major flooding events of the 1970's. Cohorts such as these, manifest physically as 'flood fingerprints' structuring the landscape; records of floods past.

The observed pattern of distribution is driven by the process of hydrochory; the passive dispersal of plant propagules, such as seed, by water. So it would appear that unlike the majority of eucalypts, to which the above statements refer, Coolibah population dynamics is uniquely and strongly directed by an alternative form of seed dispersal.

Coolibah life history, particularly expressed by the synchronous timing of reproductive phenology with a higher incidence of summer flooding events, appears dependent on the river system's naturally functioning hydrological regime.

An obvious outcome of this hydrological form of propagule dispersion would be the impact upon Coolibah gene flow and associated genetic diversity;

> *"Genetically, hydrochory may reduce spatial aggregation of genetically related individuals, lead to high gene flow among populations and increase genetic diversity in populations receiving many propagules" (Nilsson et al., 2010)*

Future work could very usefully integrate Coolibah demographic research with ^{14}C dating and population genetics across the catchment to provide insights into the interrelationships between historical hydrological regimes, tree age and genetic expression at time of establishment.

6 Dendrochronology and demography

6.1 Background

> *"The longevity of a monitoring system is crucial to its value: a monitoring system does not become of value until it has a significant past. In order to be supported into the future, at least some of the indicators must be simple and informative for stakeholders…."(Wallace et al., 2004)*

The above statement in addition to significantly emphasising the importance of commitment to long-term monitoring, also stresses that indicators used should be accessible and the usefulness of their integration comprehended by stakeholders. It was stated at the outset of this report that this autecological study of Coolibah should be viewed as an integrated adjunct to the associated assessment of the biodiversity values of the riparian plant community of the Diamantina/Warburton system and associated establishment of a permanent biodiversity monitoring program (Gillen 2017). As was recommended in the resulting report (ibid), Coolibah, as a keystone species within this river system, is readily appreciated by stakeholders for its iconic nature and role in regional biodiversity, and could be usefully integrated as an indicator species of biodiversity health in such a monitoring program.

> *"The significance of Coolibah as an indicator species of biodiversity condition operating at the scale of the riverine community is fully appreciated by considering its significant contribution to the composition, structure and functioning of the riverine ecosystem. Functionally the species acts as an ecosystem bioengineer whose trunk intercepts and obstructs the flow of wind and water, trapping soil, moisture and nutrients which in combination with shade cast by its canopy ameliorates local microclimatic and soil conditions facilitating an increased composition of plant species. The breakdown and microbial decomposition of Coolibah litter contributes directly to the cycling of carbon and associated nutrients in situ, contributing to the cycling of nutrients into and through the aquatic ecosystem of adjacent waterholes and channels. Structurally, Coolibah as a large and long lived tree provides a myriad of habitats from roots to branches at an individual level for a wide range of microbial, invertebrate and vertebrate taxa. Discarded limbs and branches falling directly into adjacent water bodies provide habitat for a range of aquatic fauna." (Gillen 2017)*

To consider Coolibah as a potential indicator species requires the development of a detailed understanding of the life history of the species, particularly identifying those stages in life history where the species is most vulnerable (Coomes and Allen, 2007, Maxwell et al., 2016, Pelton, 1953). A major component in the development of this body of knowledge is identifying the current state of demographic structure of the population within the region. Does this structure reveal a distorted pattern of clustered age classes of particular ages? How long does the species live and what is its growth rate at various stages of life history?

There is very little understanding, if any, concerning the growth rates and longevity of Coolibah, particularly across the range of environmental conditions that exist in the study area. A search of the literature revealed no record of the application of dendrochronological techniques, including radiocarbon dating methods, to determine the differential growth rates of Coolibah.

Dendrochronological investigation can provide insights into questions of population structure, longevity and growth rates. Dendrochronology: the science of tree-ring dating has a considerable research history in the northern hemisphere where much work has focussed on coniferous tree species. This particular tree group displays well defined development of annual growth rings, related to the regularity of annual seasonal growth. However, within the *Eucalyptus* genus most species generally don't display this anatomical regularity of growth rates, instead responding to more variable climatic conditions, reflected by a less coherent ring structure and high frequency of intra-annual growth bands. As a result it was generally considered that the genus possessed limited potential for dendrochronological research (Ogden, 1978). However, this early pessimistic predication of potential has failed to deter research albeit limited. Brookhouse (2006), in his seminal review of this body of research, relating to around 30 species of mainly temperate ecosystems, and in contrast to Ogden, concluded that the eucalypts may indeed possess significant dendrochronological potential.

Dendrochronological research examining a riparian species, *Eucalyptus camaldulensis*, River Red Gum, which occurs sympatrically with Coolibah over parts of its range, revealed that its growth pattern was clearly bound to periods of elevated moisture availability, typically associated with significant flood events. Anatomically periods of drought, juxtaposed with flood could be observed through "*changes in fibre geometry, vessel geometry, vessel arrangement and also changes in wood colour or density.*" (Argent et al., 2004). The anatomic expressions of flood were reflected by periods of virtual cessation of growth. Most significantly the research revealed that the extreme flood events of the 1970's, resulting in a major recruitment of the species, produced the greatest expression of major growth. Based on these findings the study recommended that future research combine examination of anatomical expression (rings) with isotopic analysis (dating) to unlock the climatic history recorded within the anatomical structure.

This recommended approach was successfully adopted in a dendrochronological study in Tasmania where radiocarbon dating was used to determine the age structure of a stand of *Eucalyptus regnans*. Rather than the commonly held view of the longevity of the species being around 350-450 years, the study revealed ages in excess of 500 years (Wood et al., 2010). Ironically the driving force or ecosystem process of disturbance initiating the recruitment of this cohort was a major fire event; in contrast significant River Red Gum and Coolibah recruitment periods are driven by major periods of flood that persist over a number of sequential years.

6.2 Consequences of recruitment disruption

> *"Recruitment patterns and processes are poorly known for most common and widespread tree species in Australia's extensive inland riparian landscapes."(Maxwell et al., 2016)*

It is broadly recognised in the literature that total grazing pressure exerts a significant negative impact upon the ecosystem structure and function of riparian and woodland ecosystems (Desert Channels, 2012-2017). An obvious and potentially serious expression of this impact is the suppression of recruitment of long lived perennial plant species; this extends to other ecosystems across the rangelands. Research conducted on a range of long-lived tree and shrub species within South Australian rangelands has revealed the detrimental impact of loss of recruitment cohorts on the demographic population structure of these species (Crisp, 1978, Crisp and Lange, 1976, Lange and Purdie, 1976, Lange and Sparrow, 1992). The suppression of recruitment results in a distortion of age distributions across the population resulting in a population heavily represented by older individuals. In extreme cases this can result in a senescent population doomed to extinction unless recruitment events are successful (Crisp, 1978, Lange and Purdie, 1976). This situation is exacerbated in arid ecosystems where recruitment events are associated with rare windows of opportunity provided by uncommon rainfall or flooding events that support germination, establishment and persistence in the landscape.

Within the Diamantina/Warburton study area, during all phases of field work, there was a notable absence of Coolibah seedlings which would have been expected following prior flooding events during the period 2009-11. This absence was in contrast to the widespread occurrence of seedlings observed during field work on the Cooper Creek system in 2012 (Gillen and Reid, 2013). There was, however, evidence of earlier recruitment cohorts across the study region expressed typically by a stunted or 'Bonsaied' form of Coolibah sapling, exhibiting evidence of continued regrowth attempts following grazing. Additionally patches of saplings of around 4-5 metres in height were observed often on outer floodplain fringes and flood runners projecting into the floodplain that were thought to be associated with the floods of the 1970's.

6.3 Radiocarbon analysis

Carbon is present naturally in three isotopic forms; two of these ^{12}C and ^{13}C are present as stable isotopes in contrast to ^{14}C which is radioactive. ^{14}C is created in the atmosphere as a result of the interaction between ^{14}N and neutrons associated with cosmic rays. The ^{14}C concentration in the atmosphere has varied considerably in the past providing an effective signature of distinctive concentration values over time and can be used to determine a calibration curve; Figure 15. The atmospheric concentrations vary subtly between northern and southern hemispheres hence internationally ratified calibration curves referred to as IntCal04 have been developed for both hemispheres (Hua, 2004, Hua, 2009).

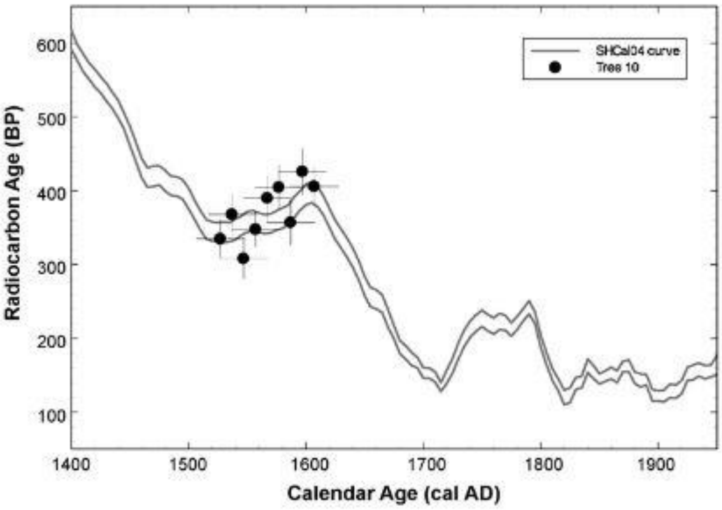


Figure 15 14C Calibration curve(Wood et al., 2010)

The ^{14}C generated in the atmosphere is further oxidised to produce $^{14}CO2$ which is then absorbed by plants such as Coolibah as a result of photosynthetic and respiratory processes and absorbed into the plant structure; in the case of Coolibah , ^{14}C is incorporated sequentially within its structure as the tree develops. From the point of time of absorption the radioactive ^{14}C concentration begins to decrease in accordance with the known rate of radioactive decay of the isotope. By assessing the range ^{14}C concentrations, using accelerated mass spectrometry (AMS), across a section of the radius of trunk growth of the Coolibah and then comparing the results with those of a curve of known long term atmospheric ^{14}C concentrations the age of the tree can be estimated and growth rate derived.

As a result of atmospheric atomic weapons testing from c1955 to c1963 atmospheric ^{14}C almost doubled in concentration, producing what has since been referred to as the "bomb-spike" period (Figure 16); producing a characteristic curve depicting the spike post bomb testing period and its subsequent amelioration over time since cessation of testing (Reimer et al., 2004). The dating procedure requires the matching of ^{14}C concentration results with the SHcal04 calibration curve using the available oxcal radiocarbon calibration software program.

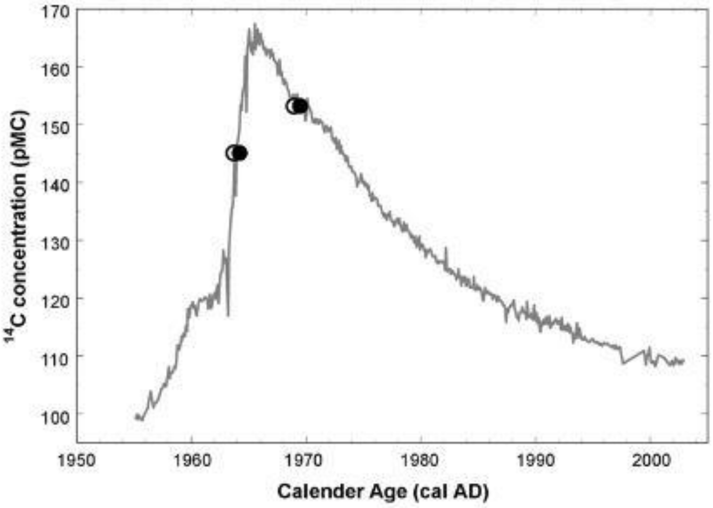


Figure 16 14C "Bomb Spike"(Wood et al., 2010)

In assessing the longevity of an individual Coolibah the combination of the two calibration curves facilitates the concomitant accurate dating of recent and much older wood material.

6.4 Methodology

Field Sampling

An initial phase of field work, 2014, focussed on the assessment of the suitability of a standard 5mm diameter increment borer for the hand extraction of Coolibah sample cores. The aim was to collect samples for 'proof of concept' ^{14}C analysis and to determine the feasibility of the future collection of a range of cores longitudinally down the Diamantina/Warburton system (Figure 17).

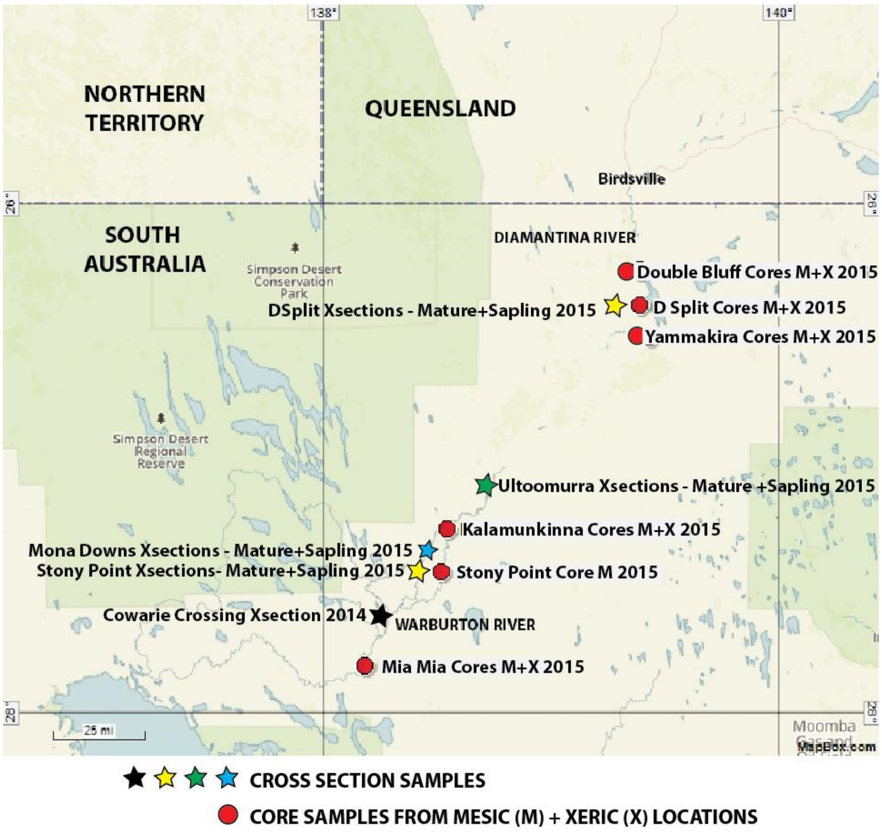


Figure 17 Distribution of samples, 2014-2015

Unfortunately the density of the timber quickly rendered this sampling approach obsolete; not only was coring extremely difficult, the resistance of the timber was strong enough to shear the corer. Consequently a cross section sample was sawn from a fallen Coolibah located at Cowarie Crossing on the lower Warburton River. As a result of the successful ^{14}C dating of this one sample (results below) a second phase of sample collection was conducted during 2015. Due to the earlier failure of the increment corer a larger, purpose built, power driven, corer was borrowed from the CSIRO's, Australian Tree Seed Centre, Canberra (Figure 18).

Figure 18 Left, increment corer; Upper Right, CSIRO corer; Lower right, 20mm cores

The aim during this second phase was to confirm the estimate of growth rate determined from the Cowarie Cross section by the collection and dating of multiple samples from the top and bottom of the system and from individual riparian (mesic) and outer floodplain (xeric) trees at each site/waterhole sampled. A total of 27 cores of 20mm diameter were extracted from mature trees and subsequently mounted on timber sections (Figure 18). In addition to coring, cross sectional samples were also collected from both fallen mature and sapling Coolibah.

Radiocarbon Analyses

From the Cowarie Crossing section collected in 2014, small samples of wood were extracted at regular distances from the outer edge of the cross-section (Figure 19).

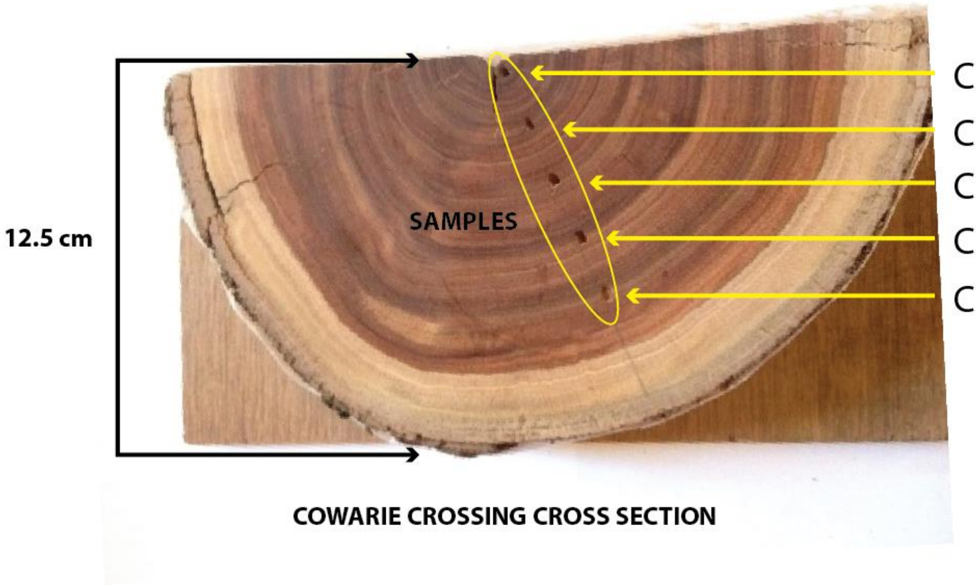


Figure 19 Coolibah cross section from Cowarie crossing

All ^{14}C analyses were conducted by Dr Stewart Fallon, Department of Earth Sciences, Australian National University. Following a standard treatment protocol (See (Vogel et al., 1984) for greater details) these samples were chemically treated before extracting a 1.5mg sub sample which was then combusted at 900° for 6 hours to produce CO_2.and subsequent graphite pellets. These graphite pellets were then subjected to ^{14}C analysis using the Australian National University's Single Stage Accelerator

Mass Spectrometer. The results were then reported as fraction of modern Carbon ($F^{14}C$) relative to Oxalic Acid-1 and corrected for δ13C. The radiocarbon dates for each sub-sample were then calibrated to calendar year ages using OxCal 4.2 and the Southern Hemisphere calibration curve as explained earlier (Bronk Ramsey, 2009a, Bronk Ramsey, 2009b, Hogg et al., 2013, Stuiver and Polach, 1977).

The above procedures were repeated in 2016 for the ^{14}C analysis of samples collected in 2015 for the purpose of determining;

- Coolibah growth rate comparison across core samples collected in 2015
- age of a cross section of mature Coolibah from Mona Downs Waterhole, Cowarie Station; and
- ages for three sapling Coolibah.

6.5 Results

^{14}C dating - Cowarie Crossing Cross section

The outcomes from this assessment provided confidence regarding the validity of using ^{14}C analytical procedures for the demographic investigation of Coolibah. The results (Table 1) revealed an averaged growth rate of approximately 1.04mm per annum, as estimated from the two dates determined from the modern ^{14}C bomb pulse period; 1956 and 1975. This 19 year timeframe included periods of major drought and major flood so it was hoped that the anatomical responses, or signatures, to these major disturbances could be usefully observed in the growth structure and help identify similar periods of major flooding over the life history of the specimen. As the results show the tree with a trunk radius of 12.2cm was estimated to be around 114 years old. There will always be a degree of uncertainty involved in determining the actual date of commencement of growth for those eucalypt species, such as Coolibah, that may form a lignotuber (swelling at the base of the trunk). These lignotubers gain expression, as exhibited by the 'Bonsaied' sapling forms discussed previously, following continued suppression of foliage over a number of years such that the eventual trunk, if the growth suppression is released, is younger than the lignotuber below. (Williams and Brooker, 1997)

Table 1 ^{14}C dating results for Cowarie cross section

Sample Name	Other ID	$D^{13}C$	±	% Modern C	±	D14C	±	14C age	±
C-1	13013	-29.3347	1	136.37	0.31	363.7	3.12	>MODERN	
C-2	13014	-23.3529	1	101.07	0.2	10.75	1.97	>MODERN	
C-3	13015	-23.361	1	98.01	0.19	-19.91	1.94	160	20
C-4	13016	-28.7367	1	98.63	0.2	-13.73	1.97	110	20
C-5	13017	-24.6807	1	97.72	0.21	-22.81	2.09	185	20
C-3 rpt	13018	-27.5301	1	97.95	0.2	-20.46	2.03	165	20

Sample	Calibrated Calendar Age	Calendar Age Estimation	Years of Growth	Average Sample Position from outer edge (mm)	Growth Rate (mm/yr)	Average Growth Rate (mm/yr)
C1	1975		39	41	1.05	1.04
C2	1956		58	60	1.03	
C3		1937	77	80.5		
C4		1918	95	100		
C5		1900	114	119		

^{14}C dating – 2015 Cores

The intent of the assessment of multiple cores, widely distributed over the length of the river system, (Figure 17) was to corroborate the growth rate findings determined for the Cowarie Cross specimen. As the Cowarie specimen had been located in the 'mesic' environment of river channel bank only those cores collected from trees growing in similar 'mesic' situations were analysed.

Two samples from each core were assessed from the outer region of the trunk, representative of the period of modern ^{14}C or "bomb-pulse-period", to compare with those outer samples assessed for the Cowarie sample. The results are shown in Table 2; a range of growth rates from 1.3 to 1.8mm per annum was determined.

Table 2 Average growth rates

Sample	Average Growth Rate (mm/yr)
Double Bluff	1.8
Kalamunkinna	1.3
Mia Mia	1.3
Yammakirra	1.5
Stony Point	1.3
D Split	Inconclusive

Figure 20 depicts the location of the ^{14}C determined dates for all samples from the cores on the calibration curve representing the radiocarbon bomb-pulse period.

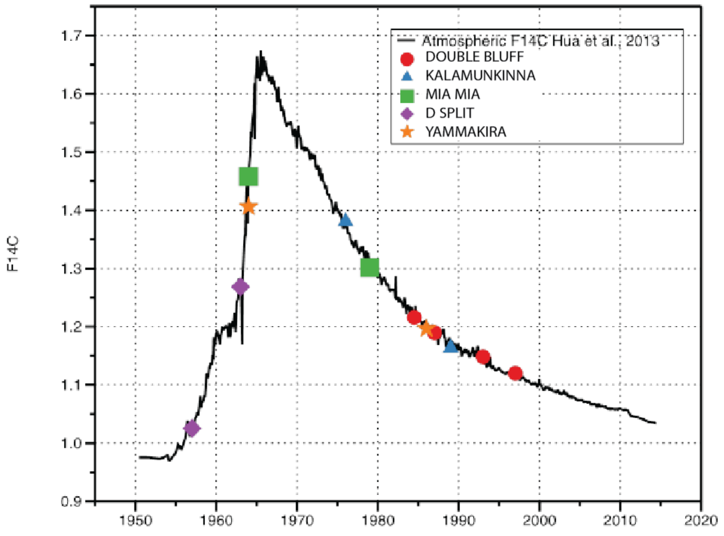


Figure 20 Atmospheric F14C from the Southern Hemisphere zone 1,2 (Hua et al., 2013). Tree wood F14C measurements calibrated to calendar age using Atmospheric F14C from the Southern Hemisphere zone curve.

It should be mentioned that in addition to cores collected from 'mesic' locations at each site a second core was collected from a tree at the same site but located off channel, and in more 'xeric' conditions on the adjacent floodplain. Given these drier more physiologically challenging floodplain conditions it could be hypothesised that these cores will reveal slower growth rates than their mesic counterparts. The costs associated with ^{14}C analysis ($400 per sample) precluded the assessment of all material collected during the study and was restricted to a sub-sample in order to determine proof of concept.

^{14}C dating – Mona Downs Cross Section

The cross section from the Mona Downs Waterhole, Cowarie Station, was obtained from a fallen tree in the channel riparian zone (Figure 21).

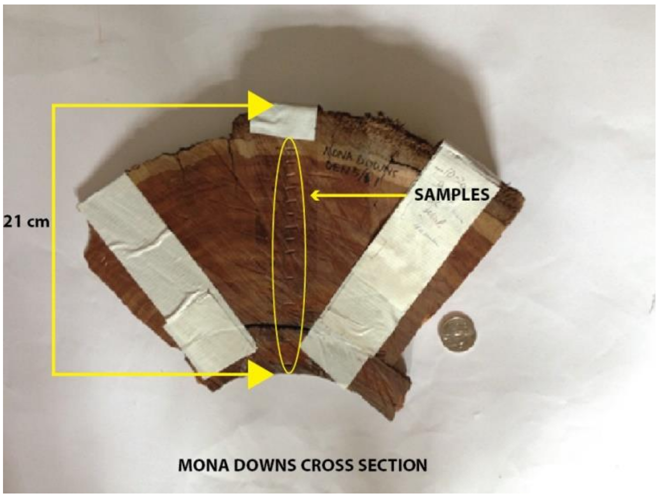
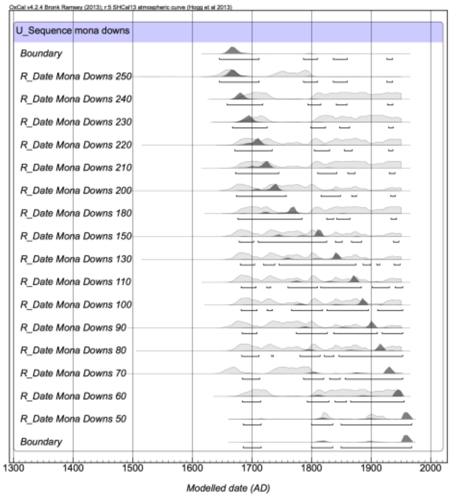


Figure 21 Coolibah cross section from Mona Downs Waterhole

The aim was to build on the aging results achieved for the Cowarie sample based on the assumption that trunk diameter was a respectable surrogate for age of an individual in developing an insight into population structure; larger the diameter, the older the tree. As shown in Figure 22 sixteen samples were taken at regular intervals across the radius of the specimen with the intent of maximising the chances of locating/matching the resulting ^{14}C results on the calibration curve as shown in Figure 23.



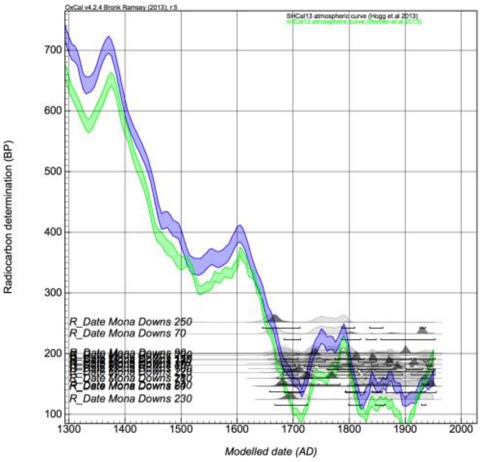


Figure 22 estimated ^{14}C Dates

Figure 23 ^{14}C dates on calibration curve

The trunk diameter for the Mona Downs specimen was roughly twice that of the Cowarie specimen (21cm to 12.5cm respectively). Modelling the ^{14}C results resulted in a predicted age of over 300 years with a probability of 90.2% accuracy as shown in Figure 24.

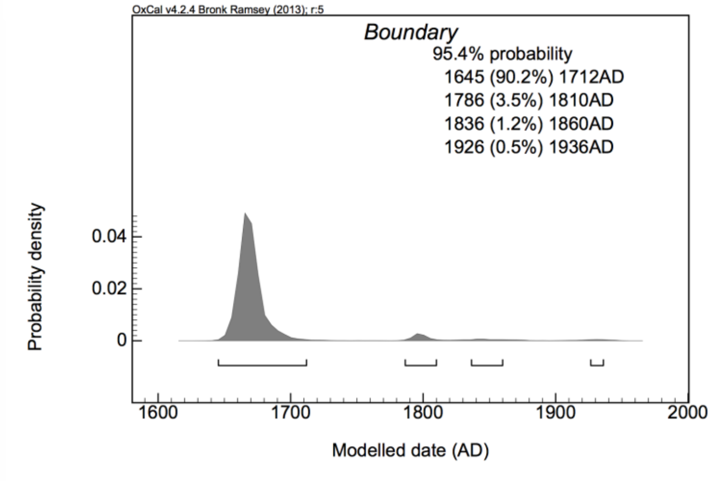


Figure 24 Potential age of Mona Downs tree

^{14}C dating – Sapling Cross Sections

As mentioned earlier, the massive floods of the 1970's associated with a cluster of very wet seasons driven by a sequence of ENSO driven La Nina years, provided optimum conditions for a major recruitment event for Coolibah. As shall be discussed in more detail later in the report, these rare windows of opportunity result in the mass broad scale dispersal of seed via floodwaters across considerable distances both longitudinally and laterally across the river system and associated floodplain. The provident conditions created by a sequence of floods maintain suitable soil moisture conditions facilitating the persistence of emerging saplings. Such was the case for the 1970's floods. The resulting recruitment is now represented by patches or 'contours' of saplings, the location of which often represents the outer edge or maximum extent of floodwaters during this period. Figure 25 shows the ^{14}C dates obtained for one such sapling that could possibly be related to the 1970's flood event.

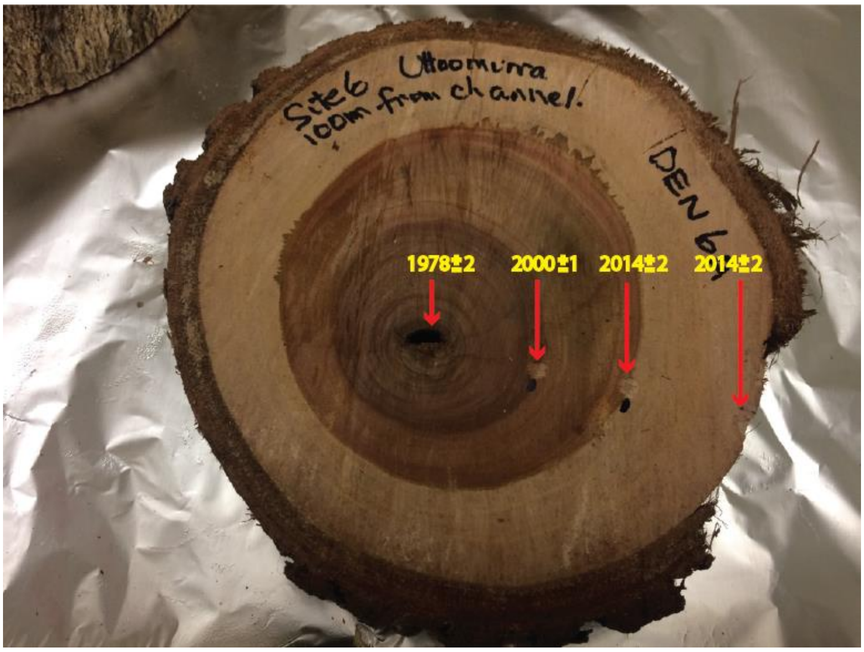


Figure 25 Sapling cross section, Ultoomurra Waterhole

7 Coolibah Recruitment: seed viability, flotation and seeding growth

7.1 Introduction

Notably, following recent significant flood pulse events during the period 2009-2011 prior to commencement of field work in 2014, there was no obvious widespread evidence of recruitment of Coolibah observed during the period 2014-2016. Over all of the 21 sites (63 transects) assessed during the period there was virtually no record of recent Coolibah seedling or sapling development.

Following widespread rains in early 2016 Coolibah seedlings were observed at only one of the 21 sites re-assessed floristically, namely Wadlarkaninna Waterhole, Kalamurina Station (Figure 26). In contrast, a comparative survey of Cooper Creek waterholes following the above mentioned periods of flood, found that many of the sites surveyed revealed positive evidence of recent recruitment of the range of perennial shrubs and trees of the riparian fringe, including Coolibah.

There was, however, during the field work periods of 2014-2016, clear evidence of previous recruitment events represented by older cohorts of indeterminate age. It does appear from the findings relating to ^{14}C dating of saplings that the distribution of saplings of a certain diameter across the region's floodplains associated with the extreme flood events during the 1970's represents a significant recruitment event. Also observed during the current project were saplings representative of a mix of differently aged cohorts that displayed the obvious effects of constant grazing pressure. This constant pressure resulted in multiple re-sprouting events resulting from constant suppression, in turn resulting in a multi-stemmed low sapling form emanating from an obvious lignotuber at the base; the 'Bonsaied' morphology referred to earlier.

These initial observations; lack of recruitment and constant grazing pressure; raised several research questions that informed the development and direction of the investigation into the ecology of *Eucalyptus coolabah*. These questions can be summarized broadly as follows;

- What are the ecosystem processes driving and supporting the recruitment of Coolibah in the region?
- What is the nature and pattern of distribution of the species within the Diamantina/Warburton system and beyond?
- What is the current demographic structure of the Diamantina/Warburton Coolibah population?
- What are the phenological characteristics that drive the recruitment of the species?
- What is the nature of seed viability and longevity in the species?
- What ecosystem characteristics support seedling and sapling development and survival?

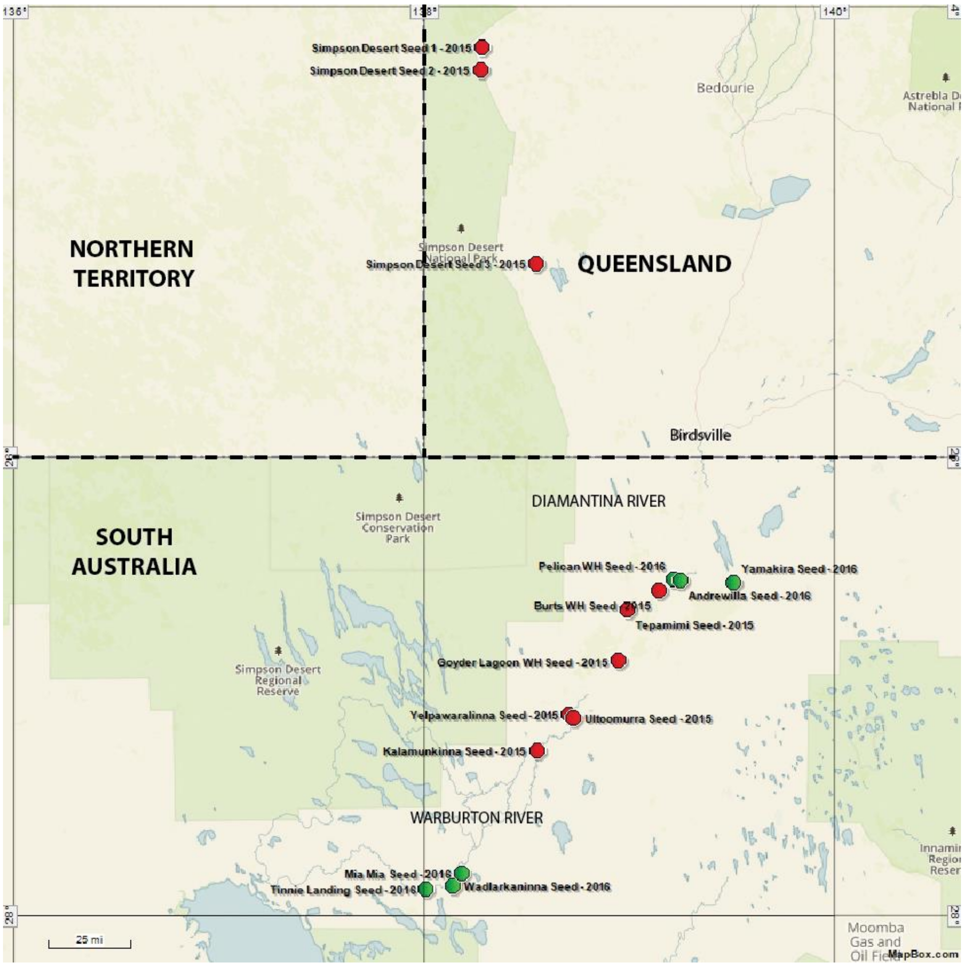


Figure 26 Distribution of sites from which Coolibah seed was collected 2015-2016

7.2 Seed Viability and Longevity Methodology

Research School of Biology, Australian National University

Following field work in 2014, seed collected opportunistically from one fruiting individual during May, was supplied to the Research School of Biology, Australian National University to conduct pilot viability and longevity trials.

For the viability trails 3 batches of 25 seeds were followed over a four week period monitoring rate of germination and the final total of germinated seeds at termination of trial. Chamber conditions for the trail included a diurnal temperature variation of 25-15° C, 12/12 hours day/night, a chamber light intensity of 30 µmol/m2/sec and a relative humidity of 35-40%.

The seed longevity trials were conducted using a methodology developed at the Royal Botanic Gardens, Kew, U.K (Long et al., 2017, Merritt et al., 2014). The methodology was developed to determine the comparative longevity of seed viability between species for ex-situ seed bank collections. The methods involves the simulation of aging of test seed under controlled of 45°C and 60% relative humidity to provide an indication of natural seed- persistence in the 'wild'. 11 batches of 25 seeds were treated under the above controlled conditions over eleven different time periods in order to determine the point in time (p_{50}) where 50% of seed fail to germinate; an indication of loss of viability.

Australian Tree Seed Centre, CSIRO

A subsidiary aim of the seed collection process was to supply the Australian Tree Seed Centre, CSIRO (CSIRO - ATSC), Canberra, with seed material for Coolibah for their seed bank. Consequently seed was only lodged from those trees from which a suitably large amount of seed was collected. Thus seed from a total of 12 trees was lodged, 8 collected during 2015 and the remaining 4 from 2016. The distribution of trees sampled over this period is depicted in Figure 26.

A standard procedure for the lodgement of seed with the CSIRO - ATSC, involves germination trails for all samples lodged.

The results from these trials for the 12 samples lodged provided an insight into the variation in seed viability between individuals across the wider region. The results also served to complement those achieved at ANU.

Seed collected *en masse* from an individual is a combination of both fertile seed and sterile 'chaff'. Rather than undertake the laborious and difficult task of separating chaff from seed over multiple trails, CSIRO - ATSC utilises batches of standard weight from each tree sample for germination trials. This standardisation enables direct comparison between individuals regarding germination success rates. The tests are conducted under controlled light, temperature (35^0C) and moisture conditions. Seed germination is followed over time, noting germination numbers, until the stage at which all seeds have germinated or a residual fail to germinate.

7.3 Seed Viability and Longevity Results

Germination results obtained from both ANU and CSIRO trials resulted in almost 100% seed germination within a week (see Appendices 1 & 2 for more detail of CSIRO trials). During the ANU trials 50% of all seed germinated within 2 days (Table 3).

Table 3 ANU Germination Results (Replicate weight = 0.2 g)

	Week 1		**Week 2**		**Week 3**		**Week 4**	
	# Germin	% Germin	#	&	#	%	#	%
Replicate	25	100	25	100	25	100	25	100
Replicate	24	96	24	96	24	96	24	96
Replicate	25	100	25	100	25	100	25	100

The CSIRO trials revealed considerable variation in seed viability between the 12 tree samples assessed, ranging from an estimated average of 350 to 14, 200 viable seeds per 10g. (Table 4)

Table 4 CSIRO Germination Results

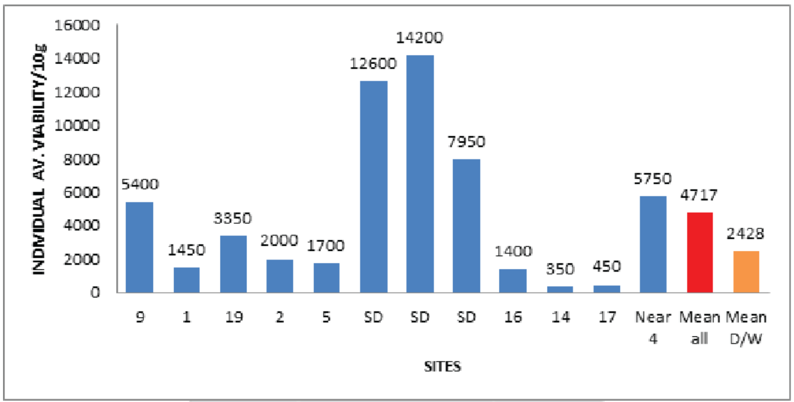
	May 2015 Diamantina/Warburton					**July 2015 Simpson Desert**			**August 2016 Diamantina/Warburton**			
	Tree 1	2	3	4	5	6	7	8	9	10	11	12
Number of germinations	108	29	67	40	34	2152	284	159	28	7	9	115
Individual av. viability per 10g	5400	1450	3350	2000	1700	12600	14200	7950	1400	350	450	5750
Site number	**9**	**1**	**19**	**2**	**5**				**16**	**14**	**17**	**Near 4**

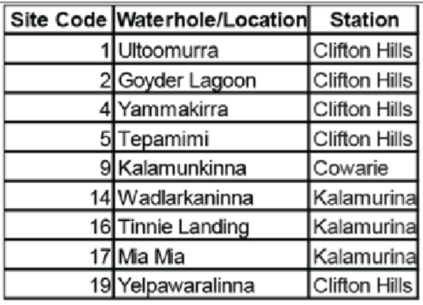
The variation expressed by these results appear to be relatively consistent with results achieved by Boland et al (1980, Maiden, 1903-33, Zimmer and Grose, 1958) in their assessment of Coolibah seed collected 108km E. of Birdsville towards Beetoota Qld. 3 Sept, 1974 (Table 5).

Table 5 Boland et a. germination results

Species	Number of viable seeds per 10g		Number of seed lots tested
	Mean or Mean ± S. D.	Highest Recorded	
E. microtheca (now E. coolabah)	3770 ± 2470	9800	24

The results for the three samples collected from the Simpson Desert were considerably greater than those recorded from the Diamantina/Warburton (Figure 27). These results do suggest that it may be informative to conduct comparative genetic assessments on both the Diamantina and Simpson seed to determine the nature of taxonomic relationship.





Site Code	Waterhole/Location	Station
1	Ultoomurra	Clifton Hills
2	Goyder Lagoon	Clifton Hills
4	Yammakirra	Clifton Hills
5	Tepamimi	Clifton Hills
9	Kalamunkinna	Cowarie
14	Wadlarkaninna	Kalamurina
16	Tinnie Landing	Kalamurina
17	Mia Mia	Kalamurina
19	Yelpawaralinna	Clifton Hills

Figure 27 Coolibah seed viability across sites

The results of the ANU seed longevity trials, revealing that Coolibah seed viability drops 50% within 101 days (Figure 28, Table 6), suggest that the seed does not remain viable under natural conditions within the soil seed bank for extended periods. According to Boland et al (1980) the seed of most *Eucalyptus* species stored ex situ in uncontrolled conditions remains viable for up to 10 years (Maiden, 1903-33, Zimmer and Grose, 1958) . However, Boland et al. (ibid) found that stored Coolibah seed in an uncontrolled environment showed significant decline in variability within 2 -3 years. They subsequently recommended storage at low temperature to extend seed viability.

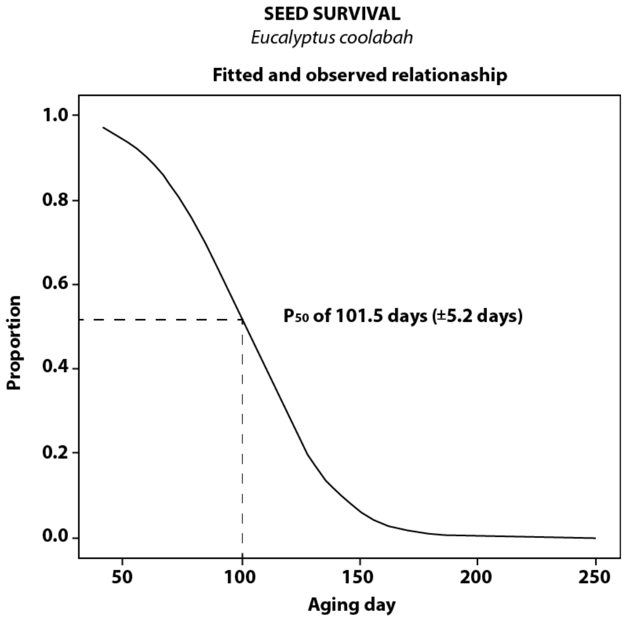


Figure 28 P_{50} for Coolibah seed

Table 6 Loss in viability over time

Species	Aging days	Germinating seed	Sown	G%
Eucalyptus coolabah	0	25	25	100
Eucalyptus coolabah	1	50	50	100
Eucalyptus coolabah	7	50	50	100
Eucalyptus coolabah	14	50	50	100
Eucalyptus coolabah	21	50	50	100
Eucalyptus coolabah	28	45	50	90
Eucalyptus coolabah	35	50	50	100
Eucalyptus coolabah	42	50	50	100
Eucalyptus coolabah	50	48	50	96
Eucalyptus coolabah	75	36	50	72
Eucalyptus coolabah	156	3	50	6
Eucalyptus coolabah	250	0	50	0

7.4 Seed Flotation Trials

In order to examine the potential for hydrochory to influence the distribution of Coolibah in the broader landscape, a simple laboratory test was conducted.

7.5 Methodology

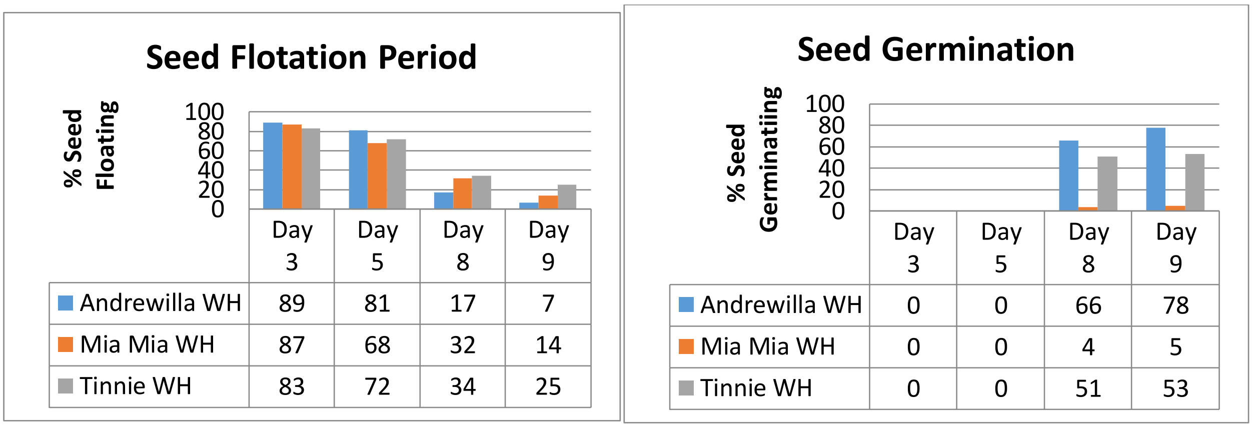
A cursory estimate of flotation duration of Coolibah seed was determined for seed from four locations; Andrewilla Waterhole, Mia Mia Waterhole, Tinnie Waterhole and Birdsville Diamantina River Crossing. The seed from Birdsville was collected in May

2017; seed from the other three sources was collected during May 2016. The inclusion of younger seed from Birdsville was in order to detect whether seed age significantly influenced flotation periods.

Ten seeds from each seed source were dropped onto the surface of 100ml of water in a plastic beaker; this was repeated for ten 100ml replicate beakers for each seed source representing a total of 100 seeds from each of the four sources.

7.6 Results

A significant proportion of the 2016 seed (>70%) (Figure 28) remained floating after a period of 5 days, after which most seed began to sink. A similar process was observed for the 2017 seed (Figure 29). Interestingly the majority of seed (2016 &2017) that sank had commenced germination, with most displaying an emergent radicle and a very small number revealing emerging cotyledons.

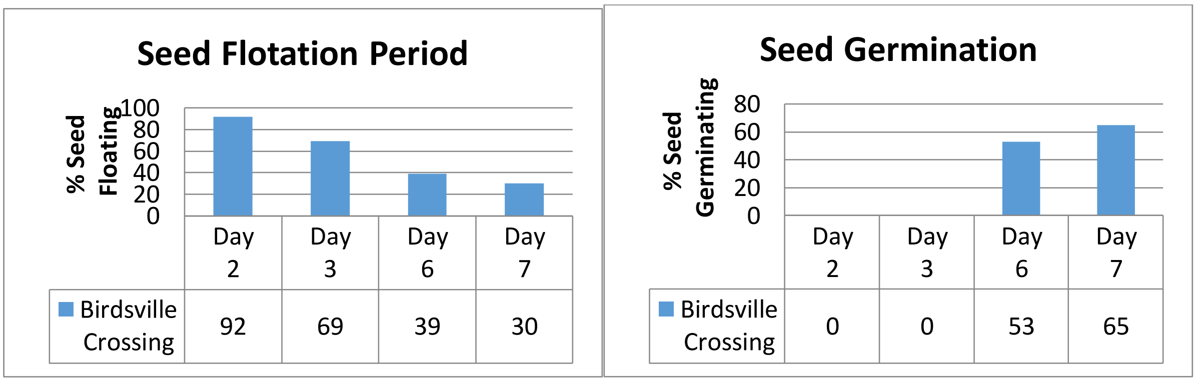

Seed Flotation Period

	Day 3	Day 5	Day 8	Day 9
🟦 Andrewilla WH	89	81	17	7
🟧 Mia Mia WH	87	68	32	14
◼ Tinnie WH	83	72	34	25

Seed Germination

	Day 3	Day 5	Day 8	Day 9
🟦 Andrewilla WH	0	0	66	78
🟧 Mia Mia WH	0	0	4	5
◼ Tinnie WH	0	0	51	53

Figure: 28 Flotation and germination of seed collected in 2016


Seed Flotation Period

	Day 2	Day 3	Day 6	Day 7
🟦 Birdsville Crossing	92	69	39	30

Seed Germination

	Day 2	Day 3	Day 6	Day 7
🟦 Birdsville Crossing	0	0	53	65

Figure: 29 Flotation and germination of seed collected in 2017

7.7 Discussion

These very preliminary results suggest the positive potential for hydrochory for dispersal given the ability of a significant proportion of seed to remain floating after a period of around 5 days. The synchronistic release of seed at a time of maximum flow and flood could hypothetically distribute seed over considerable distance within a period of 5 days. Following termination of this brief experiment; all sunken seed was sown into containers of potting mix. Twelve days after being sown 30% of this sunken seed had developed cotyledons and displayed health growth.

These are very exploratory results and should be treated with caution. A more statistically robust repeated experiment would provide greater confidence in these preliminary observations.

7.8 Seedling growth experiment

7.9 Materials and methodology

The experiment was conducted in the plant services nursery compound of the Research School of Biology, Australian National University. The following provided the focus for the design and conduct of the research;

- Four soil treatments – (Figure 29)
- Three seed source treatments
- Two soil moisture treatments – drought and flood.

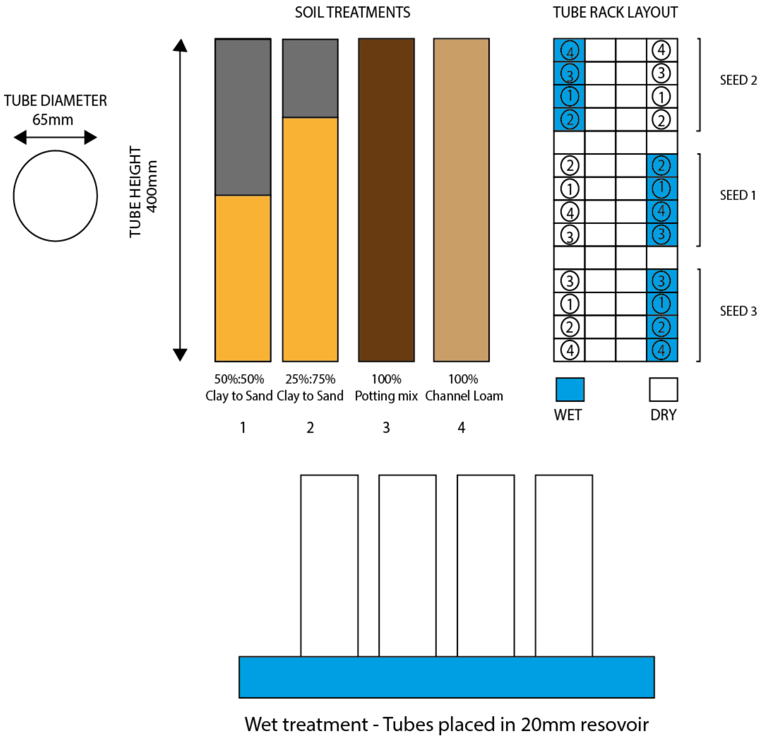


Figure 29 Experimental treatments

Coolibah seed was sourced from three locations in the study area; Kalamunkinna Waterhole, Goyder Lagoon Waterhole, Yelpawaralinna Waterhole (Figure 26). All seed was collected during May 2015. Soil from the region was sourced at Kalamunkinna Waterhole; a sandy loam alluvium from the Channel bank and a gilgaied vertisol or heavy clay from the immediately adjacent floodplain (Figure 30).

Figure 30 Soils collected from Kalamunkinna Waterhole

To facilitate the soil moisture treatment the experiment was conducted under a constructed transparently roofed but open sided structure to avoid the confounding effects of rain but facilitate the flow of air, penetration of natural light and maintain natural diurnal temperatures. Purpose built racks were constructed to hold 24 PVC freely draining tubes; each 40cm in length and 6.5.cm width. Five racks were used in total, each rack representing a complete replicate containing all treatments (Figure 31).

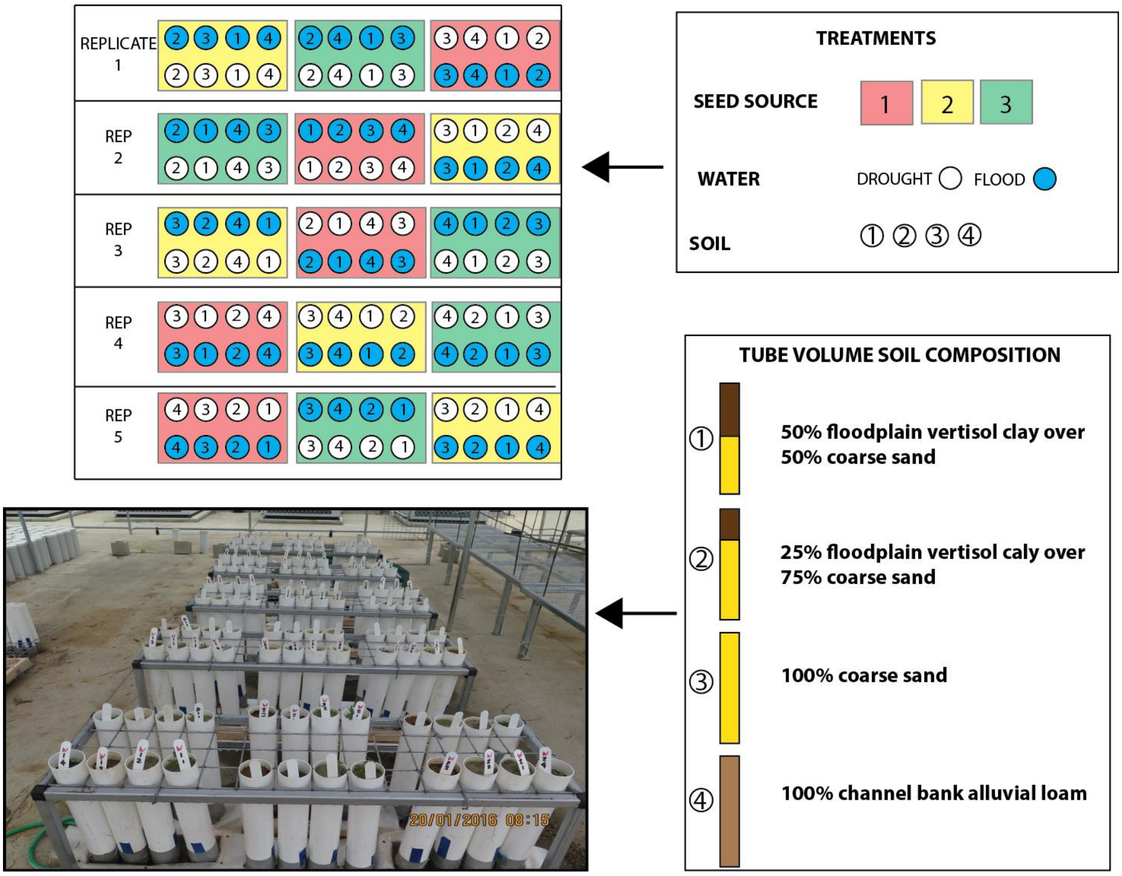


Figure 31 Experimental design

All soils in all tubes/pots were saturated to field capacity; subsequently 5 seeds were sown per pot on the 14th December 2015. Germination commenced 3 days following sowing. All pots continued to receive regular watering to maintain soil at field capacity until excess seedlings were pricked out leaving a sole seedling per pot for the duration of the experiment. The two soil moisture treatments, drought and flood, commenced on the 4th March. All drought treatments received no further watering allowing soil profiles to naturally dry out. Tubes receiving flood treatments continued to receive a regular watering of 75 ml every 3rd day. Additionally these flood treatment pots, for the duration of the experiment were kept in trays of water of around 20mm depth to maintain profile saturation and simulate flood conditions.

Measurements of plant growth commenced on the 31st of December 2015. Documentation included; number of leaf pairs; height of plant and the width and length of one leaf from each pair of leaves. These measurements were repeated approximately every week until the 12th April 2016.

Once plants began to exhibit drought and flooding stress, levels of leaf chlorophyll fluorescence and leaf chlorophyll concentration were monitored for a sub-set of plants using a Plant Efficiency Analyser (PEA; Hansatech) and Soil-Plant Analyser Development (SPAD: Konica Minolta)) meters respectively. Measurements commenced on 1st March and were repeated on three additional occasions the last being on the 12th April when the experiment was ended.

All plants were harvested from pots on the 14th April separating root and shoot biomass. All plant material was oven dried and weighed to provide a measure of total biomass produced per plant. All leaf material per plant was scanned and total leaf area per plant determined using ImageJ software.

7.10 Results

Almost 100% of the excess seed sown at the outset of the experiment eventually germinated; reinforcing the germination results achieved by the approaches reported earlier this report. Interestingly, most germination in the first 4 days of commencement, occurred in the two clay soil treatments (treatments 1 and 2) with fewer numbers germinating in the alluvium (treatment 3)and none at all in the control soil (treatment 3). By the 6th day germination had commenced in the control soil and the rate of germination in the alluvium virtually matched that of the two clay treatments. Following this early period rate of seedling development was obviously greatest in the channel loam soil.

Seedling shoot growth in the control soil, a coarse sandy potting mix, was retarded for the entire duration of the experiment for flooded and drought treatments. However, even though shoot growth development was inhibited, seedlings in this medium still exhibited impressive tap root development as shown in Figure 32.

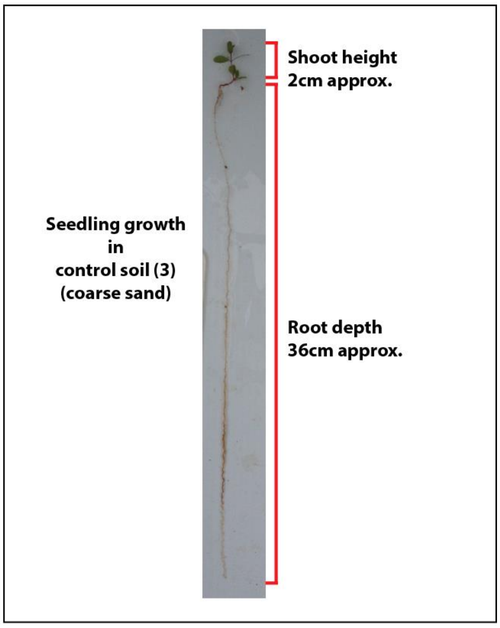


Figure 32 Seedling root growth

The retarded seedling development could be associated with a nutrient poor medium compared with the clay and alluvial soils; however, hypothetically, the clay and alluvial soils, being from the study region may also have contained indigenous mycorrhizal fungi, facilitating more productive growth. Further research could be revealing.

As shown in Table 7, analysis of variance revealed the effect of soil type to most significantly influence overall seedling production of plant biomass; seedlings growing in soil type 4, the alluvial channel bank loam, being the most productive, under both flooded and dry conditions.

Table 7 ANOVA results

Analysis of variance							
Variate: In Total_Biomass_Foliage_Stem_Roo							
Source of variation	d.f.	(m.v.)	s.s.	..s.	v.r.	F pr.	
Rack stratum	4		25.6654	0.664	0.97		
Rack. Treatment_Seed_Source stratum							
Treatment_Seed_Source	2		1.4541	0.727	1.05	0.393	
Residual	8	5.5205	0.6901				

Analysis of variance							
Rack. Treatment_Seed_Source. Treatment_DRY_WET stratum							
Treatment_DRY_WET	1		1.8327	1.8327	10.08	0.008	
Treatment_Seed_Source. Treatment_DRY_WET							
		2		1.7861	0.8931	4.91	0.028
Residual	12		2.1811	0.1818	.039		
Rack. Treatment_Seed_Source. Treatment_Soil stratum							
Treatment_Soil	3		325.4417	108.4806	102.50	<.001	
Treatment_Seed_Source. Treatment_Soil							
		6		2.3511	0.3918	0.37	0.893
Residual	36		38.0953	1.0582	2.24		
Rack.Treatment_Seed_Source. Treatment>DRY>WET. Treatment_Soil stratum							
Treatment_DRY_WET. Treatment Soil							
		3		4.3369	1.4456	3.07	0.041
Treatment_Seed_Source. Treatment_DRY_WET. Treatment_Soil							
		6		0.4393	0.0732	0.16	0.987
Residual	35	-1	16.5004	0.4714			
Total	**118**	**-1**	**392.6734**				

Figure 33, graphically presents the results of the ANOVA. The full range of statistical analyses and results is presented in Appendices 3 to 7. Flooding conditions are shown (Figure 33) to reduce overall biomass production for seedlings growing in soil treatments 1 and 4 (50% clay depth and 100% Loam). Figure 34 provides an example of this growth inhibition showing seedlings produced in the channel loam under both flooded (W) and drought (D) conditions.

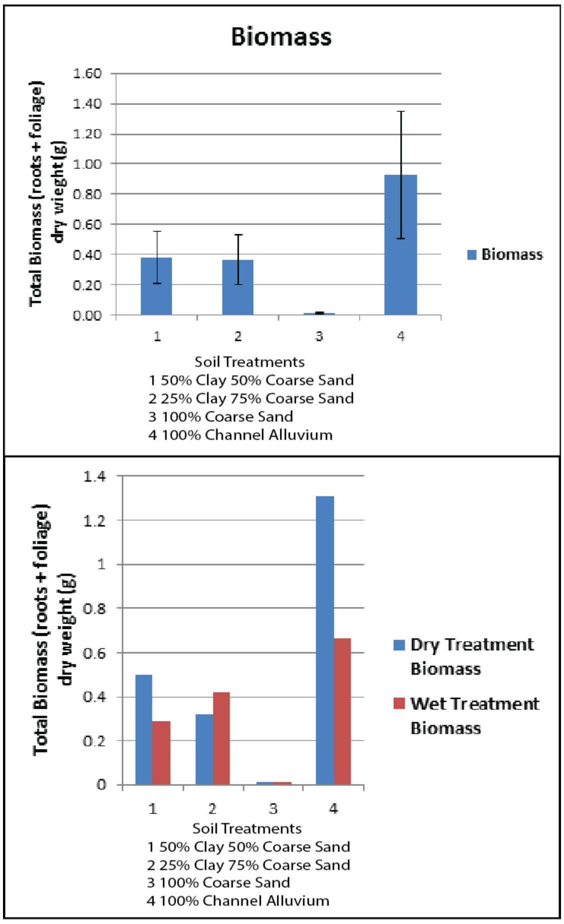


Figure 33 Experimental results; Total biomass; dry and wet treatments

Figure 34 Seed Growth, Left; Drought treatment; Right; Flood Treatment

Paradoxically the flooded treatment representing extended inundation slightly enhanced biomass production for seedlings experiencing soil treatment 2 (25% clay depth).

One of the main intents of incorporating, experimentally, the differing clay depths (25% & 50%) was to observe the influence upon root development of seedlings in comparison to that supported by the channel loam. The differing depths of clay over coarse sand were intended to simulate conditions of floodplain clay sediments of varying depth over coarse sand sediments. Within the study region these palaeo gravels and coarse sands represent a shallow aquifer system an important source of groundwater for Coolibah in the region. The clay effectively seals the coarse sediments below protecting groundwater from evaporative losses. However, these clays when dry also form a challenging edaphic barrier against the development of root systems.

Hypothetically, the rare extended sequential or clustered flooding events associated with significant La Nina extending across floodplains can saturate these sediments facilitating the easier passage of developing seedling/sapling root systems in search of groundwater below; the thinner the sediments, the greater the expectation of roots bridging a formerly dry clay barrier, and penetrating the groundwater below in a rare window of recruitment opportunity.

Observing root development and structure at the termination of the seedling experiment provided initial albeit preliminary evidence of the above hypothesized process. As Figure 35 shows root development in loam and clay displayed contrasting patterns. Root development in loam appeared more regular with a sequence of laterals branching off the tap root high in the soil profile. Contrastingly, for seedlings in clay treatments, lateral root development appeared delayed until the tap root had broken through the clay into the sands below ('groundwater system').

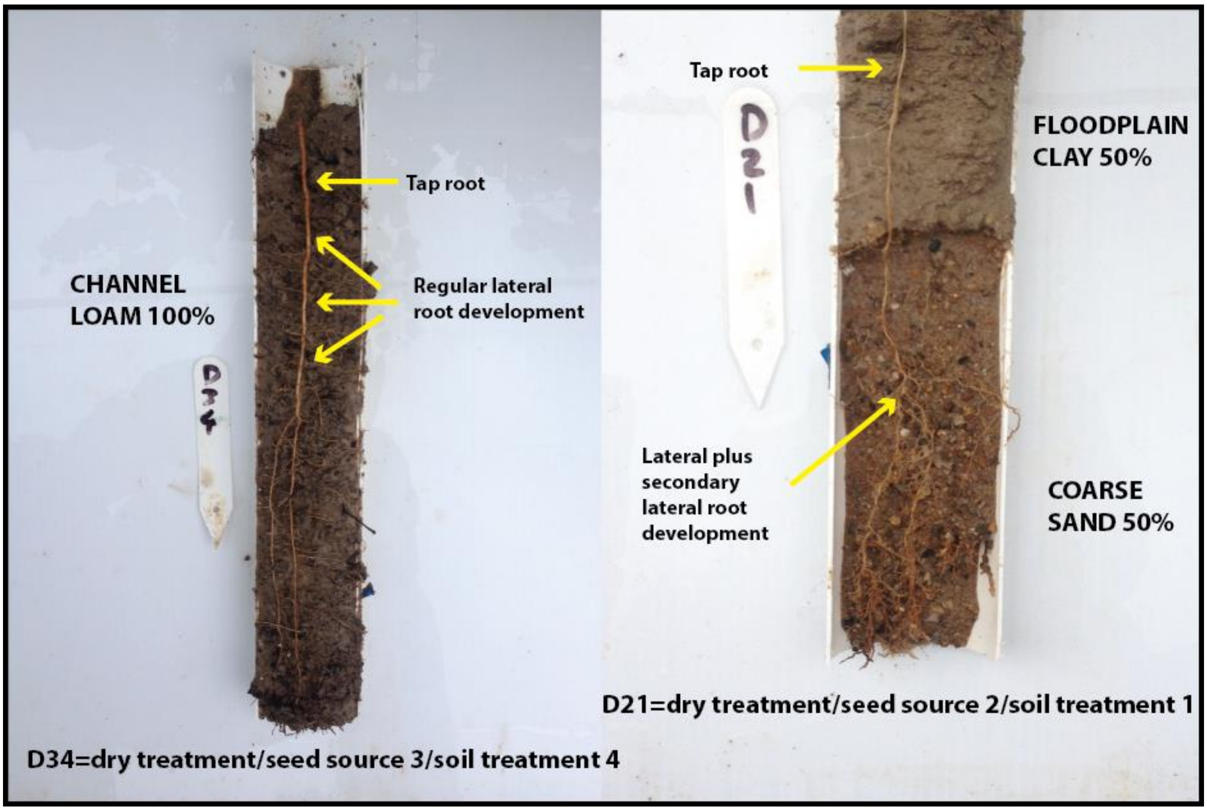


Figure 35 Comparative seedling root development between soil treatments

Excavation of seedling/saplings in the field (Figure 36) also revealed the propensity to rapidly extend a tap root in search of soil moisture during the establishment phase. In the instance depicted in Figure 36, the seedling was located in close proximity to the channel bank of D Split Waterhole where a sandy loamy soil was overlain with a shallow veneer of floodplain clay.

Figure 36 Coolibah root development; D Split Waterhole

7.11 Discussion - Seed viability and longevity

The results of the seed germination and longevity trials are usefully viewed in the context of the reproductive phenology of Coolibah. More particularly, how are flowering, fruiting and seed dispersal influenced by seasonal and interannual variations in climate?

An interesting insight into the aboriginal knowledge of Coolibah reproductive phenology is provided by Parker (1905), who in her recording of the mythology of the Euahlayi (sic, = Yuwaalayaay) people of New South Wales on the upper catchment of the Darling River system, states;

> *"Douran Doura [the north wind] woos the Coolabah (sic), and Kurrajong, who flower [collarene=Coolibah blossom] after the hot north wind has kissed them. Yarragerh [spring wind, north-east] and Douran Doura are the most honoured winds as being the surest rain-bringers." (Parker, 1905)*

The mythology effectively describes the influence of seasonal winds heralding the arrival of monsoonal rains from the north during summer months which, depending on scale, are usually associated with flood pulses or extensive flooding down inland dryland river systems.

Coolibah, as a species, appears to be strongly adapted to take advantage of these main periods of moisture for their flowering and seed dispersal. The myth accords neatly with the oft stated main flowering period for Coolibah of between December and February (Blakely, 1934, Brooker and Kleinig, 2004). This summer period of flowering coincides with an increased seasonal probability of widespread rains and flooding given the appropriate climatic conditions.

However, there is also considerable variability of time of flowering across individuals within the species across the distribution range with lesser flowering events also being recorded from March, April, May, July, September and November (Slee et al., 2006). This variability, a form of 'bet-hedging' is logical given the extremely variable nature of rainfall within this highly arid region. During this study all seed was collected during the months in the field, namely; April, May, July and August. In all instances of collection there were very few individuals flowering in any one location; often on the one tree, buds, flowers immature and mature fruits coexisted.

The timing of flowering, fruit maturation and quick seed release around the period most likely to be associated with favourable environmental conditions for recruitment, namely widespread rains and flooding, is an obvious adaptation advantage for the maximisation of major recruitment of the species. (Pettit and Froend, 2001)

Apparently most eucalypt species take 3 to 4 days to release seed from mature fruit whereas Coolibah, given optimum drying conditions releases seed within a few hours of fruit maturation (Boland et al., 1980); this 'quick release' was clearly evident in the field where mature fruit would commence shedding seed several hours later, following picking.

Seed maturation in temperate eucalypts can take several months. This maturation process would appear to be significantly shortened in Coolibah (House, 1997). For many eucalypt species, particularly those of temperate areas, seed dispersal is localised, reflected by seed fall in situ, assisted by wind over short distances when present (House, 1997, Williams and Brooker, 1997). Major Coolibah seed dispersal events would appear to be timed to exploit those periods of significant and extensive floods associated with usually associated with southern incursions of the north Australian monsoon system in late summer. Moreover, in order for dispersed seed to germinate and establish where deposited in the landscape and persist as Coolibah saplings, these suitable and uncommon extensive flooding events are clustered over several years.

The major floods of the 1970's, involving repeated extensive flood events of consecutive seasons represent one such recruitment episode. Across areas of the Diamantina/Warburton floodplains are clear representations of this flood event where seed deposited on the outer edge of the flood zone has subsequently established and supported a persistent new cohort of Coolibah saplings; an outer 'ring' of recruitment (Figure 37). So unlike the majority of eucalypt species, water borne dispersal, or hydrochory, would appear to be a most significant ecosystem process in both the physical structuring of the Coolibah population and maximising the flow of genes across the landscape.

> *"The importance of hydrochory as a significant ecosystem process, structuring riparian and wetland vegetation communities, enhancing gene flow between populations and increasing genetic diversity within populations is increasingly being realised." (Nilsson et al., 2010)*

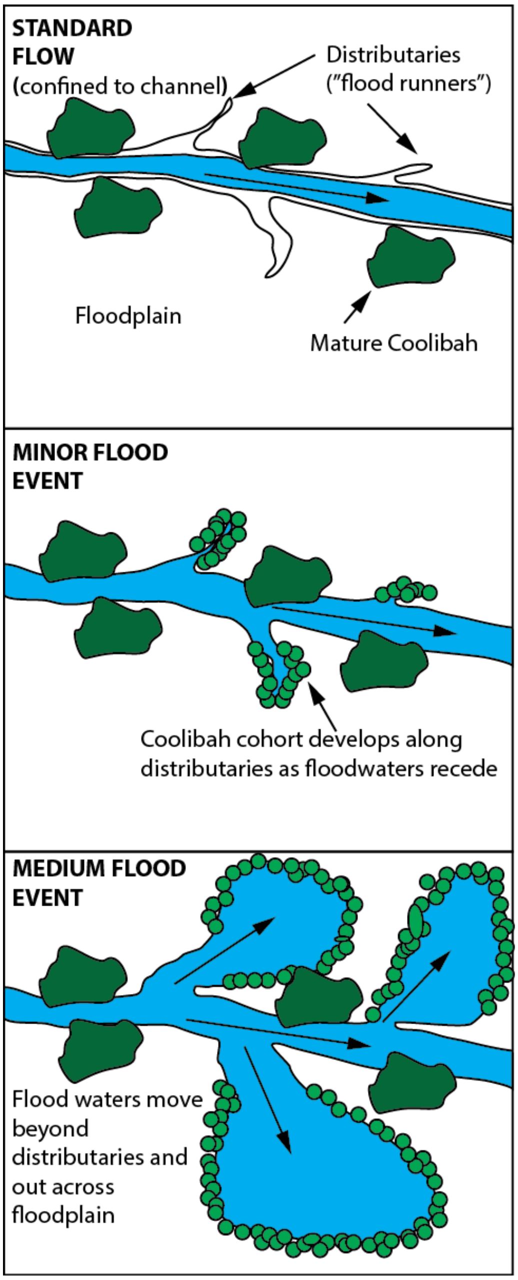


Figure 37 Conceptual model of hydrochory

7.12 Discussion - Seedling growth and development

> *"Factors contributing to seedling survival are still not well understood for many Australian arid and semi-arid zone species including riparian trees." (Argus et al., 2015)*
>
> *"..recruitment patterns and processes are poorly known for most common and widespread tree species of Australis' extensive inland riparian landscapes." (Maxwell et al., 2016)*

It is generally recognised that the most critical period in the life cycle of most desert species is the establishment of seedlings following germination (Pelton, 1953, Schütz et al., 2002). For Coolibah, the establishment and persistence of the species would seem to be closely related to a naturally functioning hydrological regime where peak flows and floods are synchronous with the reproductive phenology of the species; a 'serendipitous synchronous sequence' of timing and placement; timing of seed production and dispersal with rare clustered flood events and placement of seed via floodwaters in an environment conducive to establishment and persistence. This 'conducive environment' potentially consists of edaphic conditions that facilitate rapid root development in search of sustainable soil water conditions that enable ongoing persistence of the individual; particularly in extended periods of drought. As a phreatophyte, it is crucial for Coolibah to tap into potential groundwater systems that support this persistence.

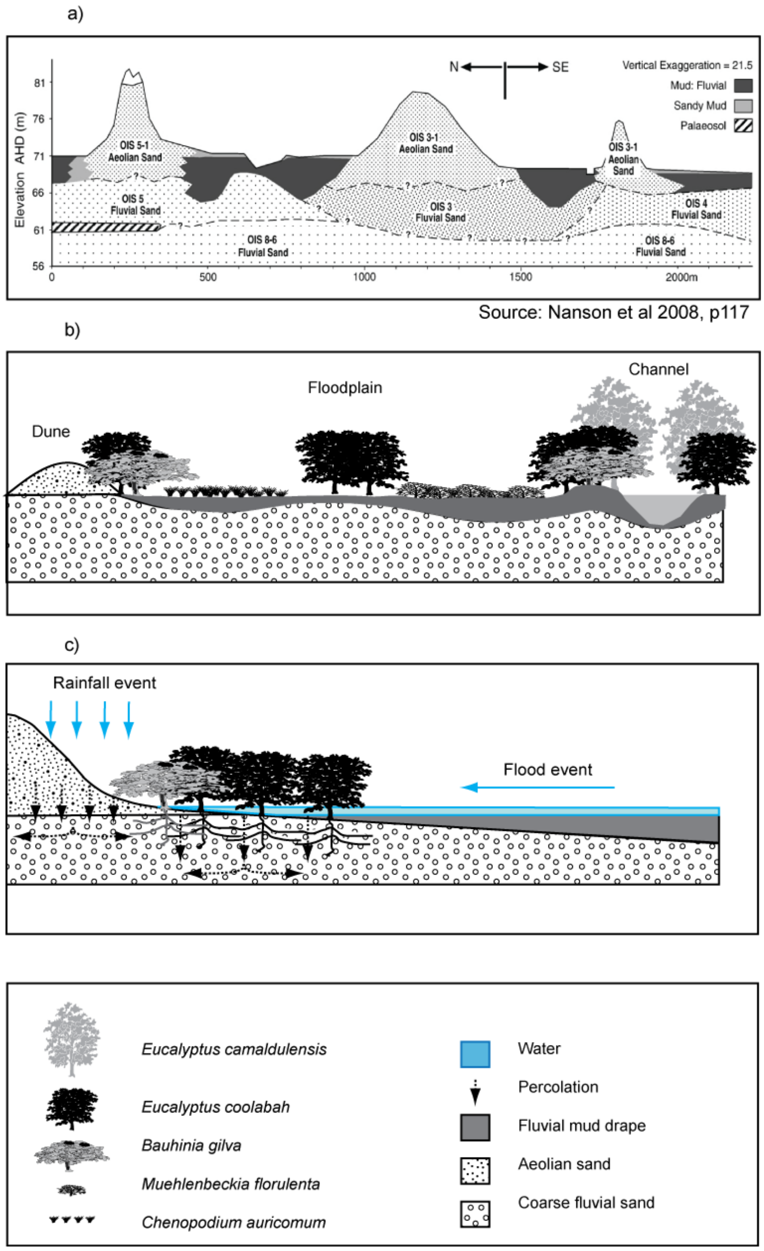
> *"Root growth may be regarded as the most important factor in early seedling survival, since rapid extension of roots enables the seedling to exploit water from previously unexplored areas of soil." (Schütz et al., 2002)*

Many eucalypt species at the seedling stage reveal a propensity for rapid root growth, extension, exploring soil medium for moisture; results from the seedling experiments and general field observations show that Coolibah is no exception (Phillips and Riha, 1994, Schütz et al., 2002). It is important to comprehend the nature of conditions and processes that support rapid root development and access to groundwater resources.

During recent synecological research on the nearby Cooper Creek system it was observed that Coolibah was usually reliably encountered in mesic areas along the main channel levee banks and adjacent immediate floodplain. However ,instances of occurrence were observed in locations of the landscape that were not edaphically suitable, in particular the xeric or drier outer periphery of the floodplain (Gillen, 2010). The following processes were proffered hypothetically to describe these observations;

> *"To become established and persist in the outer xeric regions of the floodplain would require an extended period of suitable soil moisture conditions. The clustered flooding events associated with a sequence of La Niña events over several years would provide such an opportunity. Eucalyptus coolabah would be distributed widely in the landscape and become established on a range of soil types (Puckridge et al., 2000). Subsequently when climatic conditions revert to the norm, extended periods of drought prevail and soil moisture deficit sets in, particularly in the outer regions of the floodplain. Those individuals established on the heavy clays of the floodplain proper would be severely compromised. Being rarely flooded, these inherently saline soils accumulate salts in the upper surface as a result of capillary rise associated with extended periods of high potential evaporation resulting in severe osmotic stress (Overton et al., 2006). To further compound this situation, the matric potential of these clay soils reduces freely available soil water (Russell, 1980). As previously discussed (Chapter 4), these clays also effectively swell and seal following large local rainfall events, forming an impermeable barrier to the infiltration of water (Maroulis et al., 2007, Costelloe et al., 2009).*
>
> *In contrast, those individuals established on the sandier soils of the floodplain outer margin would experience different edaphic conditions. The ability of an individual to extract soil water varies with the soil texture (matric potential) and soil water solute concentration (osmotic potential). Unlike clays, sands with a coarser structure facilitate ready infiltration of water from rain or flood flushing salts from the profile. In addition, higher temperatures in the summer months expand the sands, increasing the infiltration rate (Evenari, 1985). The coarser structure of sands also renders soil water more readily available to plants. The inverse texture hypothesis (Noy-Meir, 1973) proposes that soils of sandy coarse texture particularly in the arid zone tend to support more woody and mesophytic vegetation than finer textured heavy clays (Schwinning et al., 2004, Curran et al., 2009). The converse applies in more mesic climatic zones, hence the term 'inverse texture hypothesis'."…." A possible and plausible reason for the observations of Eucalyptus coolabah in the xeric regions of the floodplain is that the junction between the mud drape and aeolian sand superimposed upon the palaeo fluvial coarse sands below could be a significant groundwater recharge zone".(ibid)*

The accompanying conceptual model, Figure 38, attempted to visually describe the above processes.



Source: Nanson et al 2008, p117

Figure 38 Source ; (Gillen, 2010)'

Diagram a) in the conceptual model depicts geomorphological research (Nanson et al., 2008) which revealed the shift in fluvial conditions over the Quaternary. Initially a high energy system was capable of transporting a sand/gravel alluvium until a shift in climatic regime commencing around 110 ka ago caused a transition to a lower energy system carrying finer clay rich 'mud' sediments. These muds, of varying depth in relation to the surface shapes of the earlier floodplain palaeo topography (Diagram b) in Figure 38) were laid down over the more porous sands and gravel below .The clay rich muds form a virtual impervious layer, sealing the sands and gravels below which subsequently form an aquifer system; a groundwater source.

Hypothetically it is possible that it is the varying thickness of the 'mud' drape over potential groundwaters below that is critical in the establishment and ultimate persistence of Coolibah. The thinner the drape the greater the chance of total saturation following a sequence of flooding events which provide edaphic conditions suitable for the penetration of mud drape and extension of a phreatophytic root system into the groundwater zone below. The deeper the mud drape the less likely that the soil profile will be totally saturated posing a barrier to root development and preventing access to groundwater.

Interestingly on the upper Cooper Creek in South Australia extensive areas of floodplain are bereft of Coolibah suggesting that the depth of mud drape is prohibitively large preventing the persistence of the species. However, in contrast, on sections of the upper Diamantina in the study area Coolibah were observed growing directly in floodplain 'muds' suggesting conversely that the drape may be thinner, facilitating root penetration into the groundwater zone of paleo sands and gravels.

In the Cooper Creek synecological study referred to earlier, as depicted in Diagram b) of Figure 38 above, in depressions on the floodplain where the thickness of the clay sediments were such as to induce the deep cracking characteristics of vertisol soils, shrublands of *Chenopodium auricomum* (Queensland bluebush) or *Duma florulenta* (Lignum) dominate. These plant communities are also to be found within the cracking vertisols of the large swampy habitats of Embarka and Tirrawarra Swamps on the Cooper and the extensive Goyder Lagoon on the Diamantina. In each of these habitats, Coolibah is noticeably, virtually absent. This absence could be a product of increased depth of sedimentation of these floodplain basin areas; greater periods of anoxic conditions due to increased propensity to retain floodwaters ; or higher capacity for development of deeper cracking of soil profile with increased clay depth resulting in an edaphic environment hostile to Coolibah root development.

Many of the above hypothetical suggestions could be usefully investigated and developed through an appropriate research program framed within the overall context of groundwater maintenance. There is an obvious need to develop a deeper understanding of the establishment and persistence of Coolibah in the landscape in relation to groundwater dynamics, particularly the processes and locations of recharge, within these dryland river systems of the Lake Eyre Basin.

8 Palatability

8.1 Introduction

Generally it is considered that *Eucalyptus* foliage is of low nutritional value (Landsberg and Cork, 1997) even to those native mammals that utilise it let alone ruminants such as cattle. As research has shown, mature *Eucalyptus* foliage contains high concentrations of lignin and a range of plant secondary metabolites (phenolic, terpenoides and cyanogenic compounds). The combined effect of the secondary compounds; tannin and phenolics is to potentially exert negative physiological and metabolic effects on the consuming animal and in the instance of lignin to reduce the amount of total nitrogen available for digestion (Figure 39).

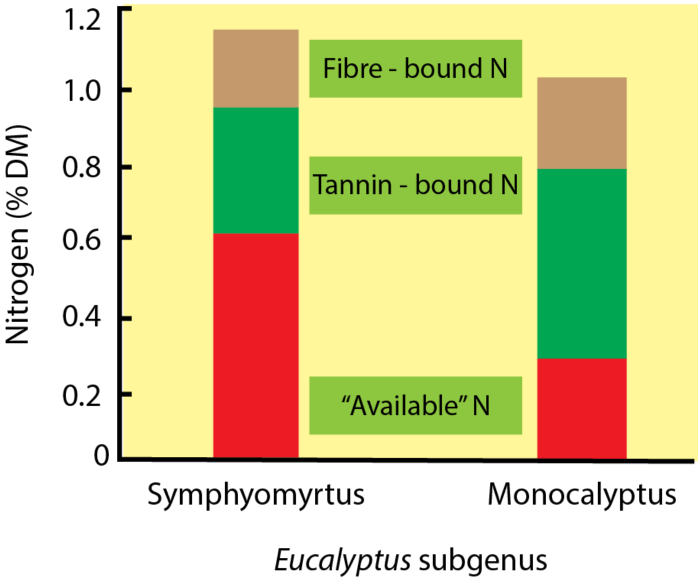


Figure 39 (Source: Dr William Foley)

Therefore in light of this apparent unpalatability, it is interesting to observe that cattle within the study zone are grazing upon both mature Coolibah and reducing saplings to bonsaied forms through continued grazing pressure upon regrowth foliage (Figure 40).

Figure 40 Left, browse line on mature Coolibah. Right, "Bonsaied" form

As the results for the nitrogen assay of foliage from the study region show (Table 8) the concentrations of available nitrogen available for both 'new' and mature foliage is low as expected. However it does appear that the levels of available Nitrogen in 'new' foliage is consistently greater than that of mature foliage, albeit still low (Figure 41).

Table 8 Available Nitrogen results for Mature and Immature foliage

Site 7 Tree 3	**N**	**SolPEG**	**Sol**	**DMDPEG**	**DMD**	**Ndigpeg**	**Ndig**	**AvailNPEG**	**AvailN**	
Mature x 2	0.842	0.204	0.341	49.085	52.494	0.664	0.471	0.560	0.401	D-Split WH
New x 2	1.295	0.334	0.446	52.980	59.814	0.568	0.441	0.740	0.570	Pandie Pandie
Site 7 Tree 1										
Mature x 2	0.919	0.257	0.386	51.582	53.834	0.575	0.367	0.529	0.336	D-Split WH
New x 2	1.119	0.278	.0395	56.980	61.753	0.589	0.334	0.658	0.379	Pandie Pandie
Site 7 Tree 2										
Mature x 2	0.877	0.239	0.311	47.654	46.391	0.611	0.298	0.540	0.261	D-Split WH
New x 2	1.253	0.266	0.402	52.005	56.963	0.603	0.355	0.755	0.445	Pandie Pandie
Site 5										
Mature x 2	1.012	0.277	0.386	49.086	51.665	0.696	.0428	0.742	0.435	Tepamimi WH
New x 2	1.319	0.300	0.366	56.877	60.092	0.719	0.470	0.950	0,622	Clifton Hills
Site 4										
Mature	0.908	0.255	0.398	46.770	49.610	0.774	0.497	0.702	0.455	Yammakira WH
New x 2	1.224	0.296	0.404	55.276	57.896	0.730	0.652	0.894	0.800	Clifton Hills
Mature x 2	0.965	0.261	0.380	47.661	50.761	0.763	0.509	0.736	0.492	

Lawler and Foley (2002) in a comparative analysis of the volatile essential oils content of seedlings and mature foliage of *Eucalyptus delegatensis* found seedling leaves contained approximately 0.1% (dry weight basis) steam-volatile essential oils whereas mature foliage contained 10 to 12 fold more oil. In considering the volatile oil content of the various leaf age classes for the species they found that; "Oil concertation in seedling leaves is invariably much lower than that of the other stages." (ibid)

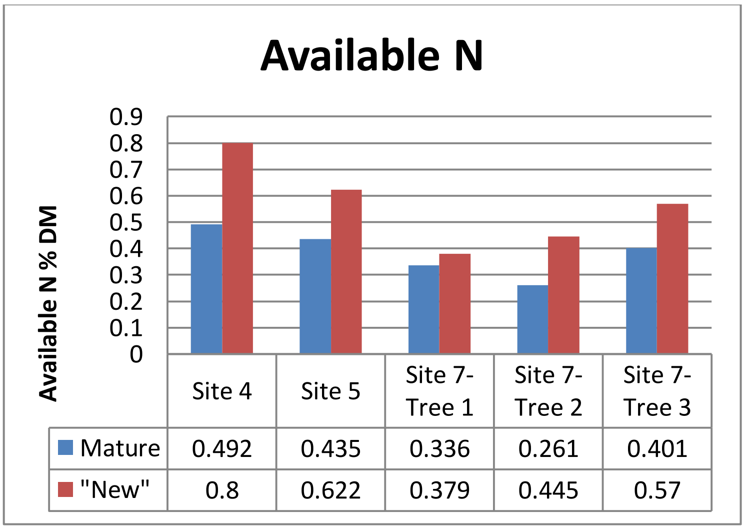


Figure 41 Graphical depiction of Available Nitrogen results

The nitrogen content of eucalypt species in known to vary between species: Prior et al.(2003) found total nitrogen concentration to vary between 0.7 to 2.3% depending upon species. Farquar et al. (2002) found a negative correlation between nitrogen concentration in the foliage of one eucalypt species *E. dichromophloia* and mean annual rainfall; nitrogen values increased as mean annual rainfall decreased. Examining the variation in chemical traits over the geographic range of *Eucalyptus globulus* ssp. *globulus*, Wallis et al. (2011) found a negative correlation between the concentrations of available N and secondary metabolites. In other words plant tannins and other secondary compounds decreased in content as available nitrogen increased.

9 Coolibah water use

9.1 Background

It is generally accepted that riparian vegetation is sensitive to shifts or changes to naturally functioning hydrological regimes (O'Grady et al., 2005). Gaining an insight into the daily and seasonal water use requirements of riparian trees such as Coolibah in the highly variable climate and hydrological regime of the Diamantina system is challenging and not an exercise to be undertaken over a short time-frame. Water use will vary according to both landscape position and soil type in addition to the hydrological extremes of flood and drought. However, developing a deeper understanding of water use of the species at a population level will facilitate more informed assessment of the potential impact that deliberate (human intervention; extraction, damming etc) or natural (climate change) alterations to the naturally functioning hydrological regime may exert upon the Coolibah population of the Diamantina system.

The research aims to provide;

- insight into the water use requirements of *Eucalyptus coolabah* and associated growth responses of Coolibah at a seasonal level enhancing the interpretation of the dendrochronological work. Significantly, the development of a water budget model can ultimately be scaled up using proven techniques to provide a much needed and valuable estimation of overall contribution of this highly significant perennial species to floodplain productivity at a regional level.
- insights into the potential influence of soil and water quality characteristics upon transpiration rates.

9.2 Methodology

Under the direction of Dr Tanya Doody, Plant Physiologist, CSIRO, temporal and spatial patterns of water use by Coolibah are being monitored by solar powered sap flow loggers placed in selected trees at two locations representing the extremes of the Diamantina/Warburton River system in the South Australian study region (Figure 42).

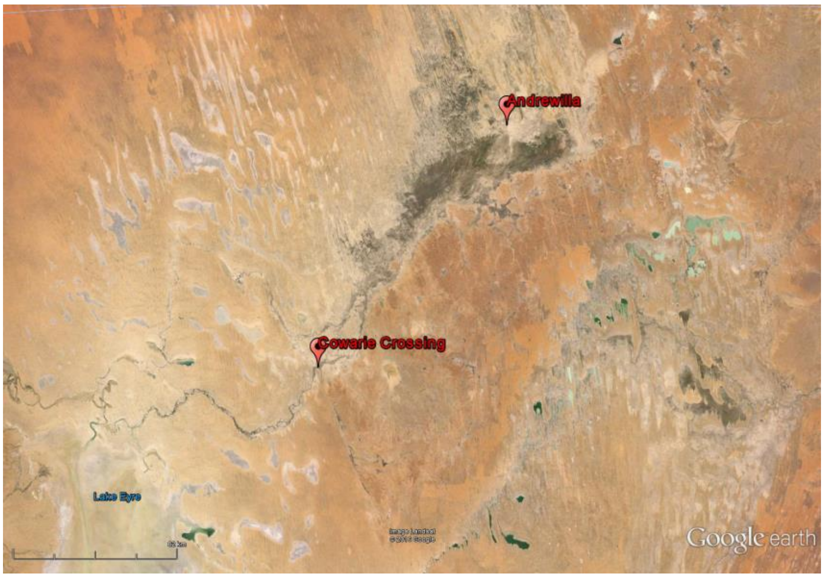


Figure 42 Location of sap flow loggers

Andrewilla Waterhole in the far north of the study region receives more regular flooding events than the Cowarie crossing Waterhole location in the far south. Associated with this decreasing flooding regime to the south is an increase in soil salinity and groundwater salinity which would be expected to impose increasing physiological stress which should be reflected in differing transpiration rates in Coolibah populations longitudinally down the Diamantina/Warburton system. Superimposed upon this gradient is the effect of soil type upon water accessibility to individual trees at a local level.

Accordingly at each location paired sites (each a 20 x 20 m quadrat) have been established in the two main contrasting soil types found along the riverine corridor (loam) and the immediately adjacent floodplain (heavy clay). Sap flow loggers have been installed in suitable trees within these quadrats; solar panels power these logging units over the long-term reducing the need for regular visitations to this remote area for downloading stored data (Figure 43). Ultimately the data resulting from this work will be used to calibrate a model for estimating actual regional evapotranspiration (ETa) along these inland river systems based on the Enhanced Vegetation Index (EVI) from the Moderate Resolution Imaging Spectrometer (MODIS) sensor on the EOS-1 Terra satellite (pers comm Tanya Doody)

Figure 43 Left, sensors attached to Coolibah trunks. Right, Solar panels powering sensors/loggers

Soil samples collected within each of the quadrats (4 in total) included;

- 10 bulk density samples collected at random to a depth of 10cm
- 1 soil profile to a depth of 50cm in 5 x 10cm increments.

At the Andrewilla location, samples were collected from within both quadrats with the intention of developing soil water characteristic curves representative of the riverine loam and floodplain clay. Five samples (each of 5cm depth) were collected to a depth of 40cm and the procedure subsequently replicated within each quadrat.

The soil assessment aims to complement the water use study by;

- providing insight into the influence of soil parameters upon transpiration characteristics of Coolibah on riverine loams and floodplain clays
- providing insight into soil parameters influencing Coolibah distribution and density in these differing soil types.

9.3 Results

Soils

All soil samples collected from all quadrats at both Andrewilla and Cowarie crossing for the purpose of determining surficial bulk densities and profile pH and Ec have been analysed; results are reported in Appendices 8 and 9. Soil moisture characteristic curves have been determined for replicate profiles in both quadrats at Andrewilla Waterhole; results are reported in Appendix J.

Water use

Unfortunately at the time of submission of this report extended flooding conditions associated with the regional rains and hydrological pulses of late 2016 have prevented Dr Doody from gaining access to both sites. A field trip is planned for late May 2017 to download all data accumulated over the past 12 months.

10 Estimated Coolibah biomass

10.1 Introduction

Affiliated with the main intent of the Biodiversity Fund Program, namely to maintain ecosystem function and increase ecosystem resilience to climate change; is the expressed secondary intent to; '*increase and improve the management of biodiverse carbon stores across the country*'.

The dryland river systems of the Lake Eyre Basin with their Coolibah dominated riparian woodlands offer such an opportunity to both maintain and potentially increase sequestered carbon through the conservation of processes that support associated biodiversity.

Associated with these riparian corridors of Coolibah and their plant communities are elevated levels of primary production and increased expression of regional biodiversity across trophic levels particularly following flood. In this context the significant biomass associated with the heavily wooded riverine corridors of the Diamantina and Warburton channels represent a potentially significant store of carbon within this desert landscape. A preliminary investigation and subsequent quantitative estimation of potential above ground woody biomass associated with these riverine corridors could provide a valuable surrogate for the contribution of Coolibah to system productivity and additionally a measure of the potential carbon sequestered within the system.

10.2 Methodology

The use of accepted allometric equations and techniques for the estimation of eucalypt carbon from a range of quantitative measurements in the field is a standard practice in Australian forestry. In order to apply such an approach within the study area the necessary quantitative measurements were incorporated within the vegetation assessment process conducted at each of 15 water holes assessed during 2014. Whilst three 100 metre transects were assessed floristically at each waterhole only the central 100 metre transect was retained as a permanent site for ongoing monitoring of biodiversity health and values. The quantification of Coolibah above ground biomass was conducted along this permanent transect. This central transect was simply converted to a 100 m line intercept transect; any individual Coolibah whose canopy was intercepted by the line transect was then measured for height, canopy width and breadth, and trunk diameter (all in metres). The diameter of all multiple trunks was recorded if present for an individual tree.

The early development of allometric equations to quantify standing biomass was conducted within the northern hemisphere, specifically for species encountered in forests and plantations. Within Australia allometric equations have been derived from the development of such equations in accordance with IPCC principles to quantify above ground carbon stores associated with the range of forest and woodland types extant predominantly in the more mesic environments of the continent (Snowdon et al., 2000, Snowdon et al., 2002). Different species have differing potentials for carbon storage according to parameters that include physical form, life cycle growth strategies, timber density and age (Jonson and Freudenberger, 2011). There have been few if any allometric equations developed specifically for arid zone eucalypt species such as Coolibah. The density of *Eucalyptus coolabah* is stated to be around 1150 kg/m^3 (Boland et al., 1984 (4th edn)). To convert above ground biomass to an estimation of sequestered carbon a conversion factor of 0.5 was used. It must be stressed that the results based on the above assumptions are approximate; more accurate estimation would require a far more rigorous process of investigation. The development of species specific equations for Coolibah would require the destructive sampling of individual trees of a range of ages to determine the allocation of carbon to both above and below ground biomass.

The practicality of applying such an approach to Coolibah in the study area was ascertained and verified by discussion with suitably qualified colleagues (Fenner School, ANU) specialising in Australian tree species. A number of assumptions were made regarding the nature and value of parameters included in the equation used for Coolibah as shown in Table 9.

Table 9 Parameter assumptions used in allometric equation

Parameters	°
Form factor	2.5
Basic density	1.15
Internal decay %	0
Expansion factor	1.3
C%	0.5
Plot area	0.1

10.3 Results

As shown in Figure 44 there is a wide variation in the amount of potential above ground carbon sequestered at any one site; ranging from a maximum of around 49 tonnes per hectare at Windmill Waterhole, Pandie Pandie Station to a minimum of 11 tonnes per hectare at Ultoomurra Waterhole, Clifton Hills Station. The overall average estimate including all 15 sites represents around 26 tonnes of carbon per hectare.

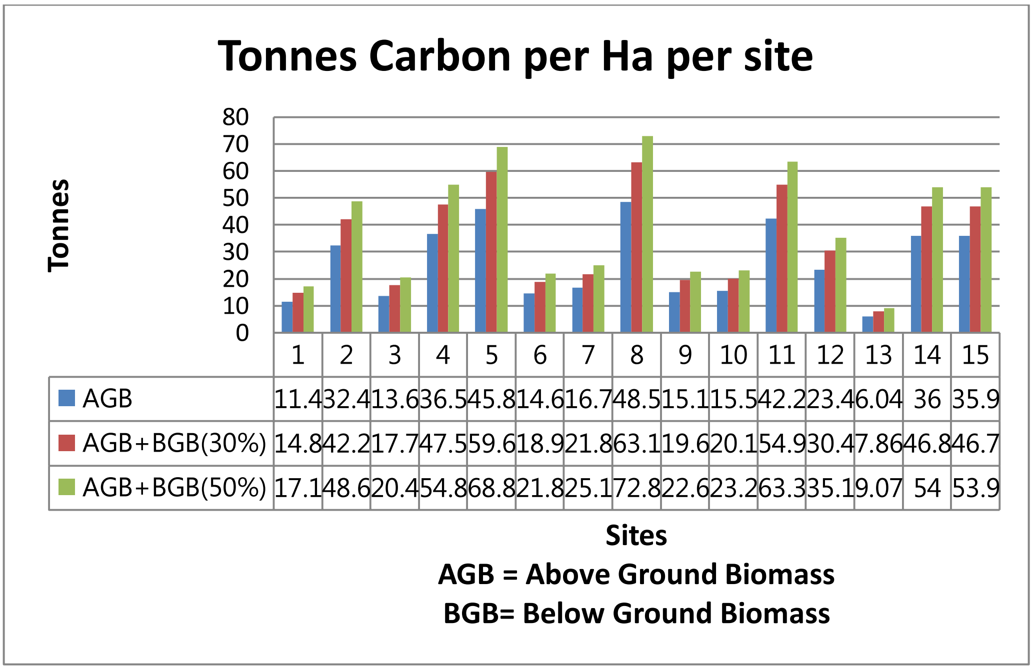


Figure 44 Estimation of potential Carbon sequestered

The riverine corridor, dominated by *Eucalyptus coolabah*, can vary in width according to local geomorphological and hydrological conditions from the width of a single tree along straight sections of the main channel to extended woodlands on the inside bends of channel meanders. This is depicted in the aerial images of both Ultoomurra and Windmill waterholes in Figure 45.

Figure 45 Comparative coolibah densities

Above ground biomass (AGB) estimates can be converted to estimates of belowground biomass (BGB) using default root-to-shoot ratios. The standard default IPCC ratio for forests is 0.26 relates to more temperate mesic environments. There is a dearth of information relating to below ground biomass values for plants of arid zone ecosystems within Australia. However, it is generally recognised that for arid trees there is a considerable increase in allocation of biomass to the root system. Zerihan et al (2006) have shown that the BGB:AGB ratio increases across a decreasing rainfall gradient. Sampling *Eucalyptus populnea* across such a gradient they found an increase in the BGB:ABG ratio of around 0.6, considerably exceeding the default preferred by the IPCC. Taking these findings into account, the results of applying BGB:AGB ratios of 0.3 and 0.5 respectively to the estimates of ABG for all sites provides an approximate range of potential total carbon sequestered by Coolibah as depicted in Figure 44 (34 to 40 t/Ha average per site).

The total amount of estimated sequestered carbon per site would be further raised by the inclusion of all permanent riparian plant species.

Given the results obtained from ^{14}C dating regarding the longevity and growth rates of mature riparian Coolibah it would appear that the carbon stored by Coolibah has been slowly sequestered over several hundred years.

11 Ethnology of Coolibah - Aboriginal uses

In the far north-east of South Australia the Diamantina River and Cooper Creek represent scarce conduits of moisture and productivity in one of the harshest landscapes on the Australian continent. These riparian ribbons supported a rich and varied biodiversity which in turn provided the base for a productive, rich and vibrant indigenous culture. Early historical accounts of explorers, pastoral pioneers and researchers abound with references to Aboriginal occupation within, and relationships to, this region, revealing how people were inextricably entwined within the varied ecosystems and dynamic ebb and flow of biological conditions driven by flooding events of local and geographically distant genesis.

The floods were the lifeblood of these desert communities;

> *"The Georgina and the Diamantina are to the back country and its inhabitants what the Nile is to Egypt and the Egyptians. The blacks waited for, and depended largely on the waters of these two streams for their good seasons and festivals. No rains, no river-floods, no glad festivals; only solemn dour food-ceremonies, enacted by drought-weary blacks to propitiate Kun-ma-ra, the Rain God." (Duncan-Kemp, 1933)*

Alice Duncan-Kemp lived on Mooraberrie Station between Farrer Creek and the Diamantina River in far south west Queensland in the early 20th Century. The flood events she described, inundated the productive grey clay soils of floodplains supporting a wide range of resulting plant material including edible seeds, tubers, fruit and other vegetable matter used for a variety of purposes.

These desert wetland systems associated with the Diamantina and Cooper systems were productive enough to support a regionally significant indigenous population. John McKinlay in charge of an expedition in search of the ill-fated Burke and Wills party, whilst travelling through the region along the Cooper system found that;

> *Go where you will, you will find them in groups of fifty and hundreds, and often many more…"(McKinlay, 1863)*

Davis a member of McKinlay's expedition party emphasised the nature of the productivity of such river systems in supporting a considerable population in observing that;

> *"..they seem to revel in plenty of food with nets of their own fabrication they dragged the creeks for fish, procuring large quantities." (Davis, 1863)*

Along both the Cooper and upper Diamantina in South Australia adjacent to more permanent water sources explorers encountered semi-permanent *"villages"*, comprising substantial durable huts of timber, grass and mud that were: "*wind and rain proof and often large enough to hold several people.*" (Howitt, 1878, Sturt, 1849)

However, by 1879, given the earlier disastrous impact of confrontation, smallpox and other diseases associated with European arrivals, Gason (1879) (a police officer stationed in the Diyari territory in South Australia for nine years) reported a substantial reduction in this broader regional population;

> *"The Dieyerie [Diyari] tribe numbers about 230, the four neighbouring tribes the Yandrawontha [Yandruwantha], Yarrawaurka [Yawarrawarrka], Auminie [Ngamini] and Wongaooroo [Wangkangurru] about 800…in all about 1030".(ibid)*

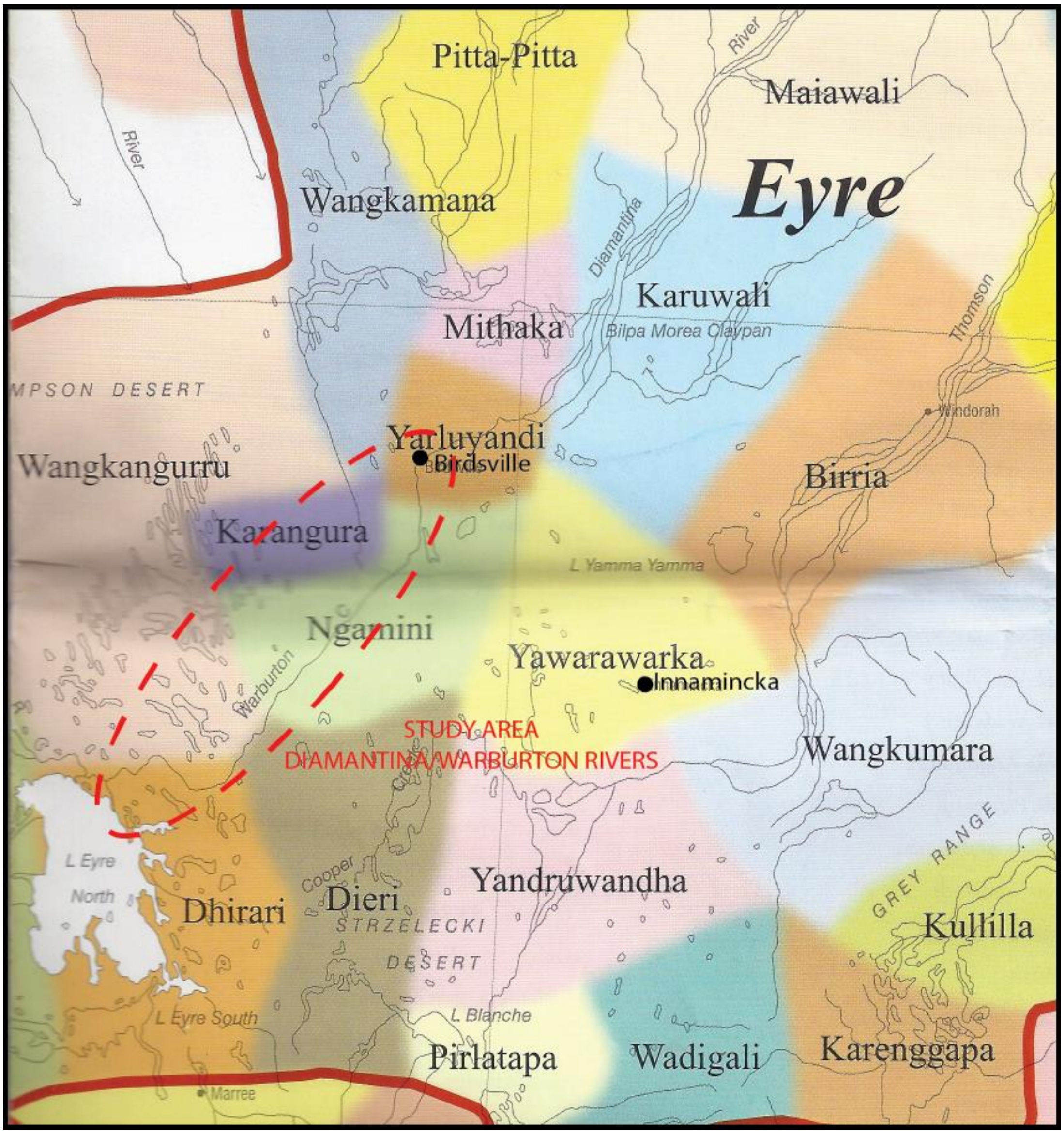


Figure 46 Aboriginal Language Groups, Lake Eyre Basin (source:(AIATSIS, 2008)

An indication of population numbers on the lower Diamantina/Warburton River system at the period of contact between Europeans and indigenous inhabitants was provided to E. M. Curr in response to his request for information on local aboriginal languages;

> *"The following vocabulary of the language of the Ominee tribe was forwarded to me by Mr. W. J. Paull, if I read the signature correctly. That gentleman informs me that the marches of the lands of the Ominee, Wongonooroo, Kuranyooroo, and Yarleeyandee tribes, all intimately connected, meet on the Warburton River, at Cowarie headstation. This country, my correspondent goes on to say, was first occupied by the Whites in 1876, at which time these tribes amounted in the aggregate to between six and eight hundred souls, at which number they still remain." (Paull, 1886)*

The impact of disease, pastoral appropriation of country and associated massacres so reduced the population that by the late 20th century Hercus was able to state authoritatively that of the four language groups once spoken in the north eastern Lake Eyre Basin region, the Ngamini and Yandruwantha languages had become extinct, Yawarrawarrka virtually so, and only two speakers of Diyari remained (Hercus, 1990). (Figure 46)

As has been emphasised in this report *Eucalyptus coolabah* as a keystone species of riparian corridors and immediately adjacent floodplains is fundamental to the structure and functioning, and associated biodiversity of these ecosystems. Echoing this natural ecosystem significance Coolibah, was also vital to the human ecology of the region; playing a fundamental role in the economy and social life of the indigenous population.

An extensive review of relevant literature for this study has resulted in a plethora of examples of the integration of Coolibah into aboriginal life. This material is presented simply under relevant sections and where possible quoted directly from the source. As stated earlier the taxonomic confusion caused by the early general use and broad acceptance of the *Eucalyptus microtheca* epithet before and after *E. coolabah* was classified in 1934 is commonly encountered in the literature. However, given the similarity and environmental proximity of the species both species would most probably have been utilised in a similar fashion hence the material below at times includes reference to one or the other species.

In conjunction with the review of literature, collections of aboriginal artefacts from the north-east portion of the Lake Eyre Basin Region in South Australia were also reviewed for Coolibah content at the National Museum of Australia, the South Australian Museum and the Melbourne Museum, Victoria. The range of timbers used for implements from this region is limited although of varied physical character. Some species such as *Acacia aneura* were utilised for specific artefacts, mainly those tools and weapons requiring a distinctive tight dense straight grain and are visually quite distinct. However, determining the identity of timbers used for other artefacts is difficult and would require appropriate technical analysis. Those artefacts mentioned in the literature as being fabricated from Coolibah were examined and photographed. A selection of these is provided at the end of this section (Figure 56 and Figure 57). The freshly exposed longitudinal grain of Coolibah examined in the field revealed a distinctive 'wavy grain form', also visible on fallen Coolibah logs and on the surface of a number of the artefacts photographed. Examples of this distinctive grain are presented in the sequence of adjoining photographs depicting freshly exposed timber, fallen log and coolamon.

11.1 "Coolibah" and associated nomenclature

The Australian National Dictionary centre presents the following entry for "Coolibah";

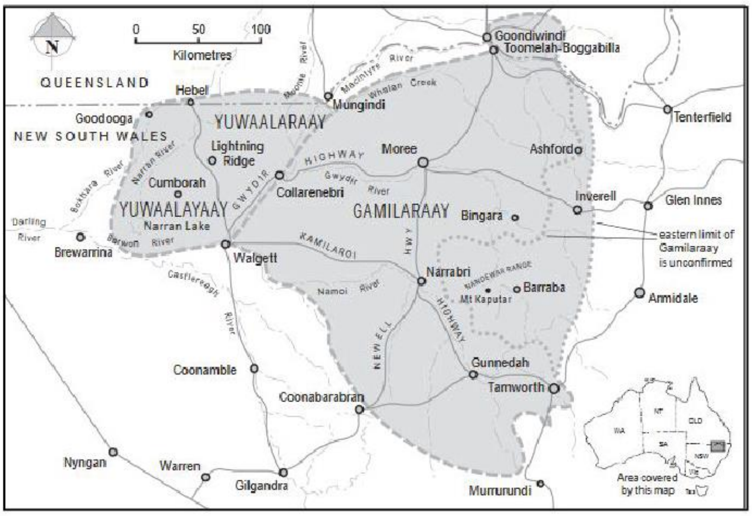
> *The word is a borrowing from Yuwaalayaay (and neighbouring languages), an Aboriginal language of northern New South Wales. In the earlier period it was spelt in various ways, including* ***coolabah****,* ***coolobar****, and* ***coolybah****.*
>
> *It is a term for any of several eucalypts, especially the blue-leaved Eucalyptus microtheca found across central and northern Australia, a fibrous-barked tree yielding a durable timber and occurring in seasonally flooded areas.* ***Coolibah*** *is first recorded in the 1870s.*
>
> *1876 Sydney Morning Herald 9 August: The country consists of open plains, with myall and coolabah.*

(http://andc.anu.edu.au/australian-words/meanings-origins/c)

An inspection of the relevant term in the *Gamilaraay (GR), Yuwaalaraay(YR),and Yuwaalayaay (YY) Dictionary* entry reveals the following;

> *"gulabaa (YR, YY, GR) noun, coolabah tree(Eucalyptus coolibah ssp.arida).*
> *This is a medium-sized tree that grows in watercourses and depressions and has a very hard timber. Branches and leaves can be used to stun fish in waterholes, but may need to be left overnight, and used for cooking emu in a ground oven. The leaves are boiled in water and sweetened with honey; this liquid is drunk to relieve colds and whooping cough. Flour can be made from the seeds: branches are broken off and laid on a claypan, the seed capsules will open after five days, and the debris is collected and winnowed. Seeds can then be soaked, cleaned, dried and ground, and the resulting paste eaten. The roots may be tapped for water and the inner bark can be beaten and applied as a poultice for snake bite and severe headache.* ***Possibly from gula (tree fork) and –baa (place of, time of). Possible source of English 'coolabah'****. " (Ash et al., 2003)*

The Yuwaalayaay language group is located in the upper catchment of the Darling River System, northern New South Wales as shown in Figure 47.



(Source: Ash et al, 2003)

Figure 47 Location of Yuwaalayaay language group

Joseph Maiden in his *Forest Flora of New South Wales* under the entry *Eucalyptus microtheca* stated that "*This is the true Coolabah of the aborigines, variously spelt Coolybah, Coolibar, Coolybar.*" (Maiden, 1917). Maiden was describing the species as encountered in New South Wales; hence this would refer under current taxonomy to *E. coolabah*. However, Maiden then goes on to add that *Eucalyptus microtheca* is also referred to as "Jinbul" and Kurleah" by the aborigines of southern Carpentaria region. (ibid). Given the location these names would relate to the current *Eucalyptus microtheca* which is restricted in distribution to these northern locations.

In his other well-known work "The useful native plants of Australia" Maiden offers a more extensive list of aboriginal names*; "It has many aboriginal names. The following are some of them – "Callaille "and "Yathoo", Murchison River (Western Australia); "Targoon," Riverina (New South Wales); "Jimbul Kurleah," Cloncurry River, and other parts of Northern Queensland; "Coolybah," or "Coolibar," Western Queensland and about the Darling, New South Wales; "Goborra" or "Goborro", Western New South Wales; "Koloneu", Queensland."* (Maiden, 1889)

The aforementioned Duncan-Kemp, of Mooraberrie Station, Queensland, within the territory of the Mittaka language group, records that the native name for *Eucalyptus coolabah* in the region was "karabadi". She also mentioned the timber being used for firewood and firesticks and for making message sticks and large coolamons ("koordoo"). Coolibah seed was termed "karapiri" and was crushed and converted into damper ("patti"). The gum or kino of coolibah was also utilised, most probably for medicinal purposes (Duncan-Kemp, 1933, Duncan-Kemp, 1964).

Within the language groups of the north east area of South Australia the following native names have been recorded for Coolibah. From the Cooper Creek region, Yandruwandha and Yawarrawarrka language groups; "Kulparoo" (Cornish and Salmon, 1886), "Kalpurru" (Kerwin and Breen, 1981, Tolcher, 1986).

Recorded from the Pandie Pandie Region on the Diamantina in South Australia; Ngameni and Wonka-nguru [Wonkanguru] language; "pattera", "puttera" (Johnstone and Cleland, 1943).

For the lower Cooper, Dieri language; "pathara" (Gason, 1879); "pattara " (Helms, 1896) "pattara" (Howitt and Siebert, 1904); Howitt (1904) also provides "ngarumba" which he associates with Dieri and Yawarrawarrka; "patara" (Berndt and Vogelsang, 1939). Interestingly in the context of Coolibah, Gason also provides an extensive range of Dieyerie [Dieri] words which also include additional terms that relate to parts or physical aspects of the tree, or life stages; "patharacoorie" = young tree sapling; "pittacopara"= roots of trees; "patharapowa" = seed of Coolibah; "Wompinie" = In the shade, sheltered from the sun; "Oolyie" = gum; "Wurta" = The butt, the trunk; "Yuntha" = a piece of wood (Gason, 1879)

11.2 Coolibah as source of food

General observations

> *"Their food is principally vegetable, animals being very scarce, if we except rats and their species, and snakes and other reptiles, of which there is an unlimited number. There are no kangaroo, and very few emu, the latter of which is their favourite food; and occasionally, in very hot weather, they secure one by running it down." (Gason, 1879)*
>
> *"…as there is great difficulty in their being able to procure much flesh of any kind, oppossums and kangaroo being scarce; their principle food being oats (sic), lizards, snakes, birds, mussels, and roots " (Cox, 1881)*

In relation to the above statement, Cox J C was reporting from the Cloncurry River 270 miles south of Normanton on the Gulf and 570 miles west of Townsville.

> *"The aboriginals appear to be possessed of considerable knowledge of indigenous plants and their uses in their several districts, as well as the periods of their flowering and fruiting; they also use many for their supposed medicinal qualities; and considering that nearly half of their daily food consists of roots and fruits it is no matter for surprise that they should possess some knowledge of plants." (Palmer, 1883)*
>
> *"Their food may be described as consisting of everything having life…..Seeds generally are called "Bowar", of which the Portulac – the "Manyoura bowar" – is the most prized. It is collected in large quantities by the natives after rains. It is even sometimes collected in such quantities as to be preserved for future use. Near Lake Lipson, one of my party found about two bushels contained in a grass case daubed with mud. It looked like a small clay coffin and was concealed." (Howitt, 1878)*
>
> *"As regards their food, it varies with the season. That which they appeared to me to use in the greatest abundance was seeds of various kinds, as of grasses of several sorts, of the mesembryanthemum [Portulaca spp.?], of the acacia and of the box tree" (Sturt, 1849)*

Coolibah seed utilisation and preparation

> *"The following information was obtained from a Mickeri native. The branches are broken off and taken to a claypan, where the seed (paua wudlia, pau kurdi) becomes liberated from the capsules in about five days' time. The seed and debris are collected and placed in a coolamon, and then rubbed with the hands to clean and dry the seed. The latter is then treated in the same way as that obtained from grasses. About two handsful are placed in a lower millstone with a groove along one side and ground with a smaller stone till very fine. The moist mass is then collected into a dish (pitchi) held below the edge of the lower stone. This paste (paua bilu) may be eaten dry, but the main portion is usually cooked in hot ashes." (Johnstone and Cleland, 1943)*
>
> *"The term mickeri or mickri people is commonly applied to those coming from the sandhill (dako, Dieri; wadlu, Arabana; mudloo, Wonka-nguru; daku, Ngameni) region west of the Diamantina and Warburton and including the Simpson Desert. The term is given because the tribesmen (now chiefly Ngameni and Wonkamala) obtain their water from supplies from soaks (mickri, Wonga-nguru; ngapa tjili, Ngameni) commonly deep in the sand."(ibid)*
>
> *"The seed of the coolibar (sic) (Eucalyptus bicolor, A. Cunn) (sic), also constitutes a staple article of diet, when grass-seed is scarce: locally it is known as ka-ra-pa-ri. With a hooked stick some terminal branches of this tree are pulled down and, just as they are, spread out to dry on a piece of ground cleared for the purpose. Here they lie, according to the heat of the sun, for half-a-day, a day, till sunset, or the following morning. The ends of the branches are then all collected together, and the seed obtained by damping the distal extremities and brushing them off into water, as in the case of the Katoora. Before the ultimate drying, however, the coolibar seed is kept for a couple of hours or so in water, which during this time is repeatedly changed, so as to remove all traces of the "gum." After being ground on the pappa-stone it is eaten raw." (Roth, 1897)*

"One called "Pappa" is made from the seeds of the coolibah gum. The seed-laden branches are pulled down and heaped in the sun, where in an hour or two the pods open and the seeds fall on the ground. Then they are collected in a cooliman (sic) taken to camp, cleaned by sifting in a cooliman, grass and leaves coming to the top, and earth and gravel settling on the bottom. The quantity required is then damped in a cooliman, from whence it is taken in handsful and ground on a flat stone which is obtained from one locality in latitude 20deg 30min across the South Australian border, a spot under the control of an old native, from whom permission must be obtained. The grain is ground by a store held in the hand and a peculiar movement sends the flour over the edge into a receptive cooliman. This damp paste is either eaten raw, or is mixed in an unsightly mass and cooked in hot ashes." (Coghlan, 1898) (NW tribes of the Georgina River)

"Seeds comprise by far the major part of Walbiri vegetable foods." (Meggitt, 1957)

"There are a number of trees and plants in the Walbiri environment which do not normally provide food, although some would doubtless be used reluctantly in times of sever food shortage. Some of these, such as Eucalyptus microtheca and Acacia farnesiana (budunari) regularly provide food for other tribes, so it seems that mere availability does not guarantee that an edible plant will be used in a given area." (ibid)

"Patharapowa - - The seed of the box-tree, ground and made into loaves." (Gason, 1879)

"The seeds of the "boxwood" (Eucalyptus microtheca) are eaten everywhere where they can be collected in sufficient quantities, especially in the neighbourhood of Lake Eyre. It is the size of a grain of sand; by shaking the twigs covered with ripe seeds over a hollowed out piece of wood it is possible to obtain enough in a short period of time to satisfy ones hunger. The largest quantity of vegetable food - about 1 hectolitre - I saw in the possession of the Aborigines of a central tribe consisted of these seeds.... The seeds of Eucalyptus microtheca, Claytonia, grasses etc. are cleaned, where possible, by winnowing, grinding them with the addition of water on grindstones to produce a pap or paste. This is baked in hot ashes and then consumed without any further ado" (Eylmann, 1908)

"On inspection we found that a small black ant had laboriously collected quantities if the seed of a panic grass and arranged these around the openings of their nests. These had been scooped up in handsfull by the women, who otherwise would have been unable to obtain any quantity of grain as this had all fallen out of the heads of the grass." (Cleland, 1936) [It is also possible that Cooliabh seed was collected in a similar fashion; coolibah seed was observed around ant mounds in the study area (Figure 48)

Figure 48 Coolibah seed collected by ants, Yellow Waterhole, Kalamurina Station

Vertebrates

The Opossum (Trichoglossus vulpecula) is now rarely met with in the immediate vicinity of Boulia. Elsewhere it may be caught either in the daytime or at night by moonlight: in both cases by climbing the trees with, if necessary," "steps" cut alternately on either sides of the trunk." (Roth, 1897)

"On the Strzelecki Creek "Large gums [Coolibah] appeared in the now dry creeks, and most of them showed the footholds cut by natives of a bygone age with stone tomahawks." (Waite, 1917)

"I remember seeing a blackfellow with his girdle full of unfledged Budgerygars (sic) (shell parakeets), which he had stuffed under by the heads. The trees on the edge of Sturt's Desert were small box-trees, full of holes, and were full of birds and their nests." (Howitt, 1878)

Invertebrates

"Cobboboo - A nut found on the box-tree, on breaking which it discloses a grub; this is probably a gall."
(Gason, 1879)

"The female of the Coccid [scale insect] Apiomorpha ovicola Sch., found in a gall almost certainly on a Eucalyptus [can only be E. coolabah] at Pandi (sic) on the Diamantina, is also eaten by the natives." (Cleland, 1957)

"Across the arid zone, desert dwellers used a hook to remove edible grubs from holes bored deep into trunks of large gumtrees, particularly river red gums and coolibahs growing along creek beds." (Clarke, 2012)

"I mean the well-known witchetty grub of the inland. Remarkably it has never been established what the adult creature is that develops from the young form. The species that is prevalent in the neighbourhood of Sterling Station was called nematt by the Aborigines, and where numerous had a length of 8 - 10 cm and a circumference of 4 - 5 cm. Both ends of the body are yellowish brown. The remaining part toward the front is a purply colour and behind that a dirty white colour. These larvae live in the wood of gum trees between 19 and 27 degrees latitude and mainly occur in the redgum (Eucalyptus rostrata)[E. camaldulensis]. In other parts of the interior, where the aforementioned tree is scarce, east of Lake Eyre for instance, they occur in the boxwood (Eucalyptus microtheca). According to Mr Rudigers, an intelligent German from the Kilalpanina (sic) Mission, a large nocturnal moth develops from it."(Eylmann, 1908)

"The witchetties provide a not inconsiderable portion of the food for many tribes. They are not easily obtained - as a rule to obtain them their passages in the wood or the web in the ground must be exposed, which involves some labour with an axe or shovel, or digging stick - for a man it is not difficult to collect sufficient; in half a day on the larger creeks lined with gum trees it is possible to get a substantial meal. For example, I once met a group of six Diari near the mission's woolshed marching down Cooper's Creek - the riverbed there being eight miles wide and closely covered with Eucalyptus microtheca - who got 700 white and purple witchetty grubs." (Eylmann, 1908)

"One of the classic foods in the southern half of Australia is provided by several species of Ghost moths of the Family Hepialidas. Abantiades and Trictena are two genera of moths of large size and there are many species of the genus Oxycans which are eaten. The larvae of many of these Ghost moths live underground as external feeders on the roots of gum trees, and on several species of Acacia.....In addition to the Hepialidae, some of which bore directly into the stems of trees, there are the equally large wood-boring moths of the Cossidae, sometimes called Goat moths..." (Tindale, 1966)

"Several kinds of edible beetle grubs occur in Queensland and one species of Longicorn Beetle [Cerambycidae], Eurynassa australis was greatly relished by the natives who collected them from the decayed trunks of trees."
(Campbell, 1926)

"The secretions produced by aphids are found in the interior on the twigs and branches of gum trees (Eucalyptus rostrata and Eucalyptus microtheca). These are basin shaped, like the shell of the patella and are similar in the colour and taste of their sugar. It can easily and certainly be established that this tit-bit is an animal secretion. By

removing one of these basin-shaped objects an orange-coloured insect, attached by its abdomen, becomes apparent, approximately 1.5 mm long, it vigorously creeps around and after strong stimulation randomly exudes a soft white thread which completely covers the outside of the basin." (Eylmann, 1908)

"It is amazing the quantity of secretions that are found on the "redgum" and "boxwood". I have only seen a few trees of the latter species that were not infested. An Aborigine from the interior, whose country includes an area that is covered with the trees mentioned above, is, at certain times of the year, in a position to completely satisfy their need for sweet things. As for the small basin, in all cases they are very small - an average height of 1.5 - 2 mm and a diameter of 4 - 5 mm - they are, however, easily removed with teeth and tongue from the leathery leaves. When I stayed at the Kilalpanina (sic) Mission in July 1900 the young charges of the mission often made excursions to Cooper's Creek to feast on the "manna of the desert". Needless to say an eight year old boy, on one occasion, ended up with a bad attack of indigestion".(Eylmann, 1908)

"Honey or 'sugar-bag" as the more civilised aboriginals call it, is found throughout the North-West Central District, especially along the river courses, except perhaps the Upper Mulligan, and is obtained by one or other of the following methods. Its locality in the particular tree is tracked: during the winter-time by watching carefully for the minute pellets of dung lying on the ground around the butt; in the summer months, by observing the bees going in and out of their nest: and at occasion by putting the ear down to some natural orifice at the base of the tree and listening for the insects hum and buzz. The trunk is often tapped lightly with the fingers or with a stone for indications of a hollow core: a likely situation for a nest. When the nest has been discovered, the limb may be removed bodily, or the tree climbed: the latter measure can be effected by cutting nicks or steps alternatively higher and higher on either side of the trunk and stepping from one to the other. To remove the honey from the cavity either the hand or a stick is inserted; this is swept round and round to prevent the glutinous mass from dripping off, somewhat after the style of a spoon with some thick syrup on it." (Roth, 1897)

11.3 Coolibah as source of moisture

Water Source [Figure 49]

"Needle bush (Hakea leucoptera), Red Mallee (Eucalyptus oleosa) and even the Box (E. microtheca) afford another means of procuring water. Their roots are dug up, cut into short lengths, and placed to drain in a pirrha or wooden bowl. Quite a quantity of water is yielded that has been stored up by these plants." (Aiston and Horne, 2009 (2nd ed.))

"From the root of the coolabah (sic), Eucalyptus microtheca, water was sometimes obtained..." (Johnstone and Cleland, 1943)

"It requires, however, the knowledge of an aboriginal to hit upon the proper tree, for which there are probably some outward signs only known to them, because my own efforts led me only accidently to a root holding water, after trying a good many before without obtaining a drop." (Helms, 1896)

"In other parts of Australia, during seasons of drought, the natives obtained water from the roots of the Red Mallee (Eucalyptus oleosa) and the Coolibah or Dwarf Box (E. microtheca)." (Mac Pherson, 1939)

"The operator or operators commence by thrusting a sharp-pointed stick (generally the tops of their spears) into the earth at a distance of 15 or 20 feet from the tree; this is to find the roots, which generally are found at a depth varying from a few inches to a foot beneath the surface, and the reason for commencing at that distance from the trunk is that the root near the tree is too woody, and not sufficiently porous to contain water. Having struck the root, they quickly remove the soft superincumbent earth for a distance of 20 or 30 feet with their wooden shovels, and cutting the root off at each end remove it, and then cut it up into lengths of about 18 inches, knock the bark off, and putting one end into some vessel, and the other into the mouth, blow vigorously for a few seconds, and the water runs out in a small stream. Shortly after rain, and when the earth is moist, the water will drip from the root

when held up, and the supply is greater, showing that the yield is affected by rain. Roots which are (with the bark on) about the size of a man's wrist are the best, as when larger they become woody, and contain less water. It is astonishing how soon water can be got by this means. I have my self, and quite unassisted, obtained a quart pot full in less than half an hour, and I feel sure, were the fact more generally known, that it would be the means of saving many valuable lives, as anyone provided only with a tomahawk need never perish from thirst in country where this or any of the other trees I have mentioned are to be found. The water is beautifully clear and cool, and free from any unpleasant taste."(Bennet K H in (Maiden, 1917))

Figure 49 Water from Eucalyptus root (Noble and Bradstock, 1989)

Sweet Drink

"The two principal drinks were gullendoorie--that is, water sweetened with honey; and another made of the collarene, or flowers of the Coolabah (grey-leaved box), or Bibbil (poplar-leaved box) flowers, soaked all night in binguies (canoe-shaped wooden vessels) of water. Just about Christmas time the collarene is at its best; and then, in the olden days, there were great feasts and corroborees held." (Parker, 1905)

11.4 Coolibah as Pharmacopoeia

Medicine

"The inside bark is beaten up and used as a poultice for snake bites, crushed and heated with hot stones in water." (Palmer, 1883)

"The barks contain kino-tannic acids and other constituents. The inside bark of Eucalyptus microtheca, Coolibah or Tangoon or Dwarf –Box in Queensland was beaten up and applied as a poultice for snake bite...In Queensland also, Dr Walter Roth reported that in the Mitakoodi tribe, for severe headache, a poultice was made from box-tree bark, hammered and pounded and soaked in hot water." (MacPherson, 1939)

"Steam from eucalypt spp. Leaves especially of broad-leafed box and mallee, placed over coals is inhaled to relieve common colds and influenza." (Meggitt, 1957) Walbiri Language Group

"..a narrow hole about six feet deep was excavated and lined with these leaves [Coolibah]: layers of very hot stones were placed in the hole, and when the desired temperature was reached these stones were removed; the patient, wrapped in an emu skin blanket (multara), was taken to the hole, stripped naked, placed in the bed and covered to the neck with warm sad and eucalyptus leaves, remaining there for 10-15 minutes; he was then covered in the emu-skin and taken back to camp, the whole procedure being carried out under instructions from a "medicine man" (nulujera)" ((Johnstone and Cleland, 1943) paraphrasing Duncan-Kemp)

"Walbiri (especially men) collect and chew as narcotics both pituri (djunbunbu, Duboisia sp.) and tobacco (djanjunu, Nicotiana sp.). They often mix with the chewing wad in order to make it bite the palate, the ash of the

> *burned leaves and/or bark of: jadanby, Acacia estrophiolata; jildilpa, Grevillea striata; djirindi, Grevillea sp.?; wabalingi, coolibah, Eucalyptus microtheca.(Meggitt, 1957)*
>
> *"The only application of a poultice that has come under observation is the practice prevailing among the Mitakoodi for the cure of a bad headache: some box-tree bark, subsequently to having been hammered and pounded, is soaked in hot water, and the mass so produced held with a piece of bark, cloth, &c., by the hand—not tied—to the particular part affected. On other occasions, in the same tribe, a bundle of heated fresh leaves may be tied on to the forehead for a similar purpose." (Roth, 1897)*
>
> *"Ash from burnt twigs is sometimes use for mixing with pituri." (Johnstone and Cleland, 1943)*
>
> *"In various parts of Australia, poultices were made of bruised and heated gum leaves....Headaches were treated by inhaling the steam of heated gum leaves." (Mac Pherson, 1939)*

In referring to the exudation from trunk of eucalypt referred to as a kino *"In addition to other constituents it contains some form of tannic acid (tannin)"*, W E Roth also relates that *Eucalyptus* Kino *(popularly known as "gum") "was employed by the Mitakoodi tribe of north-west Central Queensland...In the form of pills for the relief of diarrhoea." (Mac Pherson, 1939)*

Poison

> *"Native name on Cloncurry, "Jinbul or Kurleah". The Coolibar (sic) or flooded box found on all gulf waters, often in in flooded ground, of a crooked growth, about 30 feet high. The small branches are cut up, and with the leaves are laid in water for several days to sicken the fish; it is universally used for this purpose." (Palmer, 1883, Palmer, 1884)*
>
> *"Various species of Eucalyptus have been used as fish poisons." (MacPherson, 1939)*

11.5 Coolibah and hunting

Camouflage

> *"Corellas (Licinitis nasica)(sic), Galahs (Cacatua roseicassila)(sic). Cockatoos, &c., are entrapped on the water in the late afternoon, at Roxburgh, Carandotta, etc., in the Upper Georgina District. The hunter, after tying numerous grass twigs and leafy boughs round his head, neck, and face, which are thus completely concealed, swims out to some log or " snag" projecting just out of the water, and supports himself there by its aid, with only his head out. As the birds come down to drink they fly round the bushes, and alighting on the log, &c., are easily caught by the legs, pulled under the water, their necks wrung, and stuck one after another in the hunter's waist-belt."(Roth, 1897)*

Emu caller [Figure 54]

> *"The " call," a sort of " drumming" sound is imitated by blowing into a hollow log some 2 to 3 feet long, from which the inside core has been burnt so as to form an aperture about 3 inches in diameter: when in use, the tube is held close to the ground in which a slight excavation has been made. These "call-tubes" are met with throughout North-West-Central Queensland." (Roth, 1897)*
>
> *"Boobeen is a primitive cornet, a hollowed piece of Bibbil [Eucalyptus populnea] wood, one end partially filled up with pine gum, and ornamented outside with carvings. To blow through it is an art, and the result rather like a big horn. The noise is said to be very like an emu's cry, and this emu bugle will certainly, they say, draw towards it a gundooee, or solitary emu." (Parker, 1905)*
>
> *"The hunting of the emu was done with the aid of the "boobinch". The boobinch was used to call the emu and was like a miniature didgeridoo. The boobinch was made by carefully selecting a hollow piece of wood and covering the mouth piece with either black clay or beeswax. The hunter would then go out into the bush and the boobinch was used to call the emu off the nest." (McKellar, 1984)*

Fencing [Figure 50]

> *"Sometimes a long alley-way (Pitta-Pitta yel-ka yel-ka) is built up in a convenient situation with bushes, boughs, and saplings intertwined." (Roth, 1897)*
>
> *"The Aborigines in inland South Australia not only kill emus with a boomerang but also catch them in traps. These are dug near waterholes and in some areas consist of a five foot deep pit that has a spear placed upright in the middle of it in such a way that the point is approximately fifteen centimetres below the surface. The opening is covered with half-broken sticks that are then covered with grass and the whole then covered with soil. Two small fences made of plaited twigs are placed in such a way to force the bird to cross over the trap when it goes for water." (Eylmann, 1908)*

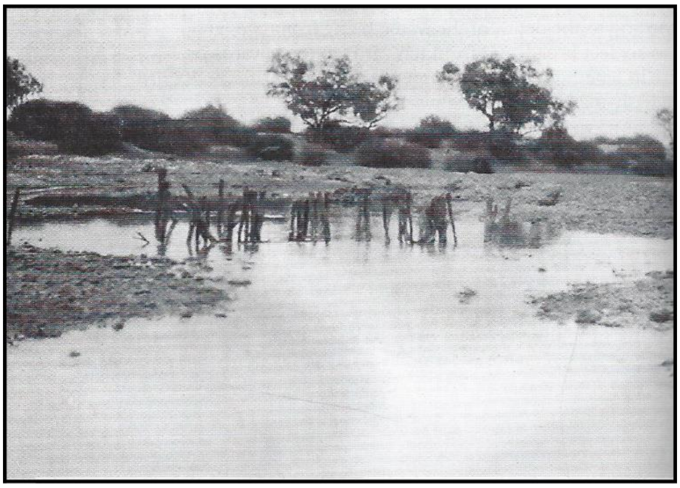


Figure 50 Timber fish trap (Aiston and Horne, 2009 (2nd ed.))

> *"When the young ones are getting big, [Pelican young] they build a yard for them on the bank of the lake and then go down into the water and herd the baby birds back [into the yard]....Then for two or maybe three weeks they camp there, living on birds, while the birds feed on fish that their parents bring them and them in the yard....The biggest ones, that are nearly ready to fly, they kill and cook and eat." (Kerwin and Breen, 1981)*

11.6 Coolibah as building material

Shelter [Figure 51]

> *"The native habitations, at all events those of the natives of the interior, with the exception of the Cooper's Creek tribe, had huts of a much more solid construction than those of the natives of the Murray or the Darling, although some of their huts were substantially built also. Those of the interior natives however were made of strong boughs with a thick coating of clay over leaves and grass. They were entirely impervious to wind and rain, and were really comfortable, being evidently erections of a permanent kind to which the inhabitants regularly returned. " (Sturt, 1849)*
>
> *"Their huts are of two kinds – summer and winter huts. The former are mere break-winds (sic) of branches or the stalks of marsh-mallows. The latter are made like bee-hives of sticks, then covered with tufts of grass or weeds, and finally with earth or sand thrown in the top and beaten down." (Howitt, 1878)*
>
> *"The wurleys at a permanent camp, dome shaped circular erections built of logs, cane grass and mud." (Wells, 1893)*

Figure 51 Shelter under construction (Basedow, 2012 (2nd ed.))

Food platform

> *"In the middle of the camp is the dunpara or platform, which is about five feet high, and is used to keep food and water from the dogs….This is a platform made by sticking four stout forked sticks into the ground and piling upon them five other logs." (Aiston and Horne, 2009 (2nd ed.))*

Burial [Figure 52]

> *"The graves are just such as are spoken of by Capt. Sturt – large mounds of sand, covered with logs and brush." (Howitt, 1878)*
>
> *"…on the upper part of the river they bury their dead piling wood on the grave; near the junction of the Thompson they suspend the bodies in nets, and afterwards remove the bones; while on the Cooper Creek the graves are mounds of earth 3 to 4 feet high, apparently without any excavation, and surmounted by a pile of dead wood." (Gregory, 1858-59)*
>
> *"Stems of the coolabah are laid lengthwise on graves." (Johnstone and Cleland, 1943)*
>
> *"The body is placed within the grave and covered with bushes and pieces of wood, the last so the wild dogs cannot uncover the remains." (Berndt and Vogelsang, 1939)*

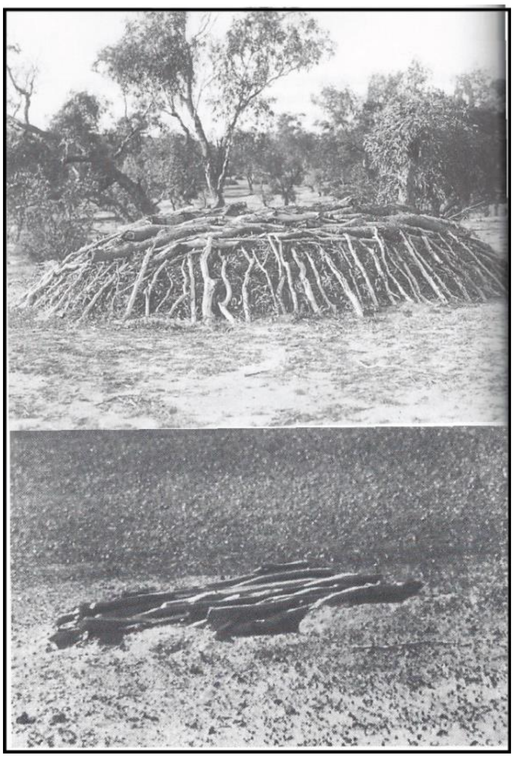


Figure 52 Graves (Basedow, 2012 (2nd ed.))

11.7 Coolibah and ceremony

Music

> *"Both sexes, as has been already mentioned, carry on the singing and both beat time, the men alone doing this with two boomerangs, one held in either hand, made to strike one another on the flat." (Roth, 1897)*

Adornment

> *"Oorapathera - A bunch of leaves tied at the feet, and worn when dancing, causing a peculiar noise." (Gason, 1879)Gason 1874 (Pathara - A box-tree)." (ibid)*
>
> *"oora =legs, pathera or pathara = Eucalyptus microtheca". (Johnstone and Cleland, 1943)*
>
> *"..a bunch of singed leaves tied on to the ankles and wrists. The object of these singed leaves (used only by the men) is to cause a rustling or crackling noise when dancing." (Roth, 1897)*
>
> *"On the inner side of each ankle a little bunch of box leaves was tied, which rustled on moving, for he represented a moora, and without the rustling no one would know he was there, as he would be invisible." (Aiston and Horne, 2009 (2nd ed.))*
>
> *"During corrobborees, performers would prepare behind a screen composed of Coolibah branches and foliage." (see Figure 53) (Aiston and Horne, 2009 (2nd ed.))*

Figure 53 Screen of Coolibah foliage (Aiston and Horne, 2009 (2nd ed.))

11.8 Coolibah and communication

Message sticks [Figure 54]

"Circumstances often arise which may prevent an individual setting out for the "swapping-ground" or local market, and in such cases he may send a substitute or agent together with a so-called letter-stick to do business for him. This letter or message stick is called ka-lor-i by the Pitta-Pitta tribes, Kool-bo by the Mitakoodi, and koong-ga by the Kalkadoon: in the last-mentioned language this word signifies a piece of wood of any description. The stick is usually a piece of wood, gidyea, ti-tree, or any other convenient [also Coolibah; see p 62, Duncan-Kemp], coloured perhaps black, red, or yellow, from two to four or more inches in length, cut to various shapes from flat to round, and incised with various marks or pattern:... With regard to the particular shapes and designs of these message-sticks, there are traces of similarity even over large areas of country. In the Boulia District they are flattened, generally thinner at the edges than elsewhere, rounded or more or less pointed at the extremities, and incised only with straight lines. These straight lines are cut either parallel with, at an angle, or across each other, and represent quite arbitrarily anything which the manufacturer chooses, from a mountain or a river to a station homestead : sometimes, the comparatively large size of the head station or chief encampment has been attempted in an extra number of lines or cross lines. The back of the message-stick bears the same or similar design as the front, or else is covered with " flash" marks, to make it look "pretty fellow" ; these marks have no other meaning whatsoever, alleged or implied." (Roth, 1897)

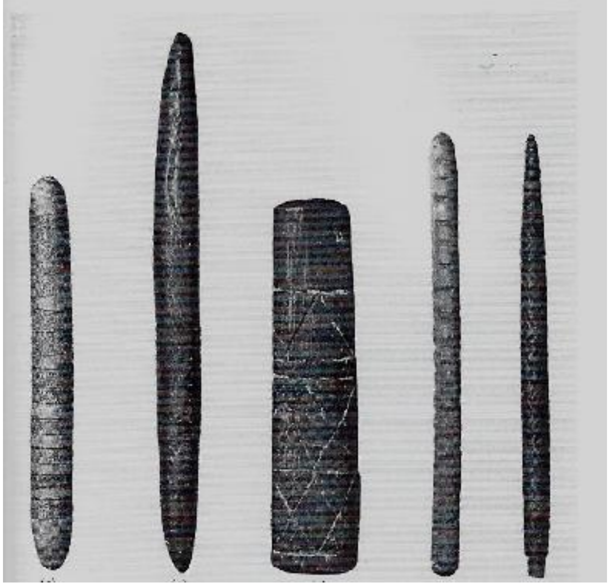


Figure 54 Message sticks(Aiston and Horne, 2009 (2nd ed.))

Communication- Smoke signals

> *"Smoke-signals and signal-fires are known to have been recognised and answered at distances upwards of ten miles apart. A variation is sometimes made in "breaking" the smoke so as to make it rise in quickly succeeding columns: these smoke-breaks are made by lighting an ordinary fire in the open, but alternately covering and removing with leafy boughs in rapid succession. "Smoke-rings" at Birdsville and the surrounding district are said to be produced by igniting some bushes placed inside a hollow log fixed up on end, on the top of which a piece of bark is placed, this being quickly slipped off in the same horizontal plane, and as speedily replaced when a "ring" is wanted." (Roth, 1897)*

Communication – Sign of Peace

> *"On nearing any camp, when accompanied by a guide, we have had to halt while he went forward. He got onto some high ground in sight of the camp, and began to bawl out something, holding up a branch in his hand." (Howitt, 1878)*
>
> *"During my exploration on the southern side of Sturt's Desert, in the country of the Ngurawola tribe, I had a good opportunity of observing the manner in which a party of strangers is received. On arriving at a shouting distance of a camp of that tribe my guide, a Yantruwunta man, halted us and, breaking off a branch of a tree, which he held up in his right hand, went nearer to a group of old men who had come forward and stood at a little distance in advance of their camp. The guide, waving his branch at arm's-length, said, in a loud tone of voice, that we were travelling peaceably (Barku-balkala). Then followed a loud-toned conversation between him and the Pinnarus [old or senior men] of the camp. Being at length satisfied, they came towards us, and led us to a place adjoining a water-channel, on the farther side of which they were encamped in a cluster of bee-hived-shaped grass huts. Here we were told to camp, and some of their young men were sent to gather wood for our fire." (Howitt, 1878)*
>
> *"In this manner [above] I was taken during several days from camp to camp in the country bordering Sturt's Desert and Lake Lipson." (Howitt, 1878)*

11.9 Coolibah and artefacts

Containers

> *"Oblong wooden bowls are made by cutting off the knees (sic) from a box-tree, and then thinning out with a kind of adze or gouge. Water is carried in them: seed cleaned; or sand dug around the huts." (Howitt, 1878)*
>
> *"Where the wood does not lend itself to 'splitting' – e.g. – the coolibar (sic) – a trunk or limb is selected as near as possible to the required shape – i.e. having a slight bend in it – ultimately to become the outer convex surface of the vessels. The proper length is next cut off the tree, and what will be its ultimate concave side slightly burned, so as to make the subsequent scooping-out with the chisel so much the easier; when roughly got into shape it is steeped in water, may be some days, wound round with twine to fix its permanent contour, and then finished off again with a chisel. Koolamons (sic) usually show a longitudinal fluting, and may be coloured red or black. They vary greatly in size from under a foot to over two and a-half in length, and up to 9 or 10 inches in width, and are either convex or slightly flat-bottomed. They are carried either on the head, or at the side or back of the body; in the latter cases, supported by a cord passed over the opposite shoulder assisted, as often as not, with the arm." (Roth, 1897)*
>
> *"The aboriginals throughout all the different ethnographical districts both know and practise various methods of bending or straightening timber, either when already cut or in the rough. Thus, a dry heat in ordinary sand, a moist heat from burning freshly-gathered gum-leaves, or moisture in general, such as soaking in water, is employed for bending any of their wooden implements into shape as required. In order to maintain and preserve the timber in the position attained by one or other of the preceding processes, the whole is covered thickly with grease and fat, saurian or mammalian." (Roth, 1897)*

"From an angle on a coolibah or box tree was cut the pirrha [wooden dish]." (Aiston and Horne, 2009 (2nd ed.))

"The Dieri, Yantowannta, Ngameni, Arunndta, Wongapitcha and other Central Australian tribes use shield or trough-shape carriers cut out of the bark of the Eucalyptus, shaped and hardened over the fire....The surfaces of these are either smooth of longitudinally grooved with a stone scraper. The largest were observed on Cooper's Creek, measuring three feet in length, one foot in width, and five inches in depth..." (Basedow, 2012 (2nd ed.))

"..across the arid zone, coolibah (flooded box), river red gum and desert bloodwood timber was used for carved wooden containers and scoops, particularly small to medium sized specimens." (Clarke, 2012)

"The Cooliman (sic) is made from the coral tree [Erythrina vespertilio] or from a hollow coolibah cleaned out with a stone chisel ("Coonty") the wood being steeped in water and twitched with a string to encourage the required shape." (Coghlan, 1898)

Digging sticks

"The woman's digging –stick, wadna, is in my opinion only developed from a broken piranburra [spear-see weapons section]. The name wadna signifies "broken" and it seems to me that it was found that the shorter weapon was handier. They were made exactly alike; both had one sharp round point and one flat, chisel-shaped point." (Aiston and Horne, 2009 (2nd ed.))

Weapons

"In north-east South Australia, a wide variety of clubs was made, from timber cut variously from coolibah, dead finish wattle, mulga and needle-bush." (Clarke, 2012)

"A singular weapon is the great boomerang, about five feet long. It is made of heavy box-wood, and is used, I believe, as a club or broadsword in close quarters. It does not seem to be carried about. I have only seen it in the camps, or hidden near them. The shields are of the usual shape, and of a soft white wood [Erythrina vespertilio], which does not, I think grow in the country." (Howitt, 1878)

"Murrawirrie, two handed sword." (Figure 55) (Gason, 1879)

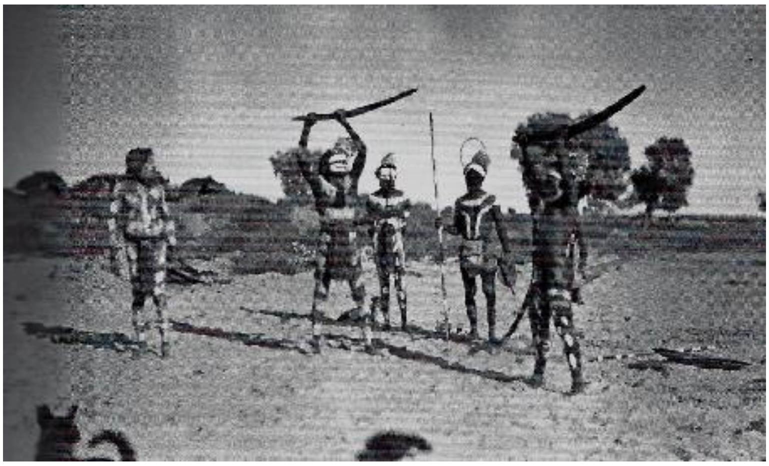


Figure 55 Fighting with Murrawirrie (Aiston and Horne, 2009 (2nd ed.))

"I was also told that the shields [made from Erythrina vespertilio] were given to them by tribes in the east, in return for girdles which they themselves made."(Howitt, 1878)

"The throwing stick (munkerara) was usually made from this tree. [Coolibah]" (Johnstone and Cleland, 1943)

"They had the long, pole-like spear called piranburra, made out of a box tree or mulga root, and employed it as much for digging as for any other purpose. It was occasionally used for fighting, but mostly for ceremonial combats, such as fights between two persons only. This spear was from about six feet long with the Yaurorka, up to

> *ten feet long with the Dieri and Wonkonguru. It was not effective as a throwing weapon at more than twenty yards and was mostly used as a lance. It was also useful when digging out wild dogs for food, one man digging while the other waited with poised piranburra until the dogs' head was uncovered. He would then drive in the spear before the dog could bite." (Aiston and Horne, 2009 (2nd ed.))*
>
> *"The munkerara (throwing stick) [spear thrower; woomera] was usually made of coolibah wood…" (Aiston and Horne, 2009 (2nd ed.))*
>
> *"The shields used were usually obtained by barter from the northern tribes. They were called murrawarroo (literally "hand-white") and were always made of soft wood [Erythrina vespertilio]. There is no suitable wood in this country, but I have seen an occasional one made from a tree that we call "whitewood", which is very soft, spongy wood, but it has a tendency to split if allowed to dry. The ideal wood is that of the bean tree (Erythrina vespertilio) and big exchange was bartered for these.....A soft wood was always preferred, as one made of hard wood would cause the weapon opposing it to glance, but the soft pithy wood would deaden the flight of the weapon."(Aiston and Horne, 2009 (2nd ed.))*

11.10 Coolibah and play

> *"Wimberoo was a favourite fireside game. A big fire was made of leafy branches. Each player got a dry Coolabah leaf, warmed it until it bent a little, then placed it on two fingers and hit it with one into where the current of air, caused by the flame, caught it and bore it aloft. They all jerked their leaves together, and anxiously watched whose would go the highest. Each watched his leaf descend, caught it, and began again. So on until tired".(Parker, 1905)*
>
> *"Woolbooldarn is an absolutely infantile game. A low, overhanging branch of a tree is chosen, and as many as it will bear, old and young, men and women, straddle it; and, holding on to the higher overhanging branches, they swing up and down with as much spring as they can get out of the branch they are on."(Parker, 1905)*
>
> *"Any leaf, piece of light bark, or even a mussel shell, by means of a peculiar motion of the wrist and arm, can be thrown in such manner into the smoke rising from an ample fire as to ascend with it like a spiral." (Roth, 1897)*

11.11 Mythology totemism and the spiritual

Mythology - general observation

The following excerpts are from observations made by Katherine Langloh Parker of the;

> *"Euahlayi [Yuwaaliyaay] tribe of north-western New South Wales, who for twenty years were my neighbours on the Narran River." (Parker, 1905)*
>
> *"The Euahlayi, however, possess myths, beliefs, and usages not recorded as extant among the Kamilaroi, but rather forming a link with the ideas of peoples dwelling much further west, such as the tribes, on Lake Eyre, and the southernmost Arunta of the centre."(Parker, 1905)*
>
> *"As throughout the chapters on the customary laws, mysteries, and legends of the Euahlayi, there occur frequent mentions of a superhuman though anthropomorphic being named Byamee (in Kamilaroi and Wirádjuri 'Baiame'), it is necessary to give a preliminary account of the beliefs entertained concerning him. The name Byamee (usually spelled Baiame) occurs in Euahlayi, Kamilaroi, and Wiradjuri; 'the Wiradjuri language is spoken over a greater extent of territory than any other tongue in New South Wales." (Parker, 1905)*

Mythology - ontology of Coolibah

> *"Mandra-mankana a Mura-mura,"…"Through his songs he caused plants to grow, some with bitter and some with pleasant tasting fruit."*

"Mandra-mankana also called Bakuta-Terkana-Tarana or Kantayulkana.....he surprised people fishing in the creek north of Lake Hope (Pando) on the Cooper and only a few escaped from him and as they escape he gave them their murdu names."

"Those who ran to the southward were the marakara, native perch; kirhabara, eel [?]; yikaura, dasyurus; ngarumba, ***box Eucalyptus*** *(****E. microtheca ?****); kanunga, bush wallaby; kapita, rabbit bandicoot."*

"These legends show clearly that the Mura-muras are believed to have been men, women, and children, resembling the present race in person, in thought, and in action, but with the difference that all of them possessed supernatural and magical powers which are nearly equalled by the powers that the medicinemen of the present time, in the Lake Eyre tribes, profess to have."

"In the beginning, the earth opened in the midst of Perigundi Lake and there came out one murdu after the other, Kaulka (crow), Katatara (budjerigar), Warukati (emu), and so on....They lay in sunshine until invigorated and 'at last stood up as kana and separated in all directions"

"The Dieri point out an island in the middle of Perigundi as the place where the murdus came out. The legend not only accounts for the totem animals, but also for the kana, that is the native inhabitants of the Lake Eyre district."

All of the above (Howitt and Siebert, 1904)

Mythology – origin of the moon

"Two young Mura-muras were annoyed with their father, the old Mura-mura Nganto-warrina, because he had gathered some nardoo and given none to them. One day their father saw them busy making long hooks (ngami) to pull out grubs (kuyikinka) from their holes in the gum trees. They told him they knew of a tree full of kuyikinkas, and the old Mura-mura climbed up to get some. As he climbed his sons kept urging him to go on higher, and all the time the tree raised itself or grew up further from the ground by reason of their magic. Then they set it on fire, and, as the burning tree rose up carrying Nganto-warrina, the sons saw that their father was being roasted, and one of them threw up a skin by his boomerang so that the old man might shelter himself from the heat. Nganto-warrina still hangs in the sky as the moon, and the Dieri say the dark mark on its face is the place where the old Mura-mura covered himself with the skin." (Howitt and Siebert, 1904)

Mythology – origin of the bull roarer

"Next Byamee made a stone bull roarer sort of thing, but this was too heavy to make the noise he wanted. One day he was chopping a big Coolabah tree close to Weetalibah water-hole, which tree, much to the horror of our blacks, was burnt down a few years ago by travellers."

"As Byamee chopped, out flew a big chip. He heard the whizzing sound it made, gave another chop, out flew another; again the whizzing sound."

"'That is what I want,' he said I'll make a Gayandi [women's name for bull roarer], men call it the Gurraymi] of wood'".'

"He cut a piece of mubboo, or beefwood, and shaped it; he tied a piece of string to a hole in one end; he hung it up in the big Coolabah tree. Then he went and cut one out of Noongah or Kurrajong, tied a string on to that and put it beside the other on the tree, and left them swinging there." (All of the above (Parker, 1905))

Totemism

"Mr Birt gives the totems of the Karingbool as follows;

Binjool; Black duck, ***Coolabah tree***

Kiarra; Wood duck, gum tree

Bunyart; Porcupine, short brigalow tree

Thadbine; Yellow backed eaglehawk, tall brigalow

"...in the case of the trees to which each class belongs; brigalow trees are the best, and most generally used for making weapons and should Kiarra or Binjool want a spear etc. from that tree they have to apply to a Bunyart or Thadbane to get it for them; while with regard to the ***gum coolibah*** *or* ***box tree****, the bark used for making their camps is generally stripped from one of these trees and Bunyart or Thadbane would have to go without bark unless a Kiarra or Binjool gave it to him. Opossums which form one of the blacks' chief articles of food are seldom found in a brigalow, but generally in any of the other trees named, and unless the opossum can be taken without cutting or injuring the tree in anyway a Bunyert or Thadbane is often under obligation to a Binjool or a Kiarra for his feed of possum." (Cameron, 1904)*

Spiritual

"Spirit-babies are usually despatched to Waddahgudjaelwon [a birth-presiding spirit] and sent by her to hang promiscuously on trees, until some woman passes under where they are, then they will seize a mother and be incarnated. This resembles the Arunta belief, but with the Euahlayi the spirits are new freshly created beings, not reincarnations of ancestral souls, as among the Arunta."

"When a baby is born, some old woman takes the Coolabah leaf out of its mouth. Such a leaf is said always to be found there if the baby was incarnated from a Coolabah tree; should this leaf not be removed it will carry the baby back to spirit-land. As soon as the leaf is taken away the baby is bathed in cold water. Hot gum leaves are pressed on the bridge of its nose to ensure its flatness; the more bridgeless the nose the greater the beauty."

"Just in front of our station store was a gnarled old Coolabah tree covered with warty excrescences, which are supposed to be seats for spirits, so showing a spirit haunt. In this particular tree are the spirits of the Moungun, or armless women, and when the wind blows you could hear them wailing. Their cruel husband chopped their arms off because they could not get him the honey he wanted, and their spirits have wailed ever since." (All of the above (Parker, 1905))

"The natives believe that the souls of the infants dwell in the foliage of the trees, and that they are carried there by the good mountain spirits, tuanjiraka, and their wives, melbata, The nearest tree to a woman when she feels the first pain of parturition, she calls ngirra, as they are under the impression that the guruna or soul has then entered from it into the child. Such a tree is left untouched, as they believe that whoever should happen to break off a single branch would become sick. But if the tree should be injured or broken down by winds or floods that person would get ill whose ngirra, that tree was." (Schulze, 1891) (Upper and middle Finke River)

The Sacred

"At Weetalibah was the tree from which Byamee cut the first Gayandi [bull roarer]. This tree was burnt by travellers a few years ago. The blacks were furious: the sacred tree of Byamee burnt by the white devils! There are trees, too, considered sacred, from which Byamee cut honey and marked them for his own, just as a man even now, on finding a bee's nest and not being able to stay and get it, marks a tree, which for anyone else to touch is theft." (Parker, 1905)

"Some distance to the north-west stood the remains of a once huge coolibah tree, with great spreading roots that formed an underground shelter. It was known to musterers as Debney's tree, but long before that it was sacred ground to the Eaglehawk tribe. In its tallest branches eagles, year after year, built their nests and reared their young. The eagle was a bird scared to the Eaglehawk tribe and this tree and the area surrounding it was their totem place." (Duncan-Kemp, 1964)

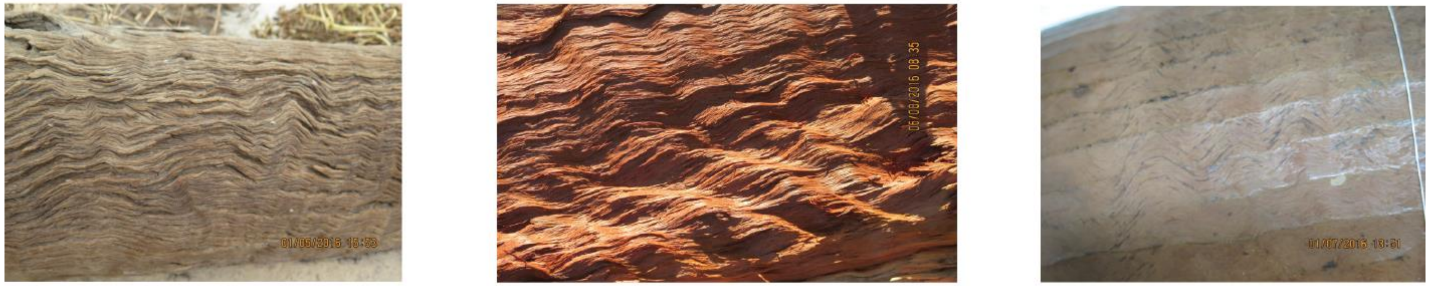
Superstition

> *"There are places covered by trees held very sacred, the larger ones being supposed to be the remains of their fathers metamorphosed. The natives never hew them; and should the settlers require to cut them down, they earnestly protest against it, asserting they would have no luck, and themselves might be punished for not protecting their ancestors." (Gason, 1879)*

> *"Trees sometimes spring and seem to have grown up where the Moora first came or last went. These trees are of course never cut down, nor are those into which their ancestors have been metamorphosed. All these objects are endowed with magical force and are often avoided as kootchi (uncanny) if they represent the moora and have his powers." (Aiston and Horne, 2009 (2nd ed.))*

Shield (MV) Shield Back (MV) Shields (SAM) Shields Back (SAM)

Coolamon (MV) Coolamon (MV) Coolamon grain (MV)



Coolibah grain (log) Coolibah grain (freshly cut, Cowarie) Coolibah (?) grain Coolamon (MV)

Figure 56; Range of artefacts from Diamantina and Cooper region (Sources: MV=Museum Victoria, Registration numbers: X9070, X51508; SAM=South Australian Museum; Registration numbers; A2245, A2231)

Boomerangs and Clubs (NMA)

Message Sticks (NMA)

Shield, Boomerangs, Club and Spear thrower (NMA)

Boomerangs (SAM)

Boomerangs (MV)

Boomerang showing grain (MV)

Boobeen or Boobinch (Emu caller) (SAM)

Figure 57: Range of artefacts from Diamantina and Cooper region (Sources: MV=Museum Victoria; Registration numbers; X94953, X94940, X94934, X94946, X72882: SAM=South Australian Museum; Registration numbers; A34545, A35319, A50688, A32033, A34546, A34533, A50698, A50687, A50690, A2937, A2936: NMA=National Museum of Australia)

12 Summary and recommendations

> *"Riparian vegetation and wetlands are regarded as high importance for the maintenance of biodiversity at a local and regional level in terms of wildlife corridors and habitat (much of it mapped by the EPA as 'of concern' biodiversity status). They should be actively managed to minimise these threats and ensure that their condition is improving." (Desert Channels, 2012-2017)*

The combined result of; detailed review of relevant literature in association with the results of field work and experimentation induces a profound respect for Coolibah; a resilient and adaptable species with the capacity to endure extremely harsh and challenging growth conditions. Coolibah, as the dominant perennial, is a vital component of the riparian vegetation of the Diamantina/Warburton River system; playing a major role in driving ecosystem structure and function and supporting associating biodiversity.

> *"…all terrestrial ecosystems are controlled and organized by a small set of key plant, animal and abiotic processes that structure the landscape at different scales." (Holling, 1992)*

In the context of this statement it is clear that Coolibah is key to the ongoing biodiversity health of the river system; a keystone species which should be integrated as an indicator species in an ongoing monitoring program;

> *"..**a keystone species approach** is focused squarely on an understanding of the mechanisms that underlie the function and structure of the ecosystem." (Simberloff, 1998)*

The keystone species approach is also strongly dependent upon the development of a detailed understanding of the life history of the keystone species; in particular aiming to identify and understand the most vulnerable phases in its life history. This autecological study and its associated synecological assessment of riparian vegetation (Gillen, 2017) has provided preliminary insights into the nature of the "*mechanisms that underlie the function and structure of the ecosystem*" and into the vulnerabilities posed by threats to these 'mechanisms'.

Results from the dendrochronological investigations emphasise the slow rate of growth of the species once established, and at this early stage of investigation, reveal its potential to be a significantly long-lived perennial. This potential longevity highlights the 'buffering' role of the species over time; stabilising channel banks, reducing potential rates of erosion; acting as bioengineer, influencing flow and depositional rates across the landscape. Coolibah also plays a significant role in the 'capture' and cycling of nutrients within this dryland river system; the longevity of the species influencing differing comparative rates of nutrient turnover resulting from leaf litter and timber decomposition. The removal of either litter or timber, produced by this slow growing, long-lived species, would have deleterious impacts upon ecosystem processes. Should tourism be focussed on specific waterholes of the Diamantina/Warburton system, fires should be prohibited. This prohibition is currently successfully implemented elsewhere in the region where visitation is high or increasing such as experienced in the Malkumba-Coongie National Park, on the Cooper, or on Kalamurina Station Reserve on the lower Warburton River.

Insights into the phenological aspects of Coolibah life history suggest a species that is uniquely adapted to exploit the mechanism of hydrochory in driving major recruitment phases; periods of great significance in the population dynamics of the species. Coolibah appears 'primed 'for major flowering events during the summer months when the potential for flooding is greatest (whilst also displaying 'bet-hedging' characteristics with variable locally limited flowering events during other months).

Coolibah seed appears; to have a limited capacity for dormancy; is readily and quickly released from mature fruit; and germinates quickly given appropriate conditions. Coolibah seedlings establish quickly; display rapid early growth, especially the capacity for tap root extension; and also exhibit the potential to endure extended periods of inundation.

However, this early seedling stage also represents perhaps the weakest link in the population dynamics of the species. Total grazing pressure impacting during the rare periods of major recruitment has the potential to severely distort population structure. It would appear that seedling foliage is more palatable, possessing slightly elevated levels of available nitrogen in contrast to mature foliage.

> *"Oil concentration in seedling leaves is invariably much lower than that of other stages [of leaf]…..The contrast in oil concentration between young and mature leaves is often marked" (Doran, 2002)*

Additionally it would appear from the literature that the foliage of members of the *Symphomyrtus* sub genus, to which the Coolibah belongs, has elevated levels of available nitrogen in comparison with other sub genera along with reduced levels of essential oils. However, the nutritive value of Coolibah foliage, as for eucalypt foliage in general, is low (Landsberg and Cork, 1997) and evidence of grazing most probably reflects that more palatable and nutritious feed is absent (Vesk and Westoby, 2001). Evidence of this apparent 'feed switching' would indicate that stock pressure should be removed in order for the system to recover.

It has also been determined for eucalypts in general that; "…*ingestion of oils require some metabolic cost to detoxify them and tannins form indigestible complexes with proteins thus decreasing the efficiency of N [nitrogen] intake..*" (Noble, 1989). Additionally;

> *"The germicidal effects of many constituents of eucalyptus foliage have suggested to some workers the potential for deleterious interaction with intestinal bacteria." (Lawler and Foley, 2002)*

Which poses the question; does the ingestion of more mature Coolibah foliage result in deterioration in stock condition?

The results from the very preliminary foray into Coolibah genetics suggest that there is considerable variation between and within populations at a catchment level. Maintenance of this variation is important in supporting the evolutionary potential of the species particularly in light of the uncertain nature of impacts associated with climate change. The variation in genetics down the river system raises the intriguing question of gene flow and the potential significance of hydrochory in driving genetic variability.

Hydrochory as a process appears to play a significant role in the population dynamics of Coolibah, driving major recruitment events following opportunities presented by a rare sequence of hydrological events of suitable spatial and temporal scale. These unique periods of hydrologically driven broad scale seed dispersal provide the opportunity for Coolibah to spread beyond the riverine corridor, colonising appropriate niches, providing additional structure to the vegetation of associated floodplains. Clearly, as depicted in the conceptual diagram of Figure 58, the hydrological regime of the Diamantina/Warburton River system is a critical 'foundational' ecosystem process; the maintenance of ecosystem patterns and processes and concomitant biodiversity structure and function would be severely and deleteriously impacted should the naturally functioning hydrological regime be disturbed or disrupted.

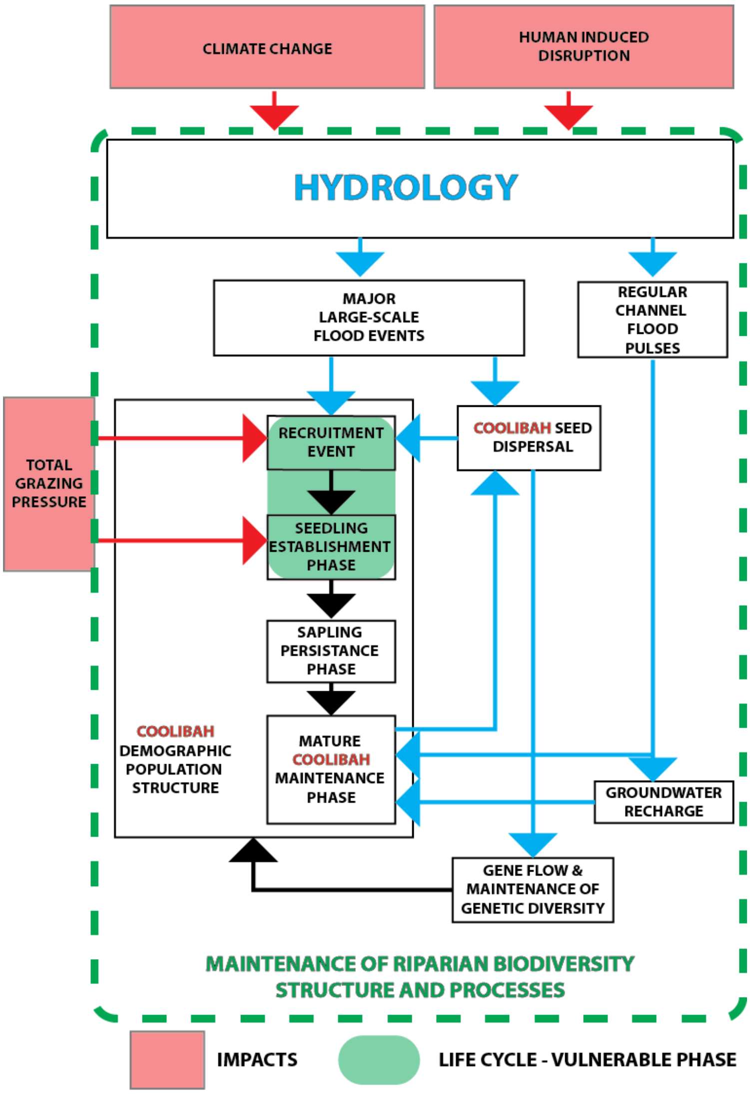


Figure 58; Conceptual understanding of main supporting drivers and threats

The main focus, in a management and conservation context should not be confined to the ‘biodiverse hotpots’ represented by major waterholes of the Diamantina/Warburton River system. The Coolibah population is maintained by a naturally functioning hydrological regime operating at a catchment level. This regime is critical for the recharge of regional groundwater systems upon which Coolibah depend during periods of extended drought. The connection of channel and floodplain is integral to the distribution and recruitment of new cohorts of Coolibah at a broad regional landscape level.

13 Acknowledgements

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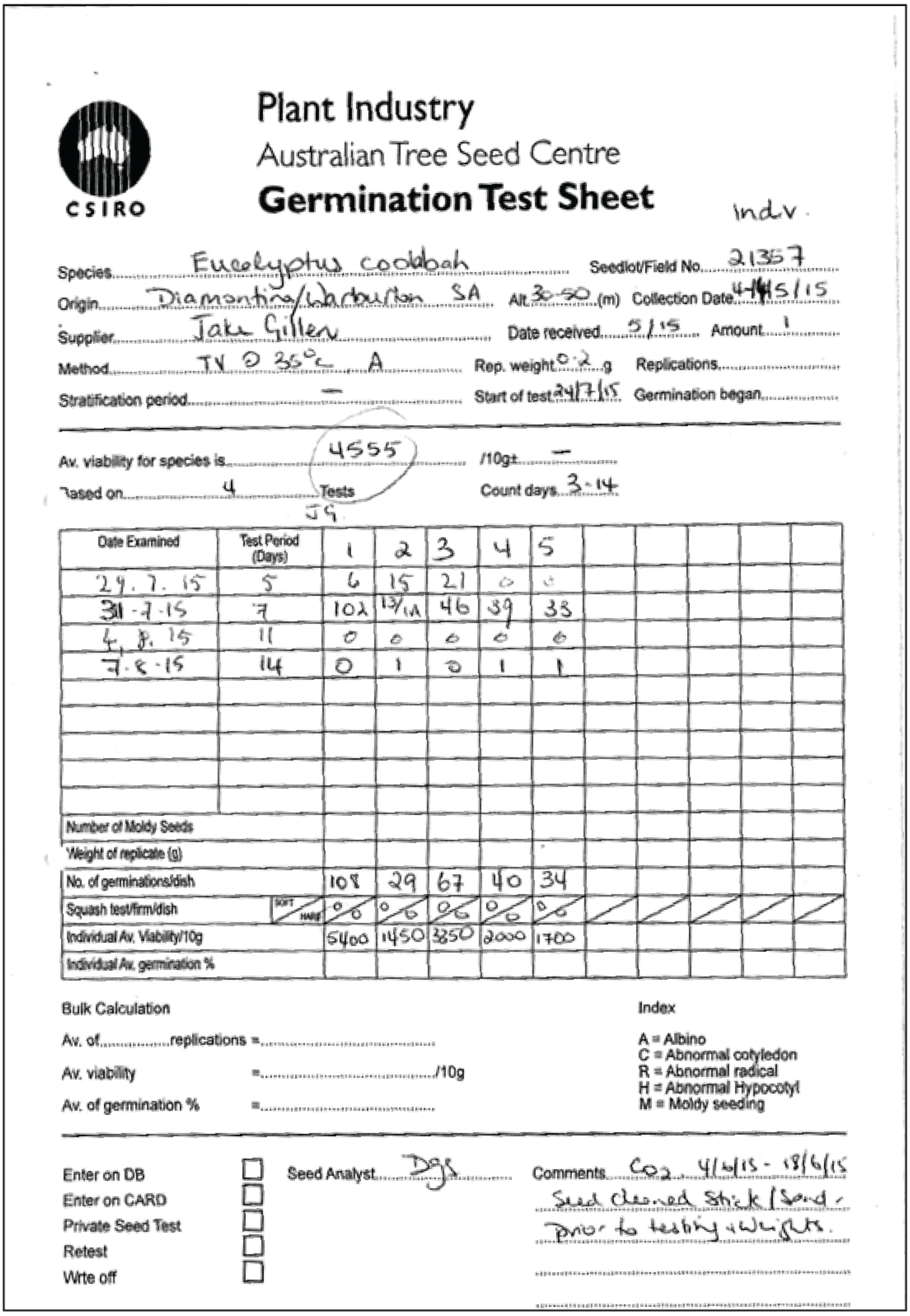
15 Appendix A

15.1 Seed Viability Results – CSIRO Australian Tree Seed Centre



CSIRO

Plant Industry

Australian Tree Seed Centre

Germination Test Sheet

indv.

Species Eucalyptus coolabah Seedlot/Field No. 21357

Origin Diamantina/Warburton SA Alt. 30-50 (m) Collection Date 4/5/15

Supplier Jake Gillen Date received 5/15 Amount 1

Method TV @ 35°C A Rep. weight 0.2 g Replications

Stratification period – Start of test 24/7/15 Germination began

Av. viability for species is 4555 /10g± –

Based on 4 Tests Count days 3-14

JG

Date Examined	Test Period (Days)	1	2	3	4	5					
29.7.15	5	6	15	21	0	0					
31-7-15	7	102	13/12	46	39	33					
4.8.15	11	0	0	0	0	0					
7-8-15	14	0	1	0	1	1					
Number of Moldy Seeds											
Weight of replicate (g)											
No. of germinations/dish		108	29	67	40	34					
Squash test/firm/dish	SOFT/HARD	0/0	0/0	0/0	0/0	0/0	/	/	/	/	/
Individual Av. Viability/10g		5400	1450	3850	2000	1700					
Individual Av. germination %											

Bulk Calculation

Av. of ....replications = ...

Av. viability = .../10g

Av. of germination % = ...

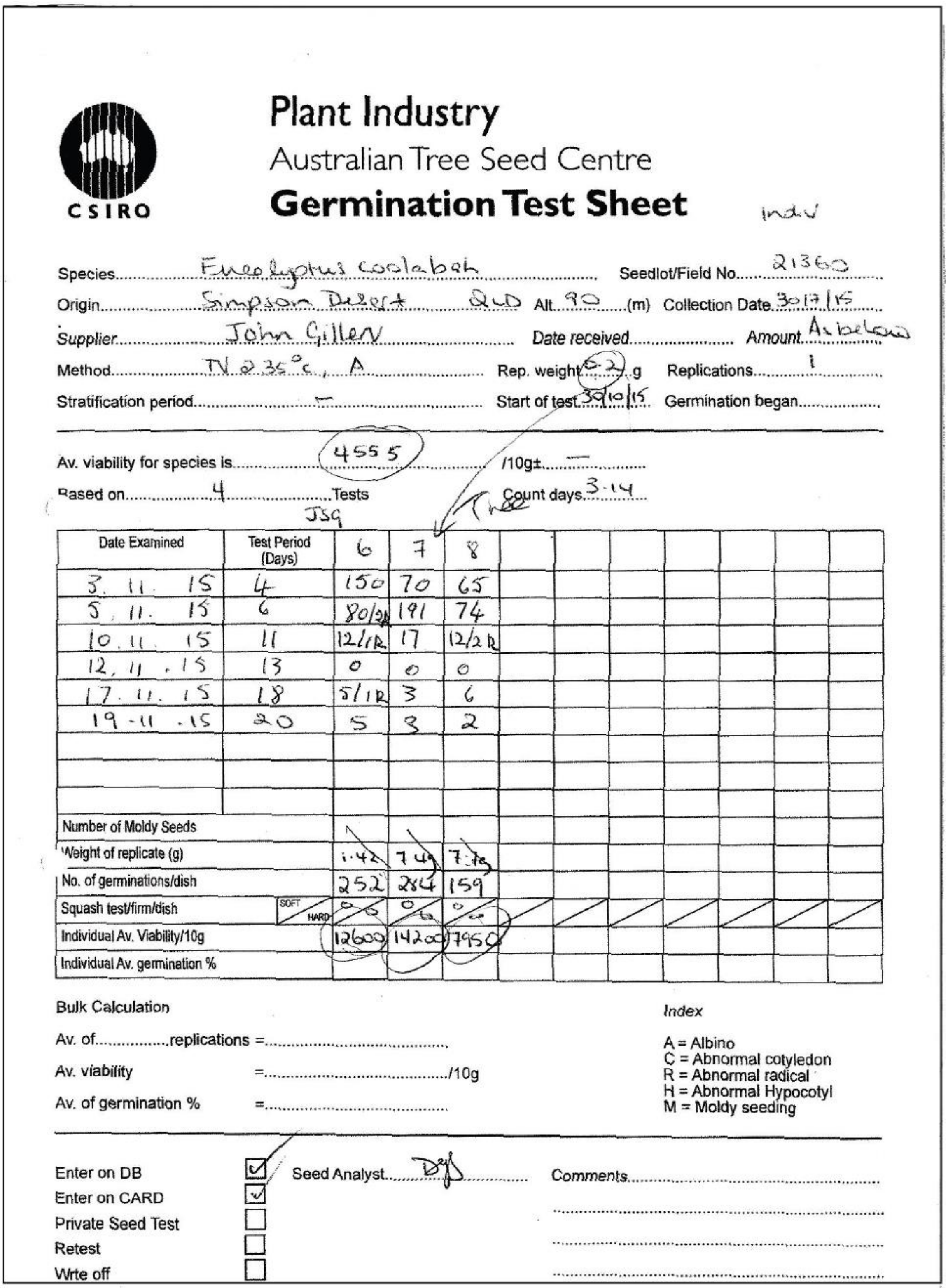
Index

A = Albino
C = Abnormal cotyledon
R = Abnormal radical
H = Abnormal Hypocotyl
M = Moldy seeding

Enter on DB ☐
Enter on CARD ☐
Private Seed Test ☐
Retest ☐
Wrte off ☐

Seed Analyst DGS

Comments CO2 4/6/15 - 18/6/15
Seed cleaned stick/sand -
prior to testing + weights.



CSIRO

Plant Industry

Australian Tree Seed Centre

Germination Test Sheet

indv

Species Eucalyptus coolabah Seedlot/Field No. 21360

Origin Simpson Desert QLD Alt. 90 (m) Collection Date 30/7/15

Supplier John Gillen Date received Amount As below

Method TV @ 35°c, A Rep. weight 0.2 g Replications 1

Stratification period – Start of test 30/10/15 Germination began

Av. viability for species is 4555 /10g± –

Based on 4 Tests JSG Count days 3-14

Tree

Date Examined	Test Period (Days)	6	7	8							
3. 11. 15	4	150	70	65							
5. 11. 15	6	80/2R	191	74							
10. 11. 15	11	12/1R	17	12/2R							
12. 11. 15	13	0	0	0							
17. 11. 15	18	5/1R	3	6							
19-11-15	20	5	3	2							
Number of Moldy Seeds											
Weight of replicate (g)		1.42	7.49	7.79							
No. of germinations/dish		252	284	159							
Squash test/firm/dish	SOFT / HARD	0/0	0/0	0/0							
Individual Av. Viability/10g		12600	14200	7950							
Individual Av. germination %											

Bulk Calculation

Av. of .... replications = ...

Av. viability = ... /10g

Av. of germination % = ...

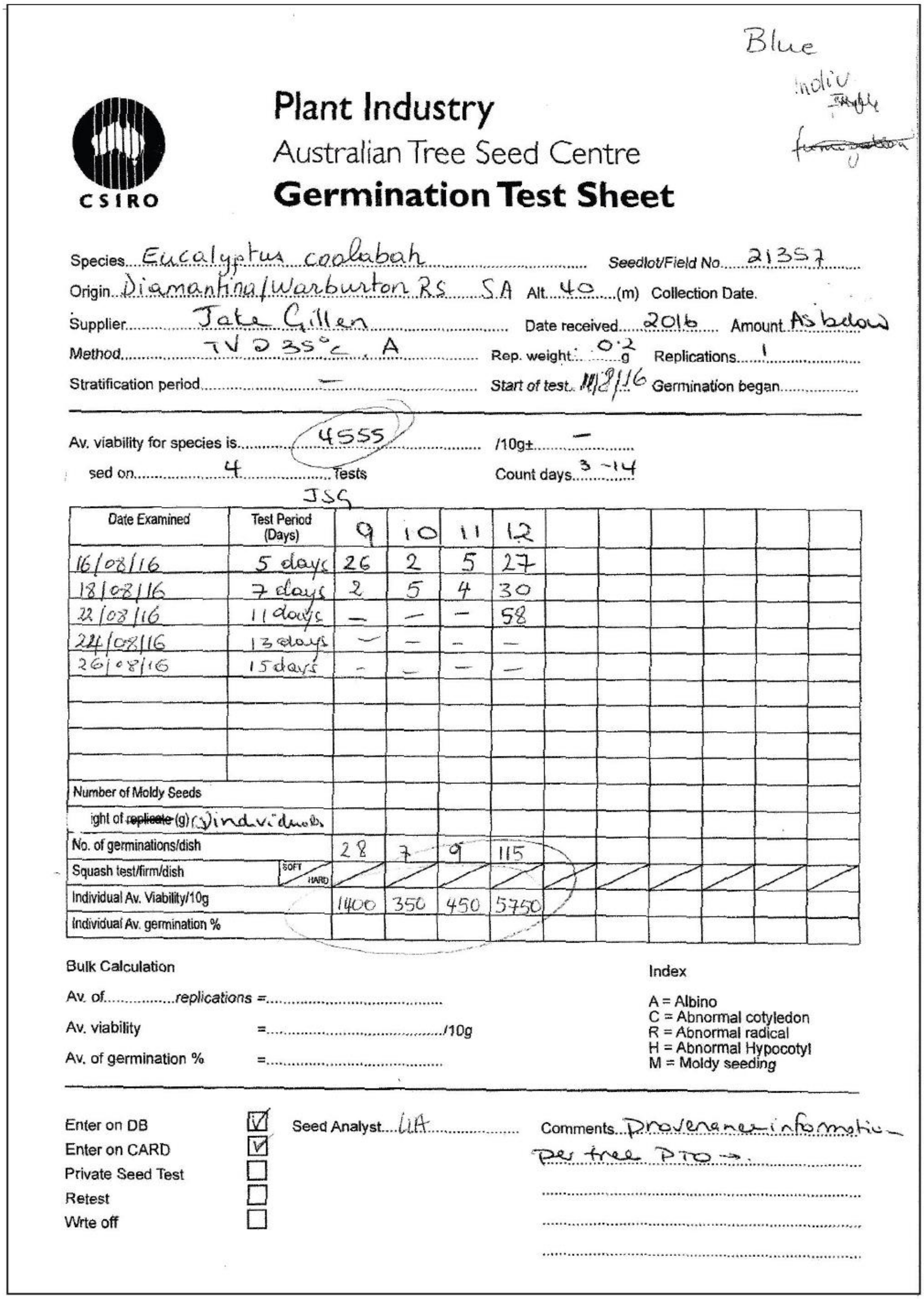
Index

A = Albino
C = Abnormal cotyledon
R = Abnormal radical
H = Abnormal Hypocotyl
M = Moldy seeding

Enter on DB ☑
Enter on CARD ☑
Private Seed Test ☐
Retest ☐
Wrte off ☐

Seed Analyst

Comments



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CSIRO

Plant Industry
Australian Tree Seed Centre
Germination Test Sheet

Species Eucalyptus coolabah Seedlot/Field No. 21357
Origin Diamantina/Warburton RS SA Alt. 40 (m) Collection Date.
Supplier Jake Gillen Date received 2016 Amount As below
Method TV @ 35°C A Rep. weight 0.2 g Replications 1
Stratification period — Start of test 11/8/16 Germination began

Av. viability for species is 4555 /10g± —
sed on 4 Tests Count days 3 -14
JSG

Date Examined	Test Period (Days)	9	10	11	12						
16/08/16	5 days	26	2	5	27						
18/08/16	7 days	2	5	4	30						
22/08/16	11 days	—	—	—	58						
24/08/16	13 days	—	—	—	—						
26/08/16	15 days	—	—	—	—						
Number of Moldy Seeds											
ight of ~~replicate~~ (g) (3) individuals											
No. of germinations/dish		28	7	9	115						
Squash test/firm/dish	SOFT / HARD										
Individual Av. Viability/10g		1400	350	450	5750						
Individual Av. germination %											

Bulk Calculation

Av. of .... replications = ...
Av. viability = ... /10g
Av. of germination % = ...

Index

A = Albino
C = Abnormal cotyledon
R = Abnormal radical
H = Abnormal Hypocotyl
M = Moldy seeding

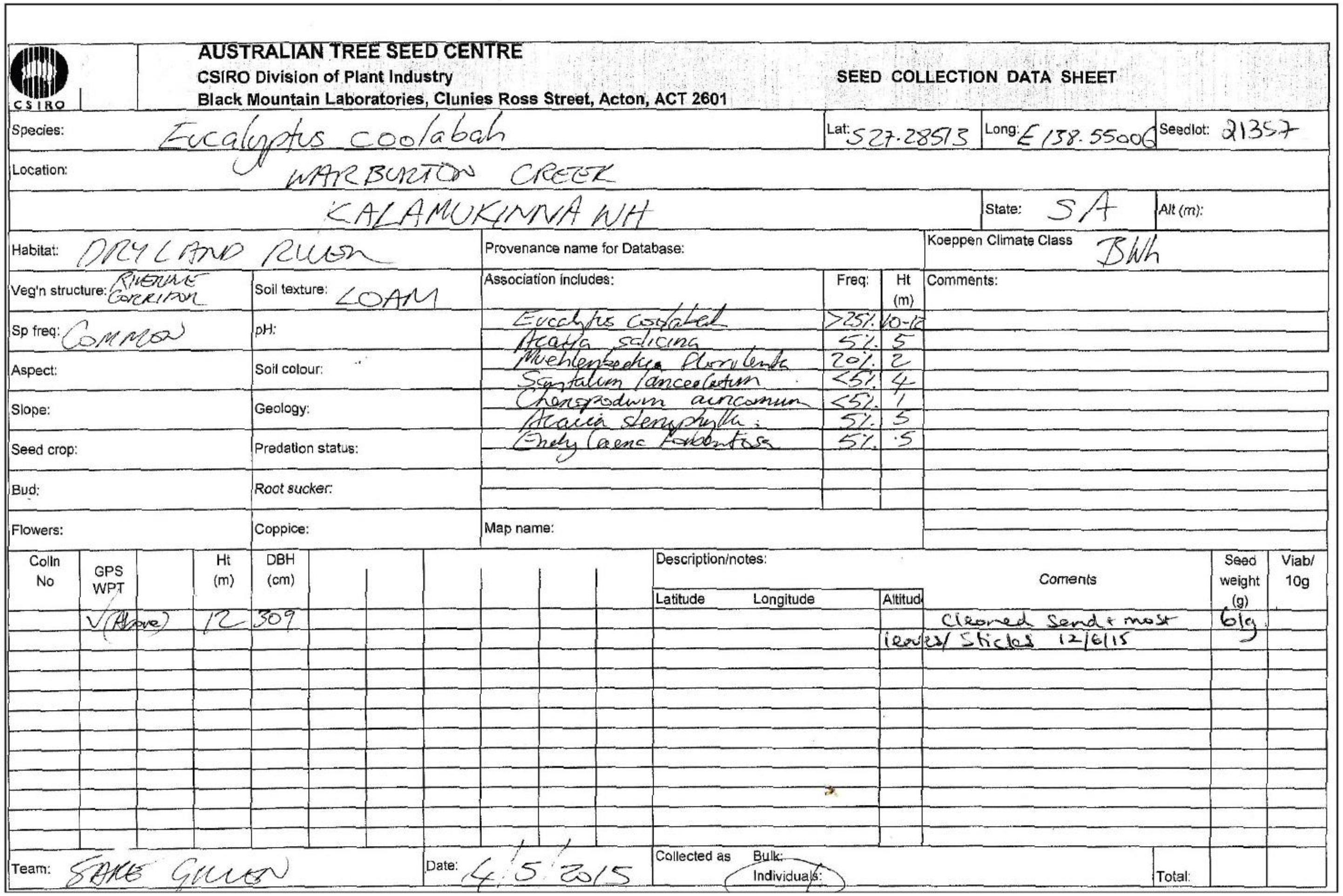
Enter on DB ☑
Enter on CARD ☑
Private Seed Test ☐
Retest ☐
Wrte off ☐

Seed Analyst UA

Comments Provenance information per tree PTO →.

16 Appendix B

16.1 Seed Collection Details



AUSTRALIAN TREE SEED CENTRE
CSIRO Division of Plant Industry
Black Mountain Laboratories, Clunies Ross Street, Acton, ACT 2601

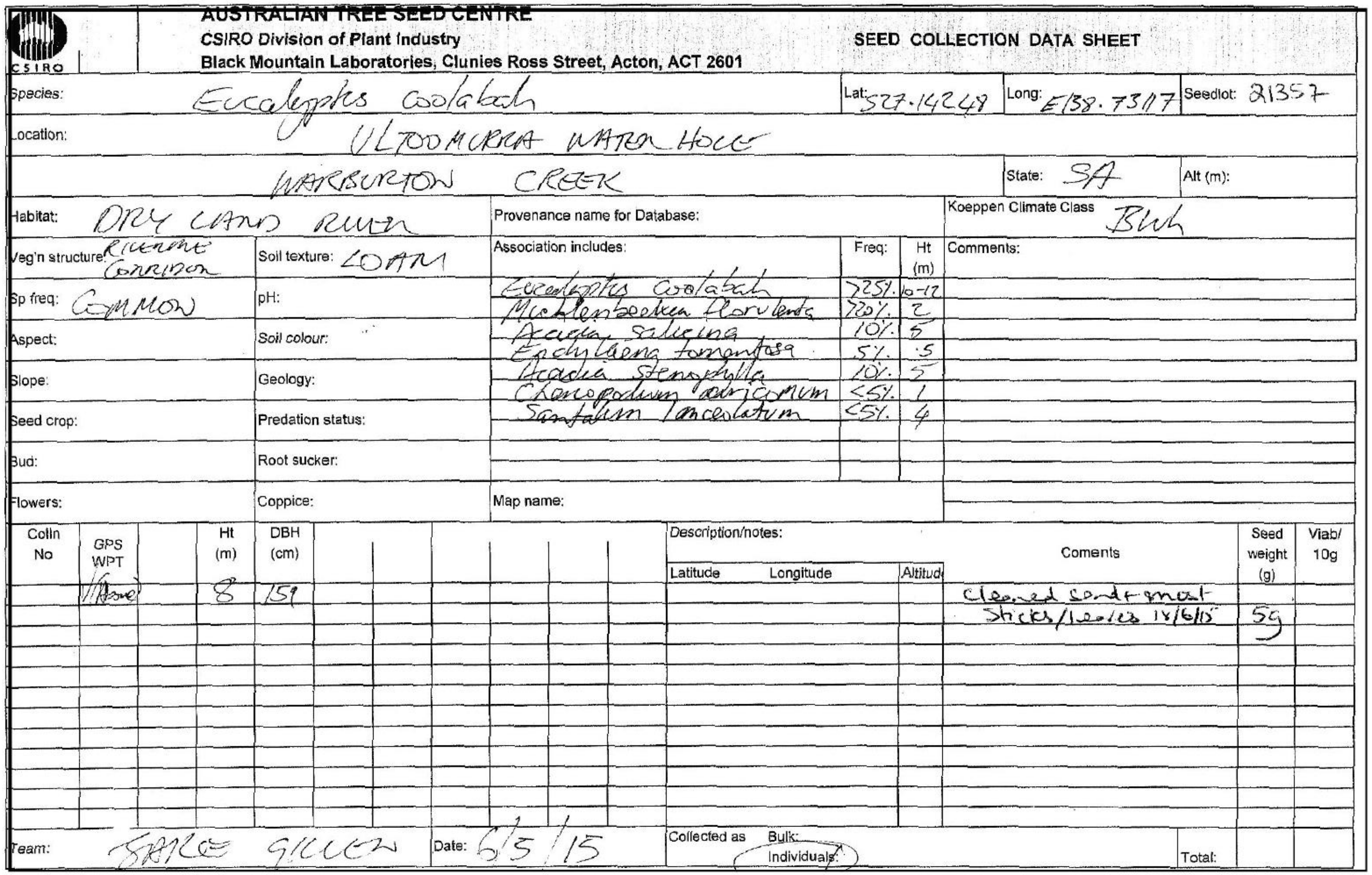
SEED COLLECTION DATA SHEET

Species: Eucalyptus coolabah
Lat: S27.28513
Long: E138.55006
Seedlot: 21357
Location: WARBURTON CREEK KALAMUKINNA WH
State: SA
Alt (m):
Habitat: DRYLAND RIVER
Provenance name for Database:
Koeppen Climate Class: BWh
Veg'n structure: RIVERINE CORRIDOR
Soil texture: LOAM
Comments:
Sp freq: COMMON
pH:
Aspect:
Soil colour:
Slope:
Geology:
Seed crop:
Predation status:
Bud:
Root sucker:
Flowers:
Coppice:
Map name:

Association includes:	Freq:	Ht (m)
Eucalyptus coolabah	>25%	10-12
Acacia salicina	5%	5
Muehlenbeckia florulenta	20%	2
Santalum lanceolatum	<5%	4
Chenopodium auricomum	<5%	1
Acacia stenophylla	5%	5
Enchylaena tomentosa	5%	·5

Colln No	GPS WPT	Ht (m)	DBH (cm)	Description/notes: Latitude	Longitude	Altitude	Coments	Seed weight (g)	Viab/ 10g
	√(Above)	12	309				Cleaned Seed + most leaves/ Sticks 12/6/15	61g	

Team: JAKE GILLEN
Date: 4/5/2015
Collected as Bulk: [✓ Individuals:]
Total:



CSIRO

AUSTRALIAN TREE SEED CENTRE
CSIRO Division of Plant Industry
Black Mountain Laboratories, Clunies Ross Street, Acton, ACT 2601

SEED COLLECTION DATA SHEET

Species: Eucalyptus coolabah
Lat: S27.14248
Long: E138.73117
Seedlot: 21357

Location: ULTOOMURRA WATER HOLE
WARBURTON CREEK
State: SA
Alt (m):

Habitat: DRY LAND RIVER
Provenance name for Database:
Koeppen Climate Class BWh

Veg'n structure: RIVERINE CORRIDOR
Soil texture: LOAM

Sp freq: COMMON
pH:

Aspect:
Soil colour:

Slope:
Geology:

Seed crop:
Predation status:

Bud:
Root sucker:

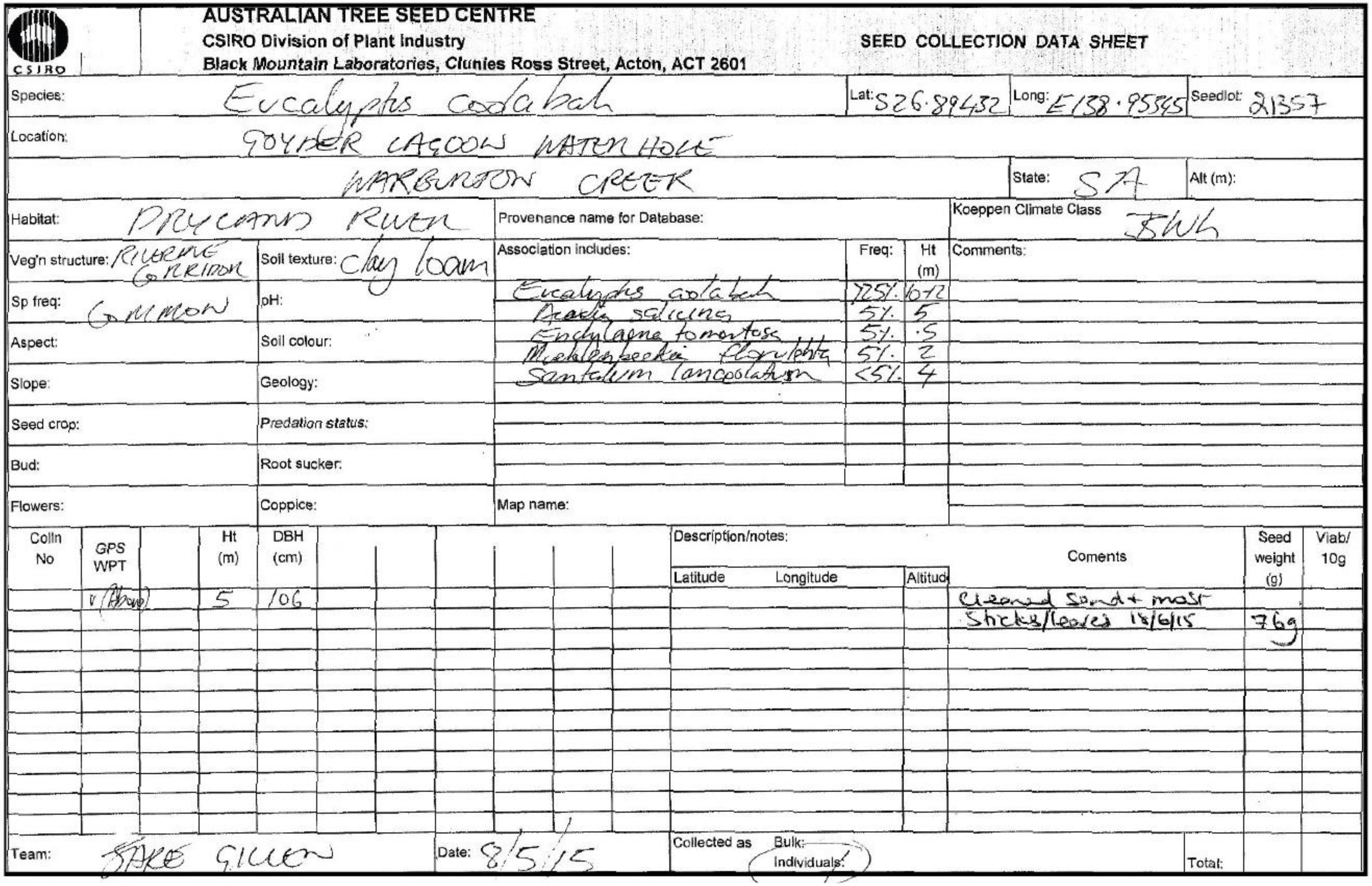
Flowers:
Coppice:
Map name:

Association includes:	Freq:	Ht (m)	Comments:
Eucalyptus coolabah	>25%	10-12	
Muehlenbeckia florulenta	>20%	2	
Acacia salicina	10%	5	
Enchylaena tomentosa	5%	.5	
Acacia stenophylla	10%	5	
Chenopodium auricomum	<5%	1	
Santalum lanceolatum	<5%	4	

Description/notes:

Colln No	GPS WPT		Ht (m)	DBH (cm)							Latitude	Longitude	Altitud	Coments	Seed weight (g)	Viab/ 10g
	(Above)		8	159										Cleaned sand + most		
														sticks/leaves 18/6/15	5g	

Team: JANCE GILLEN
Date: 6/5/15
Collected as Bulk: [✓ Individuals:]
Total:



AUSTRALIAN TREE SEED CENTRE
CSIRO Division of Plant Industry
Black Mountain Laboratories, Clunies Ross Street, Acton, ACT 2601

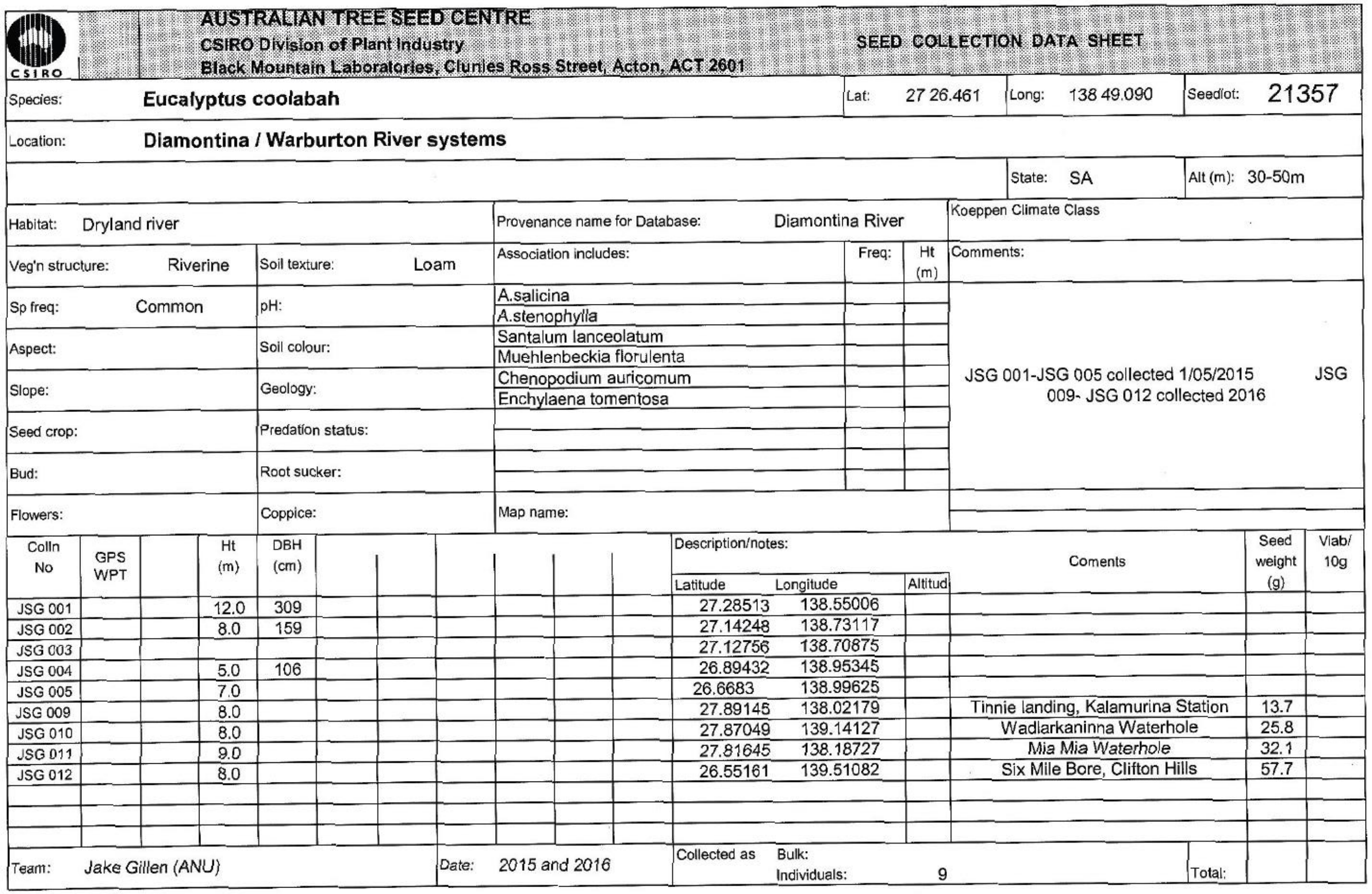
SEED COLLECTION DATA SHEET

Species: Eucalyptus coolabah
Lat: S26.89432
Long: E138.95345
Seedlot: 21357
Location: GOYDER LAGOON WATER HOLE
WARBURTON CREEK
State: SA
Alt (m):
Habitat: DRYLAND RIVER
Provenance name for Database:
Koeppen Climate Class BWh
Veg'n structure: RIVERINE CORRIDOR
Soil texture: Clay loam
Sp freq: COMMON
pH:
Aspect:
Soil colour:
Slope:
Geology:
Seed crop:
Predation status:
Bud:
Root sucker:
Flowers:
Coppice:
Map name:

Association includes:	Freq:	Ht (m)	Comments:
Eucalyptus coolabah	>25%	10-12	
Acacia salicina	5%	5	
Enchylaena tomentosa	5%	.5	
Muehlenbeckia florulenta	5%	2	
Santalum lanceolatum	<5%	4	

Colln No	GPS WPT		Ht (m)	DBH (cm)	Description/notes: Latitude	Longitude	Altitude	Coments	Seed weight (g)	Viab/ 10g
	✓ (Above)		5	106				Cleaned Seed + most Sticks/leaves 18/6/15	76g	

Team: JAKE GILLEN
Date: 8/5/15
Collected as Bulk: [✓ Individuals]
Total:



AUSTRALIAN TREE SEED CENTRE
CSIRO Division of Plant Industry
Black Mountain Laboratories, Clunies Ross Street, Acton, ACT 2601

SEED COLLECTION DATA SHEET

Species: **Eucalyptus coolabah**
Lat: 27 26.461
Long: 138 49.090
Seedlot: 21357
Location: **Diamontina / Warburton River systems**
State: SA
Alt (m): 30-50m
Habitat: Dryland river
Provenance name for Database: Diamontina River
Koeppen Climate Class
Veg'n structure: Riverine
Soil texture: Loam
Sp freq: Common
pH:
Aspect:
Soil colour:
Slope:
Geology:
Seed crop:
Predation status:
Bud:
Root sucker:
Flowers:
Coppice:
Map name:

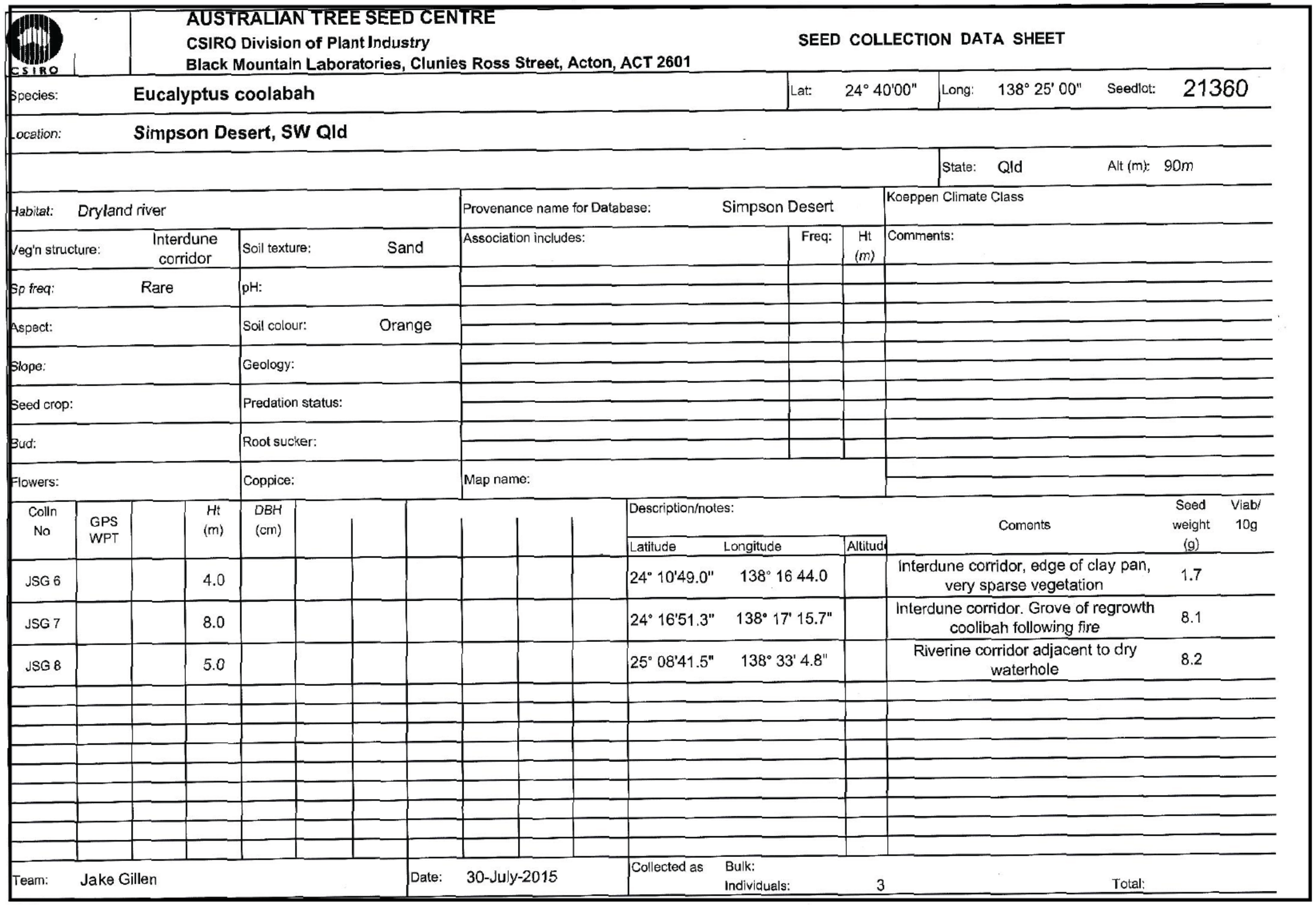
Association includes:	Freq:	Ht (m)
A.salicina		
A.stenophylla		
Santalum lanceolatum		
Muehlenbeckia florulenta		
Chenopodium auricomum		
Enchylaena tomentosa		

Comments:
JSG 001-JSG 005 collected 1/05/2015 JSG 009- JSG 012 collected 2016

Description/notes:

Colln No	GPS WPT	Ht (m)	DBH (cm)	Latitude	Longitude	Altitud	Coments	Seed weight (g)	Viab/ 10g
JSG 001		12.0	309	27.28513	138.55006				
JSG 002		8.0	159	27.14248	138.73117				
JSG 003				27.12756	138.70875				
JSG 004		5.0	106	26.89432	138.95345				
JSG 005		7.0		26.6683	138.99625				
JSG 009		8.0		27.89145	138.02179		Tinnie landing, Kalamurina Station	13.7	
JSG 010		8.0		27.87049	139.14127		Wadlarkaninna Waterhole	25.8	
JSG 011		9.0		27.81645	138.18727		Mia Mia Waterhole	32.1	
JSG 012		8.0		26.55161	139.51082		Six Mile Bore, Clifton Hills	57.7	

Team: Jake Gillen (ANU)
Date: 2015 and 2016
Collected as Bulk:
Individuals: 9
Total:



CSIRO

AUSTRALIAN TREE SEED CENTRE

CSIRO Division of Plant Industry

Black Mountain Laboratories, Clunies Ross Street, Acton, ACT 2601

SEED COLLECTION DATA SHEET

Species: **Eucalyptus coolabah**

Lat: 24° 40'00"

Long: 138° 25' 00"

Seedlot: 21360

Location: **Simpson Desert, SW Qld**

State: Qld

Alt (m): 90m

Habitat: Dryland river

Provenance name for Database: Simpson Desert

Koeppen Climate Class

Veg'n structure: Interdune corridor

Soil texture: Sand

Association includes:

Freq:

Ht (m)

Comments:

Sp freq: Rare

pH:

Aspect:

Soil colour: Orange

Slope:

Geology:

Seed crop:

Predation status:

Bud:

Root sucker:

Flowers:

Coppice:

Map name:

Description/notes:

Colln No	GPS WPT		Ht (m)	DBH (cm)							Latitude	Longitude	Altitud	Coments	Seed weight (g)	Viab/ 10g
JSG 6			4.0								24° 10'49.0"	138° 16 44.0		Interdune corridor, edge of clay pan, very sparse vegetation	1.7	
JSG 7			8.0								24° 16'51.3"	138° 17' 15.7"		Interdune corridor. Grove of regrowth coolibah following fire	8.1	
JSG 8			5.0								25° 08'41.5"	138° 33' 4.8"		Riverine corridor adjacent to dry waterhole	8.2	

Team: Jake Gillen

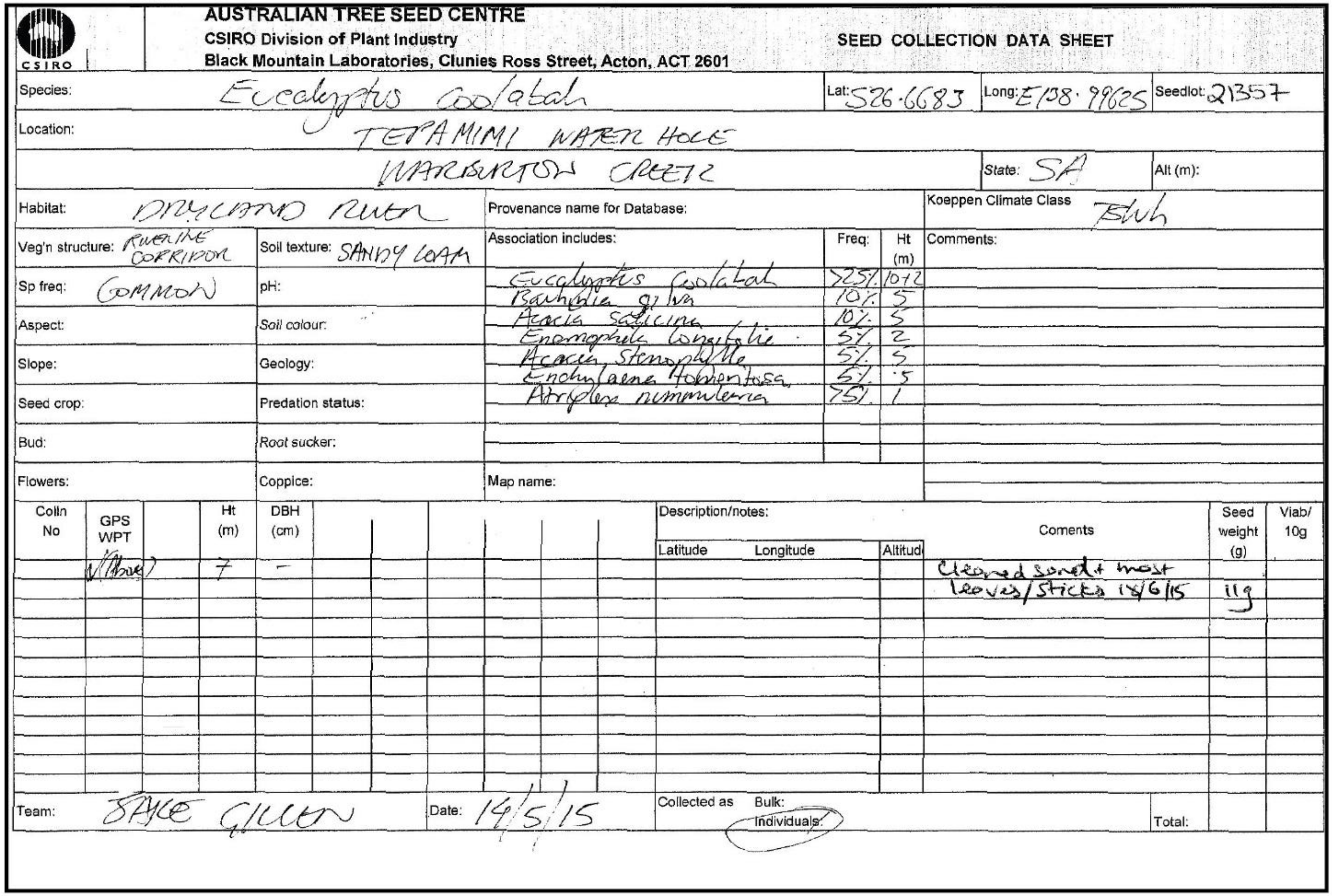
Date: 30-July-2015

Collected as

Bulk:

Individuals: 3

Total:



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AUSTRALIAN TREE SEED CENTRE
CSIRO Division of Plant Industry
Black Mountain Laboratories, Clunies Ross Street, Acton, ACT 2601

SEED COLLECTION DATA SHEET

Species: Eucalyptus coolabah
Lat: S26.6683
Long: E138.99625
Seedlot: 21357
Location: TEPAMIMI WATER HOLE
WARBURTON CREEK
State: SA
Alt (m):
Habitat: DRYLAND RIVER
Provenance name for Database:
Koeppen Climate Class: BWh
Veg'n structure: RIVERINE CORRIDOR
Soil texture: SANDY LOAM
Sp freq: COMMON
pH:
Aspect:
Soil colour:
Slope:
Geology:
Seed crop:
Predation status:
Bud:
Root sucker:
Flowers:
Coppice:
Map name:

Association includes:	Freq:	Ht (m)	Comments:
Eucalyptus Coolabah	>25%	10+2	
Bauhinia gilva	10%	5	
Acacia salicina	10%	5	
Eremophila longifolia	5%	2	
Acacia Stenophylla	5%	5	
Enchylaena tomentosa	5%	.5	
Atriplex nummularia	75%	1	

Colln No	GPS WPT		Ht (m)	DBH (cm)							Description/notes: Latitude	Longitude	Altitud	Coments	Seed weight (g)	Viab/ 10g
	W(Above)		7	–										Cleaned seed + most		
														leaves/sticks 18/6/15	11g	

Team: SPYCE GILLEN
Date: 14/5/15
Collected as Bulk: [✓ Individuals]
Total:

17 Appendix C

17.1 Seedling Growth Analyses Results – Total Biomass (g)

```
107  ANOVA [FPROB=yes; FACT=9; PSE=means;
LSD=5]lnTotal_Biomass_Foliage_Stem_Root_


Analysis of variance

Variate: lnTotal_Biomass_Foliage_Stem_Roo

Source of variation                  d.f.   (m.v.)        s.s.        m.s.      v.r.    F pr.

Rack stratum                            4               2.6654      0.6664      0.97

Rack.Treatment_Seed_Source stratum
Treatment_Seed_Source                   2               1.4541      0.7270      1.05    0.393
Residual                                8               5.5205      0.6901

Rack.Treatment_Seed_Source.Treatment_DRY_WET stratum
Treatment_DRY_WET                       1               1.8327      1.8327     10.08    0.008
Treatment_Seed_Source.Treatment_DRY_WET
                                        2               1.7861      0.8931      4.91    0.028
Residual                               12               2.1811      0.1818      0.39

Rack.Treatment_Seed_Source.Treatment_Soil stratum
Treatment_Soil                          3             325.4417    108.4806    102.51    <.001
Treatment_Seed_Source.Treatment_Soil
                                        6               2.3511      0.3918      0.37    0.893
Residual                               36              38.0953      1.0582      2.24

Rack.Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil stratum
Treatment_DRY_WET.Treatment_Soil
                                        3               4.3369      1.4456      3.07    0.041
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                        6               0.4393      0.0732      0.16    0.987
Residual                               35      (1)     16.5004      0.4714

Total                                 118      (1)    392.6734


Message: the following units have large residuals.

Rack Rack 1 Treatment_Seed_Source 1                           0.437          s.e.  0.214
Rack Rack 1 Treatment_Seed_Source 3                          -0.496          s.e.  0.214

Rack Rack 1 Treatment_Seed_Source 1 Treatment_Soil 3
                                                              2.276          s.e.  0.563

Rack Rack 2 Treatment_Seed_Source 2 Treatment_DRY_WET D Treatment_Soil 2        -1.005     s.e.  0.371
Rack Rack 2 Treatment_Seed_Source 2 Treatment_DRY_WET W Treatment_Soil 2         1.005     s.e.  0.371
Rack Rack 4 Treatment_Seed_Source 2 Treatment_DRY_WET D Treatment_Soil 1        -0.902     s.e.  0.371
Rack Rack 4 Treatment_Seed_Source 2 Treatment_DRY_WET W Treatment_Soil 1         0.902     s.e.  0.371
Rack Rack 5 Treatment_Seed_Source 3 Treatment_DRY_WET D Treatment_Soil 1        -0.958     s.e.  0.371
Rack Rack 5 Treatment_Seed_Source 3 Treatment_DRY_WET W Treatment_Soil 1         0.958     s.e.  0.371
```

Tables of means

```
Variate: lnTotal_Biomass_Foliage_Stem_Roo

Grand mean  -1.606

      Treatment_Seed_Source         1         2         3
                               -1.451    -1.677    -1.691

    Treatment_DRY_WET          D         W
                          -1.482    -1.730

     Treatment_Soil        1         2         3         4
                      -0.961    -1.004    -4.385    -0.074

      Treatment_Seed_Source   Treatment_DRY_WET         D         W
                          1                        -1.377    -1.524
                          2                        -1.671    -1.682
                          3                        -1.399    -1.983

      Treatment_Seed_Source    Treatment_Soil         1         2         3         4
                          1                      -0.677    -1.037    -4.044    -0.045
                          2                      -1.219    -0.987    -4.390    -0.110
                          3                      -0.988    -0.989    -4.720    -0.066

    Treatment_DRY_WET    Treatment_Soil         1         2         3         4
                    D                      -0.692    -1.136    -4.368     0.266
                    W                      -1.231    -0.872    -4.402    -0.413

      Treatment_Seed_Source   Treatment_DRY_WET    Treatment_Soil         1         2
                          1                   D                      -0.489    -1.081
                                              W                      -0.865    -0.993
                          2                   D                      -1.058    -1.262
                                              W                      -1.380    -0.712
                          3                   D                      -0.528    -1.066
                                              W                      -1.448    -0.912

      Treatment_Seed_Source   Treatment_DRY_WET    Treatment_Soil         3         4
                          1                   D                      -4.135     0.196
                                              W                      -3.953    -0.286
                          2                   D                      -4.479     0.115
                                              W                      -4.301    -0.336
                          3                   D                      -4.489     0.485
                                              W                      -4.952    -0.618
```

Standard errors of means

```
Table           Treatment_Seed_Source
                                   Treatment_DRY_WET
                                                     Treatment_Soil
                                                               Treatment_Seed_Source
                                                               Treatment_DRY_WET
rep.                            40             60             30             20
e.s.e.                      0.1313         0.0550         0.1878         0.1476
d.f.                             8             12             36          12.20
Except when comparing means with the same level(s) of
Treatment_Seed_Source
                                                                         0.0953
```

```
d.f.                                                                       12

Table       Treatment_Seed_Source
                                 Treatment_DRY_WET
                                                Treatment_Seed_Source
                   Treatment_Soil
                                  Treatment_Soil
                                                Treatment_DRY_WET
                                                Treatment_Soil
rep.                           10             15             5
e.s.e.                     0.3108         0.2148        0.3695
d.f.                        44.00          57.45         74.67
Except when comparing means with the same level(s) of
Treatment_Seed_Source
                           0.3253                       0.3721
d.f.                           36                        57.45
Treatment_DRY_WET
                                          0.2258
d.f.                                       62.47
Treatment_Soil                            0.1631
d.f.                                       42.53
Treatment_Seed_Source.Treatment_DRY_WET
                                                        0.3911
d.f.                                                     62.47
Treatment_Seed_Source.Treatment_Soil
                                                        0.2825
d.f.                                                     42.53

(Not adjusted for missing values)
```

Missing values

```
Variate: lnTotal_Biomass_Foliage_Stem_Roo

 Unit       estimate
5             -4.744


Max. no. iterations 7
```

18 Appendix D

18.1 Seedling Growth Analyses Results – Foliage and Stem Dry Weight (g)

```
53  ANOVA [FPROB=yes; FACT=9; PSE=means; LSD=5]lnFoliage_dry_wt_g

Analysis of variance

Variate: lnFoliage_dry_wt_g

Source of variation                 d.f.  (m.v.)        s.s.        m.s.     v.r.   F pr.

Rack stratum                           4             0.5560      0.1390     0.79

Rack.Treatment_Seed_Source stratum
Treatment_Seed_Source                  2             0.2623      0.1311     0.75   0.504
Residual                               8             1.4020      0.1753

Rack.Treatment_Seed_Source.Treatment_DRY_WET stratum
Treatment_DRY_WET                      1             1.0731      1.0731     6.85   0.023
Treatment_Seed_Source.Treatment_DRY_WET
                                       2             0.0310      0.0155     0.10   0.907
Residual                              12             1.8806      0.1567     1.11

Rack.Treatment_Seed_Source.Treatment_Soil stratum
Treatment_Soil                         3            40.8413     13.6138    47.50   <.001
Treatment_Seed_Source.Treatment_Soil
                                       6             0.8596      0.1433     0.50   0.804
Residual                              36            10.3172      0.2866     2.02

Rack.Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil stratum
Treatment_DRY_WET.Treatment_Soil
                                       3             4.0326      1.3442     9.49   <.001
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                       6             0.6869      0.1145     0.81   0.571
Residual                              33     (3)     4.7725      0.1416

Total                                116     (3)    65.0815


Message: the following units have large residuals.

Rack Rack 1 Treatment_Seed_Source 3 Treatment_DRY_WET D
                                                          -0.263          s.e.  0.125
Rack Rack 1 Treatment_Seed_Source 3 Treatment_DRY_WET W
                                                           0.263          s.e.  0.125

Rack Rack 1 Treatment_Seed_Source 1 Treatment_Soil 3
                                                           0.859          s.e.  0.293
Rack Rack 1 Treatment_Seed_Source 3 Treatment_Soil 1
                                                          -0.793          s.e.  0.293

Rack Rack 2 Treatment_Seed_Source 3 Treatment_DRY_WET D Treatment_Soil 4        -0.622    s.e.  0.197
Rack Rack 2 Treatment_Seed_Source 3 Treatment_DRY_WET W Treatment_Soil 4         0.622    s.e.  0.197
Rack Rack 5 Treatment_Seed_Source 3 Treatment_DRY_WET D Treatment_Soil 1        -0.520    s.e.  0.197
Rack Rack 5 Treatment_Seed_Source 3 Treatment_DRY_WET W Treatment_Soil 1         0.520    s.e.  0.197
```

Tables of means

```
Variate: lnFoliage_dry_wt_g

Grand mean  -1.306

   Treatment_Seed_Source          1           2           3
                             -1.241      -1.333      -1.346

 Treatment_DRY_WET          D           W
                       -1.212      -1.401

  Treatment_Soil          1           2           3           4
                     -1.250      -1.227      -2.194      -0.555

   Treatment_Seed_Source     Treatment_DRY_WET           D           W
                       1                            -1.166      -1.315
                       2                            -1.219      -1.447
                       3                            -1.250      -1.441

   Treatment_Seed_Source      Treatment_Soil           1           2           3           4
                       1                          -1.059      -1.329      -2.042      -0.533
                       2                          -1.344      -1.130      -2.303      -0.556
                       3                          -1.347      -1.223      -2.237      -0.576

 Treatment_DRY_WET      Treatment_Soil           1           2           3           4
                 D                          -1.131      -1.342      -2.197      -0.177
                 W                          -1.368      -1.113      -2.190      -0.933

   Treatment_Seed_Source     Treatment_DRY_WET      Treatment_Soil           1           2
                       1                     D                          -0.955      -1.407
                                             W                          -1.163      -1.251
                       2                     D                          -1.130      -1.322
                                             W                          -1.558      -0.938
                       3                     D                          -1.310      -1.296
                                             W                          -1.384      -1.149

   Treatment_Seed_Source     Treatment_DRY_WET      Treatment_Soil           3           4
                       1                     D                          -1.987      -0.315
                                             W                          -2.096      -0.751
                       2                     D                          -2.303      -0.122
                                             W                          -2.303      -0.990
                       3                     D                          -2.303      -0.093
                                             W                          -2.171      -1.058
```

Standard errors of means

```
Table           Treatment_Seed_Source
                                  Treatment_DRY_WET
                                                   Treatment_Soil
                                                             Treatment_Seed_Source
                                                             Treatment_DRY_WET
rep.                              40             60             30             20
e.s.e.                        0.0662         0.0511         0.0977         0.0911
d.f.                               8             12             36          18.72
Except when comparing means with the same level(s) of
Treatment_Seed_Source
                                                                           0.0885
```

```
d.f.                                                                             12

Table         Treatment_Seed_Source
                                    Treatment_DRY_WET
                                                    Treatment_Seed_Source
                      Treatment_Soil
                                      Treatment_Soil
                                                    Treatment_DRY_WET
                                                      Treatment_Soil
rep.                              10              15               5
e.s.e.                        0.1609          0.1205          0.2010
d.f.                           43.95           64.47           81.95
Except when comparing means with the same level(s) of
Treatment_Seed_Source
                              0.1693                          0.2087
d.f.                              36                           64.47
Treatment_DRY_WET
                                              0.1195
d.f.                                           63.46
Treatment_Soil                                0.0984
d.f.                                           45.00
Treatment_Seed_Source.Treatment_DRY_WET
                                                              0.2069
d.f.                                                           63.46
Treatment_Seed_Source.Treatment_Soil
                                                              0.1705
d.f.                                                           45.00

(Not adjusted for missing values)
```

Missing values

```
Variate: lnFoliage_dry_wt_g

 Unit        estimate
5              -1.644
23             -0.692
26             -0.292


Max. no. iterations 6
  54  ANOVA [FPROB=yes; FACT=9; PSE=means; LSD=5]lnStem_Dry_Wt_g
```

Analysis of variance

```
Variate: lnStem_Dry_Wt_g

Source of variation                d.f.   (m.v.)         s.s.           m.s.      v.r.     F pr.

Rack stratum                          4               0.13674        0.03418      0.28

Rack.Treatment_Seed_Source stratum
Treatment_Seed_Source                 2               0.04422        0.02211      0.18     0.838
Residual                              8               0.98039        0.12255

Rack.Treatment_Seed_Source.Treatment_DRY_WET stratum
Treatment_DRY_WET                     1               0.50873        0.50873      8.74     0.012
Treatment_Seed_Source.Treatment_DRY_WET
```

```
                               2            0.09473      0.04736      0.81     0.466
Residual                      12            0.69886      0.05824      1.05

Rack.Treatment_Seed_Source.Treatment_Soil stratum
Treatment_Soil                 3           10.51259      3.50420     37.06     <.001
Treatment_Seed_Source.Treatment_Soil
                               6            0.32891      0.05482      0.58     0.744
Residual                      36            3.40368      0.09455      1.70

Rack.Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil stratum
Treatment_DRY_WET.Treatment_Soil
                               3            2.19896      0.73299     13.21     <.001
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                               6            0.17321      0.02887      0.52     0.789
Residual                      33     (3)    1.83079      0.05548

Total                        116     (3)   20.13599
```

Message: the following units have large residuals.

```
Rack Rack 2 Treatment_Seed_Source 1                      -0.194          s.e.  0.090
Rack Rack 2 Treatment_Seed_Source 2                       0.215          s.e.  0.090

Rack Rack 1 Treatment_Seed_Source 3 Treatment_DRY_WET D
                                                         -0.175          s.e.  0.076
Rack Rack 1 Treatment_Seed_Source 3 Treatment_DRY_WET W
                                                          0.175          s.e.  0.076

Rack Rack 1 Treatment_Seed_Source 3 Treatment_Soil 1
                                                         -0.460          s.e.  0.168
Rack Rack 2 Treatment_Seed_Source 2 Treatment_Soil 2
                                                          0.398          s.e.  0.168

Rack Rack 2 Treatment_Seed_Source 3 Treatment_DRY_WET D Treatment_Soil 4       -0.324     s.e.   0.124
Rack Rack 2 Treatment_Seed_Source 3 Treatment_DRY_WET W Treatment_Soil 4        0.324     s.e.   0.124
Rack Rack 4 Treatment_Seed_Source 3 Treatment_DRY_WET D Treatment_Soil 1        0.286     s.e.   0.124
Rack Rack 4 Treatment_Seed_Source 3 Treatment_DRY_WET W Treatment_Soil 1       -0.286     s.e.   0.124
Rack Rack 5 Treatment_Seed_Source 3 Treatment_DRY_WET D Treatment_Soil 1       -0.336     s.e.   0.124
Rack Rack 5 Treatment_Seed_Source 3 Treatment_DRY_WET D Treatment_Soil 2        0.272     s.e.   0.124
Rack Rack 5 Treatment_Seed_Source 3 Treatment_DRY_WET W Treatment_Soil 1        0.336     s.e.   0.124
Rack Rack 5 Treatment_Seed_Source 3 Treatment_DRY_WET W Treatment_Soil 2       -0.272     s.e.   0.124
```

Tables of means

```
Variate: lnStem_Dry_Wt_g

Grand mean  -1.828

      Treatment_Seed_Source          1          2          3
                                -1.817     -1.855     -1.812

    Treatment_DRY_WET          D          W
                          -1.763     -1.893

     Treatment_Soil          1          2          3          4
                        -1.831     -1.802     -2.257     -1.421
```

```
Treatment_Seed_Source   Treatment_DRY_WET         D         W
                    1                        -1.791    -1.843
                    2                        -1.765    -1.946
                    3                        -1.733    -1.891

Treatment_Seed_Source      Treatment_Soil        1         2         3         4
                    1                       -1.790    -1.827    -2.211    -1.439
                    2                       -1.934    -1.718    -2.303    -1.466
                    3                       -1.771    -1.860    -2.259    -1.359

Treatment_DRY_WET    Treatment_Soil        1         2         3         4
                D                     -1.753    -1.888    -2.265    -1.145
                W                     -1.910    -1.715    -2.250    -1.698

Treatment_Seed_Source   Treatment_DRY_WET    Treatment_Soil        1         2
                    1                   D                     -1.808    -1.949
                                        W                     -1.771    -1.706
                    2                   D                     -1.841    -1.753
                                        W                     -2.027    -1.683
                    3                   D                     -1.611    -1.963
                                        W                     -1.931    -1.757

Treatment_Seed_Source   Treatment_DRY_WET    Treatment_Soil        3         4
                    1                   D                     -2.191    -1.216
                                        W                     -2.231    -1.662
                    2                   D                     -2.303    -1.162
                                        W                     -2.303    -1.770
                    3                   D                     -2.303    -1.057
                                        W                     -2.215    -1.662
```

Standard errors of means

```
Table         Treatment_Seed_Source
                                  Treatment_DRY_WET
                                                 Treatment_Soil
                                                           Treatment_Seed_Source
                                                           Treatment_DRY_WET
rep.                          40            60            30            20
e.s.e.                    0.0554        0.0312        0.0561        0.0672
d.f.                           8            12            36         15.13
Except when comparing means with the same level(s) of
Treatment_Seed_Source
                                                                    0.0540
d.f.                                                                    12

Table         Treatment_Seed_Source
                                  Treatment_DRY_WET
                                                Treatment_Seed_Source
                    Treatment_Soil
                                  Treatment_Soil
                                                Treatment_DRY_WET
                                                  Treatment_Soil
rep.                          10            15             5
e.s.e.                    0.1008        0.0710        0.1256
d.f.                       40.12         66.97         76.04
Except when comparing means with the same level(s) of
Treatment_Seed_Source
                          0.0972                      0.1230
d.f.                          36                       66.97
```

```
Treatment_DRY_WET
                                                0.0707
d.f.                                             65.89
Treatment_Soil                                  0.0612
d.f.                                             44.99
Treatment_Seed_Source.Treatment_DRY_WET
                                                              0.1225
d.f.                                                           65.89
Treatment_Seed_Source.Treatment_Soil
                                                              0.1060
d.f.                                                           44.99

(Not adjusted for missing values)
```

Missing values

```
Variate: lnStem_Dry_Wt_g

 Unit          estimate
5                -1.865
23               -1.435
26               -1.048


Max. no. iterations 7
```

19 Appendix E

19.1 Seedling Growth Analyses Results – Root Dry Weight (g)

```
113  ANOVA [FPROB=yes; FACT=9; PSE=means; LSD=5]lnRoot_Dry_Wt_g
```

Analysis of variance

```
Variate: lnRoot_Dry_Wt_g

Source of variation              d.f.  (m.v.)        s.s.       m.s.    v.r.  F pr.

Rack stratum                        4              1.5973     0.3993    0.76

Rack.Treatment_Seed_Source stratum
Treatment_Seed_Source               2              0.3598     0.1799    0.34  0.719
Residual                            8              4.1858     0.5232

Rack.Treatment_Seed_Source.Treatment_DRY_WET stratum
Treatment_DRY_WET                   1              5.4274     5.4274   20.12  <.001
Treatment_Seed_Source.Treatment_DRY_WET
                                    2              2.6298     1.3149    4.88  0.028
Residual                           12              3.2364     0.2697    0.42

Rack.Treatment_Seed_Source.Treatment_Soil stratum
Treatment_Soil                      3            211.9980    70.6660   88.23  <.001
Treatment_Seed_Source.Treatment_Soil
                                    6              1.8209     0.3035    0.38  0.888
Residual                           36             28.8350     0.8010    1.24

Rack.Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil stratum
Treatment_DRY_WET.Treatment_Soil
                                    3              4.7964     1.5988    2.47  0.079
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                    6              2.8932     0.4822    0.74  0.618
Residual                           33     (3)     21.3778     0.6478

Total                             116     (3)    280.9687
```

Message: the following units have large residuals.

```
Rack Rack 2 Treatment_Seed_Source 1 Treatment_Soil 2
                                                   -1.106          s.e.  0.490
Rack Rack 2 Treatment_Seed_Source 2 Treatment_Soil 1
                                                    1.197          s.e.  0.490
Rack Rack 4 Treatment_Seed_Source 2 Treatment_Soil 1
                                                   -1.411          s.e.  0.490

Rack Rack 4 Treatment_Seed_Source 3 Treatment_DRY_WET D Treatment_Soil 1      1.108     s.e.  0.422
Rack Rack 4 Treatment_Seed_Source 3 Treatment_DRY_WET W Treatment_Soil 1     -1.108     s.e.  0.422
Rack Rack 5 Treatment_Seed_Source 3 Treatment_DRY_WET D Treatment_Soil 1     -1.188     s.e.  0.422
Rack Rack 5 Treatment_Seed_Source 3 Treatment_DRY_WET W Treatment_Soil 1      1.188     s.e.  0.422
```

Tables of means

```
Variate: lnRoot_Dry_Wt_g

Grand mean  -2.414

   Treatment_Seed_Source           1         2         3
                              -2.377    -2.373    -2.491

 Treatment_DRY_WET         D         W
                      -2.201    -2.626

  Treatment_Soil         1         2         3         4
                    -2.037    -1.979    -4.609    -1.030

   Treatment_Seed_Source      Treatment_DRY_WET          D         W
                       1                            -2.292    -2.463
                       2                            -2.240    -2.505
                       3                            -2.071    -2.911

   Treatment_Seed_Source       Treatment_Soil          1         2         3         4
                       1                          -1.765    -2.032    -4.721    -0.991
                       2                          -2.235    -1.910    -4.390    -0.956
                       3                          -2.111    -1.996    -4.716    -1.141

 Treatment_DRY_WET       Treatment_Soil          1         2         3         4
                 D                          -1.543    -1.864    -4.654    -0.744
                 W                          -2.531    -2.095    -4.565    -1.315

   Treatment_Seed_Source      Treatment_DRY_WET       Treatment_Soil          1         2
                       1                      D                          -1.344    -1.886
                                              W                          -2.185    -2.178
                       2                      D                          -2.059    -1.706
                                              W                          -2.410    -2.114
                       3                      D                          -1.225    -1.999
                                              W                          -2.997    -1.992

   Treatment_Seed_Source      Treatment_DRY_WET       Treatment_Soil          3         4
                       1                      D                          -4.993    -0.946
                                              W                          -4.450    -1.037
                       2                      D                          -4.479    -0.717
                                              W                          -4.301    -1.196
                       3                      D                          -4.489    -0.570
                                              W                          -4.944    -1.713
```

Standard errors of means

```
Table          Treatment_Seed_Source
                                     Treatment_DRY_WET
                                                     Treatment_Soil
                                                                 Treatment_Seed_Source
                                                                 Treatment_DRY_WET
rep.                               40              60              30              20
e.s.e.                         0.1144          0.0670          0.1634          0.1408
d.f.                                8              12              36           15.61
Except when comparing means with the same level(s) of
Treatment_Seed_Source
                                                                               0.1161
```

```
d.f.                                                                    12

Table        Treatment_Seed_Source
                                Treatment_DRY_WET
                                              Treatment_Seed_Source
                    Treatment_Soil
                                  Treatment_Soil
                                              Treatment_DRY_WET
                                                Treatment_Soil
rep.                          10            15             5
e.s.e.                    0.2705        0.2049        0.3584
d.f.                       44.00         70.48         83.82
Except when comparing means with the same level(s) of
Treatment_Seed_Source
                          0.2830                      0.3549
d.f.                          36                       70.48
Treatment_DRY_WET
                                        0.2198
d.f.                                     68.73
Treatment_Soil                          0.1921
d.f.                                     40.64
Treatment_Seed_Source.Treatment_DRY_WET
                                                      0.3806
d.f.                                                   68.73
Treatment_Seed_Source.Treatment_Soil
                                                      0.3327
d.f.                                                   40.64

(Not adjusted for missing values)
```

Missing values

```
Variate: lnRoot_Dry_Wt_g

 Unit     estimate
5           -4.703
10          -1.266
29          -1.137


Max. no. iterations 7
```

20 Appendix F

20.1 Seedling Growth Analyses Results – Height (cm)

```
97  reml [p=m,c,w,means;pse=allestimates]lnHeight_cm_10_04_2016Trim
```

REML variance components analysis

```
Response variate:          lnHeight_cm_10_04_2016Trim
Fixed model:               Constant + Treatment_Seed_Source + Treatment_DRY_WET + Treatment_Soil +
Treatment_Seed_Source.Treatment_DRY_WET + Treatment_Seed_Source.Treatment_Soil + Treatment_DRY_WET.Treatment_Soil
+ Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
Random model:              Rack + Rack.Treatment_Seed_Source + Rack.Treatment_Seed_Source.Treatment_DRY_WET +
Rack.Treatment_Seed_Source.Treatment_Soil + Rack.Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
Number of units:           118 (2 units excluded due to zero weights or missing values)

Rack.Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil used as residual term

Sparse algorithm with AI optimisation
```

Estimated variance components

```
Random term                                        component            s.e.
Rack                                                 0.00000           bound
Rack.Treatment_Seed_Source
                                                     0.00207         0.00779
Rack.Treatment_Seed_Source.Treatment_DRY_WET
                                                     0.00000           bound
Rack.Treatment_Seed_Source.Treatment_Soil
                                                     0.01223         0.01711
```

Residual variance model

```
Term                                     Model(order)      Parameter             Estimate          s.e.
Rack.Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                         Identity          Sigma2                  0.0930       0.01925
```

Tests for fixed effects

```
Sequentially adding terms to fixed model

Fixed term                                Wald statistic      n.d.f.       F statistic     d.d.f.      F pr
Treatment_Seed_Source                               0.39           2              0.19       12.0     0.826
Treatment_DRY_WET                                   6.39           1              6.39       47.4     0.015
Treatment_Soil                                   1061.66           3            353.89       35.6    <0.001
Treatment_Seed_Source.Treatment_DRY_WET
                                                    0.52           2              0.26       47.5     0.772
Treatment_Seed_Source.Treatment_Soil
                                                    1.43           6              0.24       35.6     0.961
Treatment_DRY_WET.Treatment_Soil
                                                   23.84           3              7.95       47.5    <0.001
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                                    3.25           6              0.54       47.6     0.774
```

```
Dropping individual terms from full fixed model

Fixed term                                      Wald statistic    n.d.f.    F statistic    d.d.f.    F pr
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                                          3.25         6           0.54      47.6   0.774
```

Message: denominator degrees of freedom for approximate F-tests are calculated using algebraic derivatives ignoring fixed/boundary/singular variance parameters.

Table of predicted means for Constant

```
 1.895    Standard error:  0.0337
```

Table of predicted means for Treatment_Seed_Source

```
      Treatment_Seed_Source          1          2          3
                                 1.900      1.896      1.889


Standard errors

      Treatment_Seed_Source          1          2          3
                                 0.058      0.059      0.059


Standard errors

Average:                        0.05834
Maximum:                        0.05858
Minimum:                        0.05787
```

Table of predicted means for Treatment_DRY_WET

```
   Treatment_DRY_WET          D          W
                          1.954      1.835


Standard errors

   Treatment_DRY_WET          D          W
                          0.044      0.043


Standard errors

Average:                        0.04390
Maximum:                        0.04432
Minimum:                        0.04349
```

Table of predicted means for Treatment_Soil

```
     Treatment_Soil          1          2          3          4
                         2.378      2.416      0.112      2.673
```

```
Standard errors

     Treatment_Soil          1          2          3          4
                         0.065      0.064      0.065      0.064
```

```
Standard errors

Average:                        0.06423
Maximum:                        0.06480
Minimum:                        0.06366
```

Table of predicted means for Treatment_Seed_Source.Treatment_DRY_WET

```
        Treatment_DRY_WET          D          W
     Treatment_Seed_Source
                         1     1.933      1.866
                         2     1.967      1.826
                         3     1.963      1.814
```

```
Standard errors

        Treatment_DRY_WET          D          W
     Treatment_Seed_Source
                         1     0.075      0.075
                         2     0.077      0.075
                         3     0.077      0.075
```

```
Standard errors

Average:                        0.07604
Maximum:                        0.07748
Minimum:                        0.07532
```

Table of predicted means for Treatment_Seed_Source.Treatment_Soil

```
           Treatment_Soil          1          2          3          4
     Treatment_Seed_Source
                         1     2.434      2.439      0.082      2.643
                         2     2.328      2.406      0.189      2.663
                         3     2.372      2.404      0.066      2.712
```

```
Standard errors

           Treatment_Soil          1          2          3          4
      Treatment_Seed_Source
                          1      0.110      0.110      0.110      0.110
                          2      0.116      0.110      0.110      0.110
                          3      0.110      0.110      0.116      0.110


Standard errors

Average:                         0.1112
Maximum:                         0.1161
Minimum:                         0.1103
```

Table of predicted means for Treatment_DRY_WET.Treatment_Soil

```
         Treatment_Soil          1          2          3          4
       Treatment_DRY_WET
                       D     2.475      2.315      0.092      2.935
                       W     2.282      2.518      0.132      2.410


Standard errors

         Treatment_Soil          1          2          3          4
       Treatment_DRY_WET
                       D     0.088      0.085      0.088      0.085
                       W     0.085      0.085      0.085      0.085


Standard errors

Average:                       0.08542
Maximum:                       0.08796
Minimum:                       0.08457
```

Table of predicted means for Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil

```
                                     Treatment_Soil          1          2          3          4
      Treatment_Seed_Source       Treatment_DRY_WET
                          1                       D      2.440      2.360      0.091      2.842
                                                  W      2.429      2.518      0.073      2.444
                          2                       D      2.468      2.234      0.216      2.949
                                                  W      2.187      2.578      0.162      2.377
                          3                       D      2.517      2.351     -0.030      3.016
                                                  W      2.228      2.457      0.162      2.409
```

```
Standard errors

                              Treatment_Soil         1          2          3          4
    Treatment_Seed_Source     Treatment_DRY_WET
                        1                     D      0.146      0.146      0.146      0.146
                                              W      0.146      0.146      0.146      0.146
                        2                     D      0.163      0.146      0.146      0.146
                                              W      0.146      0.146      0.146      0.146
                        3                     D      0.146      0.146      0.163      0.146
                                              W      0.146      0.146      0.146      0.146


Standard errors

Average:                      0.1479
Maximum:                      0.1635
Minimum:                      0.1465

  98  vplot
  99  vdisp [pterms=Treatment_Soil;p=w,means;pse=allestimates
```

Tests for fixed effects

```
Sequentially adding terms to fixed model

Fixed term                              Wald statistic     n.d.f.     F statistic     d.d.f.     F pr
Treatment_Seed_Source                             0.39          2            0.19       12.0     0.826
Treatment_DRY_WET                                 6.39          1            6.39       47.4     0.015
Treatment_Soil                                 1061.66          3          353.89       35.6    <0.001
Treatment_Seed_Source.Treatment_DRY_WET
                                                  0.52          2            0.26       47.5     0.772
Treatment_Seed_Source.Treatment_Soil
                                                  1.43          6            0.24       35.6     0.961
Treatment_DRY_WET.Treatment_Soil
                                                 23.84          3            7.95       47.5    <0.001
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                                  3.25          6            0.54       47.6     0.774

Dropping individual terms from full fixed model

Fixed term                              Wald statistic     n.d.f.     F statistic     d.d.f.     F pr
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                                  3.25          6            0.54       47.6     0.774
```

Message: denominator degrees of freedom for approximate F-tests are calculated using algebraic derivatives ignoring fixed/boundary/singular variance parameters.

Table of predicted means for Treatment_Soil

```
    Treatment_Soil          1          2          3          4
                        2.378      2.416      0.112      2.673
```

```
Standard errors

    Treatment_Soil          1           2           3           4
                        0.065       0.064       0.065       0.064


Standard errors

Average:                  0.06423
Maximum:                  0.06480
Minimum:                  0.06366
```

```
 100  vdisp [pterms=Treatment_DRY_WET;p=w,means;pse=allestimates
```

Tests for fixed effects

```
Sequentially adding terms to fixed model

Fixed term                                   Wald statistic     n.d.f.      F statistic     d.d.f.      F pr
Treatment_Seed_Source                                  0.39          2             0.19       12.0     0.826
Treatment_DRY_WET                                      6.39          1             6.39       47.4     0.015
Treatment_Soil                                      1061.66          3           353.89       35.6    <0.001
Treatment_Seed_Source.Treatment_DRY_WET
                                                       0.52          2             0.26       47.5     0.772
Treatment_Seed_Source.Treatment_Soil
                                                       1.43          6             0.24       35.6     0.961
Treatment_DRY_WET.Treatment_Soil
                                                      23.84          3             7.95       47.5    <0.001
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                                       3.25          6             0.54       47.6     0.774

Dropping individual terms from full fixed model

Fixed term                                   Wald statistic     n.d.f.      F statistic     d.d.f.      F pr
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                                       3.25          6             0.54       47.6     0.774
```

Message: denominator degrees of freedom for approximate F-tests are calculated using algebraic derivatives ignoring fixed/boundary/singular variance parameters.

Table of predicted means for Treatment_DRY_WET

```
   Treatment_DRY_WET          D           W
                          1.954       1.835


Standard errors

   Treatment_DRY_WET          D           W
                          0.044       0.043


Standard errors

Average:                  0.04390
Maximum:                  0.04432
```

```
Minimum:                          0.04349
```

```
 101
 102  vdisp [pterms=Treatment_DRY_WET.Treatment_Soil;p=w,means;pse=allestimates
```

Tests for fixed effects

```
Sequentially adding terms to fixed model

Fixed term                                Wald statistic    n.d.f.    F statistic    d.d.f.      F pr
Treatment_Seed_Source                               0.39         2           0.19      12.0     0.826
Treatment_DRY_WET                                   6.39         1           6.39      47.4     0.015
Treatment_Soil                                   1061.66         3         353.89      35.6    <0.001
Treatment_Seed_Source.Treatment_DRY_WET
                                                    0.52         2           0.26      47.5     0.772
Treatment_Seed_Source.Treatment_Soil
                                                    1.43         6           0.24      35.6     0.961
Treatment_DRY_WET.Treatment_Soil
                                                   23.84         3           7.95      47.5    <0.001
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                                    3.25         6           0.54      47.6     0.774

Dropping individual terms from full fixed model

Fixed term                                Wald statistic    n.d.f.    F statistic    d.d.f.      F pr
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                                    3.25         6           0.54      47.6     0.774
```

Message: denominator degrees of freedom for approximate F-tests are calculated using algebraic derivatives ignoring fixed/boundary/singular variance parameters.

Table of predicted means for Treatment_DRY_WET.Treatment_Soil

```
         Treatment_Soil          1          2          3          4
      Treatment_DRY_WET
                      D      2.475      2.315      0.092      2.935
                      W      2.282      2.518      0.132      2.410


Standard errors

         Treatment_Soil          1          2          3          4
      Treatment_DRY_WET
                      D      0.088      0.085      0.088      0.085
                      W      0.085      0.085      0.085      0.085


Standard errors

Average:                          0.08542
Maximum:                          0.08796
Minimum:                          0.08457
```

```
 103
```

21 Appendix G

21.1 Seedling Growth Analyses Results – Total Leaf Area (cm^2)

```
22  reml [p=m,c,w,means;pse=allestimates]lnTotal_Leaf_Area_cm2Trim
```

REML variance components analysis

```
Response variate:          lnTotal_Leaf_Area_cm2Trim
Fixed model:               Constant + Treatment_Seed_Source + Treatment_DRY_WET + Treatment_Soil +
Treatment_Seed_Source.Treatment_DRY_WET + Treatment_Seed_Source.Treatment_Soil + Treatment_DRY_WET.Treatment_Soil
+ Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
Number of units:           85 (2 units excluded due to zero weights or missing values)

Residual term has been added to model

Sparse algorithm with AI optimisation
```

Residual variance model

```
Term                              Model(order)     Parameter            Estimate        s.e.
Residual                          Identity         Sigma2                  0.192      0.0332
```

Tests for fixed effects

```
Sequentially adding terms to fixed model

Fixed term                           Wald statistic     n.d.f.     F statistic     d.d.f.      F pr
Treatment_Seed_Source                          0.09          2            0.04       67.0     0.957
Treatment_DRY_WET                             20.13          1           20.13       67.0    <0.001
Treatment_Soil                                64.50          2           32.25       67.0    <0.001
Treatment_Seed_Source.Treatment_DRY_WET
                                               0.73          2            0.37       67.0     0.694
Treatment_Seed_Source.Treatment_Soil
                                               1.21          4            0.30       67.0     0.875
Treatment_DRY_WET.Treatment_Soil
                                              34.99          2           17.50       67.0    <0.001
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                               4.89          4            1.22       67.0     0.309

Dropping individual terms from full fixed model

Fixed term                           Wald statistic     n.d.f.     F statistic     d.d.f.      F pr
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                               4.89          4            1.22       67.0     0.309
```

Message: denominator degrees of freedom for approximate F-tests are calculated using algebraic derivatives ignoring fixed/boundary/singular variance parameters.

Table of predicted means for Constant

```
 3.323    Standard error:  0.0480
```

Table of predicted means for Treatment_Seed_Source

```
     Treatment_Seed_Source           1          2          3
                                 3.322      3.355      3.293


Standard errors

     Treatment_Seed_Source           1          2          3
                                 0.082      0.087      0.080


Standard errors

Average:                       0.08302
Maximum:                       0.08743
Minimum:                       0.08000
```

Table of predicted means for Treatment_DRY_WET

```
   Treatment_DRY_WET           D          W
                           3.546      3.100


Standard errors

   Treatment_DRY_WET           D          W
                           0.069      0.066


Standard errors

Average:                       0.06782
Maximum:                       0.06942
Minimum:                       0.06622
```

Table of predicted means for Treatment_Soil

```
    Treatment_Soil           1          2          4
                         3.185      2.912      3.873


Standard errors

    Treatment_Soil           1          2          4
                         0.082      0.082      0.086


Standard errors

Average:                       0.08306
Maximum:                       0.08589
Minimum:                       0.08165
```

Table of predicted means for Treatment_Seed_Source.Treatment_DRY_WET

Treatment_DRY_WET	D	W
Treatment_Seed_Source		
1	3.508	3.136
2	3.567	3.142
3	3.562	3.023

Standard errors

Treatment_DRY_WET	D	W
Treatment_Seed_Source		
1	0.113	0.118
2	0.133	0.113
3	0.113	0.113

Standard errors

Average:	0.1173
Maximum:	0.1333
Minimum:	0.1131

Table of predicted means for Treatment_Seed_Source.Treatment_Soil

Treatment_Soil	1	2	4
Treatment_Seed_Source			
1	3.222	2.862	3.882
2	3.150	2.978	3.937
3	3.182	2.896	3.801

Standard errors

Treatment_Soil	1	2	4
Treatment_Seed_Source			
1	0.139	0.139	0.147
2	0.147	0.147	0.160
3	0.139	0.139	0.139

Standard errors

Average:	0.1437
Maximum:	0.1600
Minimum:	0.1386

Table of predicted means for Treatment_DRY_WET.Treatment_Soil

```
      Treatment_Soil           1           2           4
 Treatment_DRY_WET
                   D       3.460       2.757       4.422
                   W       2.910       3.067       3.325
```

```
Standard errors

      Treatment_Soil           1           2           4
 Treatment_DRY_WET
                   D       0.118       0.118       0.125
                   W       0.113       0.113       0.118
```

```
Standard errors

Average:                          0.1174
Maximum:                          0.1251
Minimum:                          0.1131
```

Table of predicted means for Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil

```
                                   Treatment_Soil           1           2           4
      Treatment_Seed_Source     Treatment_DRY_WET
                          1                     D       3.388       2.848       4.290
                                                W       3.057       2.877       3.473
                          2                     D       3.499       2.621       4.582
                                                W       2.800       3.336       3.291
                          3                     D       3.492       2.803       4.393
                                                W       2.872       2.988       3.210
```

```
Standard errors

                                   Treatment_Soil           1           2           4
      Treatment_Seed_Source     Treatment_DRY_WET
                          1                     D       0.196       0.196       0.196
                                                W       0.196       0.196       0.219
                          2                     D       0.219       0.219       0.253
                                                W       0.196       0.196       0.196
                          3                     D       0.196       0.196       0.196
                                                W       0.196       0.196       0.196
```

```
Standard errors

Average:                          0.2030
Maximum:                          0.2530
Minimum:                          0.1960
```

```
  23  vplot
  24  vdisp [pterms=Treatment_Soil;p=w,means;pse=allestimates
```

Tests for fixed effects

Sequentially adding terms to fixed model

```
Fixed term                                    Wald statistic    n.d.f.    F statistic    d.d.f.     F pr
Treatment_Seed_Source                                   0.09         2           0.04      67.0    0.957
Treatment_DRY_WET                                      20.13         1          20.13      67.0   <0.001
Treatment_Soil                                         64.50         2          32.25      67.0   <0.001
Treatment_Seed_Source.Treatment_DRY_WET
                                                        0.73         2           0.37      67.0    0.694
Treatment_Seed_Source.Treatment_Soil
                                                        1.21         4           0.30      67.0    0.875
Treatment_DRY_WET.Treatment_Soil
                                                       34.99         2          17.50      67.0   <0.001
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                                        4.89         4           1.22      67.0    0.309
```

Dropping individual terms from full fixed model

```
Fixed term                                    Wald statistic    n.d.f.    F statistic    d.d.f.     F pr
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                                        4.89         4           1.22      67.0    0.309
```

Message: denominator degrees of freedom for approximate F-tests are calculated using algebraic derivatives ignoring fixed/boundary/singular variance parameters.

Table of predicted means for Treatment_Soil

```
     Treatment_Soil          1          2          4
                         3.185      2.912      3.873
```

Standard errors

```
     Treatment_Soil          1          2          4
                         0.082      0.082      0.086
```

Standard errors

```
Average:                  0.08306
Maximum:                  0.08589
Minimum:                  0.08165
```

```
  25  vdisp [pterms=Treatment_DRY_WET;p=w,means;pse=allestimates
```

Tests for fixed effects

Sequentially adding terms to fixed model

```
Fixed term                                    Wald statistic    n.d.f.    F statistic    d.d.f.     F pr
Treatment_Seed_Source                                   0.09         2           0.04      67.0    0.957
Treatment_DRY_WET                                      20.13         1          20.13      67.0   <0.001
Treatment_Soil                                         64.50         2          32.25      67.0   <0.001
Treatment_Seed_Source.Treatment_DRY_WET
                                                        0.73         2           0.37      67.0    0.694
```

```
Treatment_Seed_Source.Treatment_Soil
                                              1.21         4           0.30       67.0       0.875
Treatment_DRY_WET.Treatment_Soil
                                             34.99         2          17.50       67.0      <0.001
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                              4.89         4           1.22       67.0       0.309

Dropping individual terms from full fixed model

Fixed term                          Wald statistic     n.d.f.    F statistic      d.d.f.       F pr
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                              4.89         4           1.22       67.0       0.309
```

Message: denominator degrees of freedom for approximate F-tests are calculated using algebraic derivatives ignoring fixed/boundary/singular variance parameters.

Table of predicted means for Treatment_DRY_WET

```
   Treatment_DRY_WET          D          W
                          3.546      3.100


Standard errors

   Treatment_DRY_WET          D          W
                          0.069      0.066


Standard errors

Average:                      0.06782
Maximum:                      0.06942
Minimum:                      0.06622
```

```
 26
 27  vdisp [pterms=Treatment_DRY_WET.Treatment_Soil;p=w,means;pse=allestimates
```

Tests for fixed effects

```
Sequentially adding terms to fixed model

Fixed term                          Wald statistic     n.d.f.    F statistic      d.d.f.       F pr
Treatment_Seed_Source                         0.09         2           0.04       67.0       0.957
Treatment_DRY_WET                            20.13         1          20.13       67.0      <0.001
Treatment_Soil                               64.50         2          32.25       67.0      <0.001
Treatment_Seed_Source.Treatment_DRY_WET
                                              0.73         2           0.37       67.0       0.694
Treatment_Seed_Source.Treatment_Soil
                                              1.21         4           0.30       67.0       0.875
Treatment_DRY_WET.Treatment_Soil
                                             34.99         2          17.50       67.0      <0.001
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                              4.89         4           1.22       67.0       0.309
```

```
Dropping individual terms from full fixed model

Fixed term                                      Wald statistic    n.d.f.    F statistic    d.d.f.    F pr
Treatment_Seed_Source.Treatment_DRY_WET.Treatment_Soil
                                                          4.89         4           1.22      67.0   0.309
```

Message: denominator degrees of freedom for approximate F-tests are calculated using algebraic derivatives ignoring fixed/boundary/singular variance parameters.

Table of predicted means for Treatment_DRY_WET.Treatment_Soil

```
     Treatment_Soil          1          2          4
   Treatment_DRY_WET
                   D     3.460      2.757      4.422
                   W     2.910      3.067      3.325


Standard errors

     Treatment_Soil          1          2          4
   Treatment_DRY_WET
                   D     0.118      0.118      0.125
                   W     0.113      0.113      0.118


Standard errors

Average:                        0.1174
Maximum:                        0.1251
Minimum:                        0.1131

 28
 29
```

22 Appendix H

22.1 Soil Analyses Results – Andrewilla Waterhole pH, EC & Bulk Density Values 10 x 10cm (depth) samples per quadrat

Loccation	Quadrat	Sample	EC (µS/cm)	pH	wet (g)	dry (g)	H2O loss (g)	BD (g/cc)
Cowarie Xing	1 (Channel Bank)	1	66.7	6.8	728.7	716.8	11.9	1.29
Cowarie Xing	1	2	99.6	6.3	595.8	583.0	12.74	1.05
Cowarie Xing	1	3	64.4	6.4	655.9	644.1	11.8	1.16
Cowarie Xing	1	4	42.3	6.5	781.0	775.9	5.1	1.39
Cowarie Xing	1	5	60.5	6.1	741.6	733.6	8	1.32
Cowarie Xing	1	6	80.2	6.0	523.5	505.7	17.82	0.91
Cowarie Xing	1	7	118.5	5.9	446.5	430.7	15.76	0.77
Cowarie Xing	1	8	63.6	6.1	744.2	734.0	10.2	1.32
Cowarie Xing	1	9	46.9	6.0	738.2	730.5	7.7	1.31
Cowarie Xing	1	10	64.5	5.9	655.2	642.6	12.6	1.15
Cowarie Xing	2 (Floodout flat)	1	144.9	6.1	835.0	820.4	14.6	1.47
Cowarie Xing	2	2	71.5	6.2	806.7	794.9	11.8	1.43
Cowarie Xing	2	3	119.1	6.2	828.7	813.2	15.5	1.46
Cowarie Xing	2	4	80.3	6.3	790.6	781.2	9.4	1.40
Cowarie Xing	2	5	42.8	6.3	793.0	785.9	7.1	1.41
Cowarie Xing	2	6	69.7	6.3	777.1	772.1	5	1.39
Cowarie Xing	2	7	0.501 (mS/cm)	6.1	833.2	821.8	11.4	1.47
Cowarie Xing	2	8	91.6	6.2	806.0	790.3	15.7	1.42
Cowarie Xing	2	9	68	6.3	743.7	726.6	17.1	1.30
Cowarie Xing	2	10	75.9	6.2	724.9	704.2	20.7	1.26
Andrewilla WH	1 (Channel Bank)	1	135.5	7.8	706.8	692.4	14.4	1.24
Andrewilla WH	1	2	96.5	7.1	666.3	652.5	13.8	1.17
Andrewilla WH	1	3	280.7	7.4	700.8	681.8	19	1.22
Andrewilla WH	1	4	148.7	7.0	671.3	654.6	16.7	1.17
Andrewilla WH	1	5	129.8	7.0	688.8	674.7	14.1	1.21
Andrewilla WH	1	6	110.2	7.3	784.0	772.6	11.4	1.39
Andrewilla WH	1	7	0.609 (mS/cm)	7.0	581.8	566.2	15.61	1.02
Andrewilla WH	1	8	230	7.0	564.6	539.6	24.98	0.97
Andrewilla WH	1	9	166.8	6.7	636.9	614.3	22.6	1.10
Andrewilla WH	1	10	148	6.6	580.9	558.8	22.08	1.00
Andrewilla WH	2 (Floodout flat)	1	236.4	6.9	708.1	695.7	12.4	1.25
Andrewilla WH	2	2	101.8	7.3	747.8	732.4	15.4	1.31

Loccation	**Quadrat**	**Sample**	**EC (µS/cm)**	**pH**	**wet (g)**	**dry (g)**	**H2O loss (g)**	**BD (g/cc)**
Andrewilla WH	2	3	118.2	7.6	713.3	697.8	15.5	1.25
Andrewilla WH	2	4	159.7	7.5	724.0	709.8	14.2	1.27
Andrewilla WH	2	5	87.3	7.5	724.8	708.1	16.7	1.27
Andrewilla WH	2	6	75.7	7.5	714.1	698.0	16.1	1.25
Andrewilla WH	2	7	116.1	7.5	700.7	684.4	16.3	1.23
Andrewilla WH	2	8	93.7	7.6	759.4	741.7	17.7	1.33
Andrewilla WH	2	9	216.8	7.8	697.3	683.8	13.5	1.23
Andrewilla WH	2	10	128.1	7.9	689.4	671.8	17.6	1.21

23 Appendix I

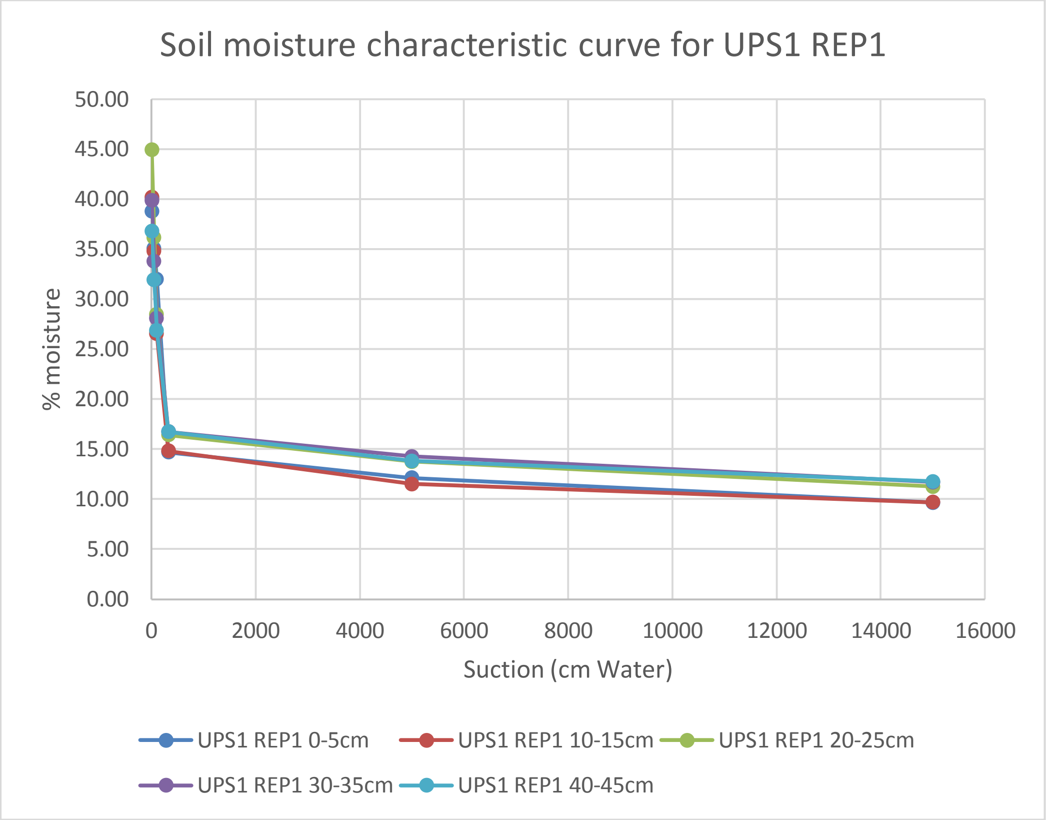
23.1 Soil Analyses Results – Andrewilla Waterhole, Soil Profile- pH & EC, 1 x 50 cm profile per quadrat, 5 x 10cm increments down each profile

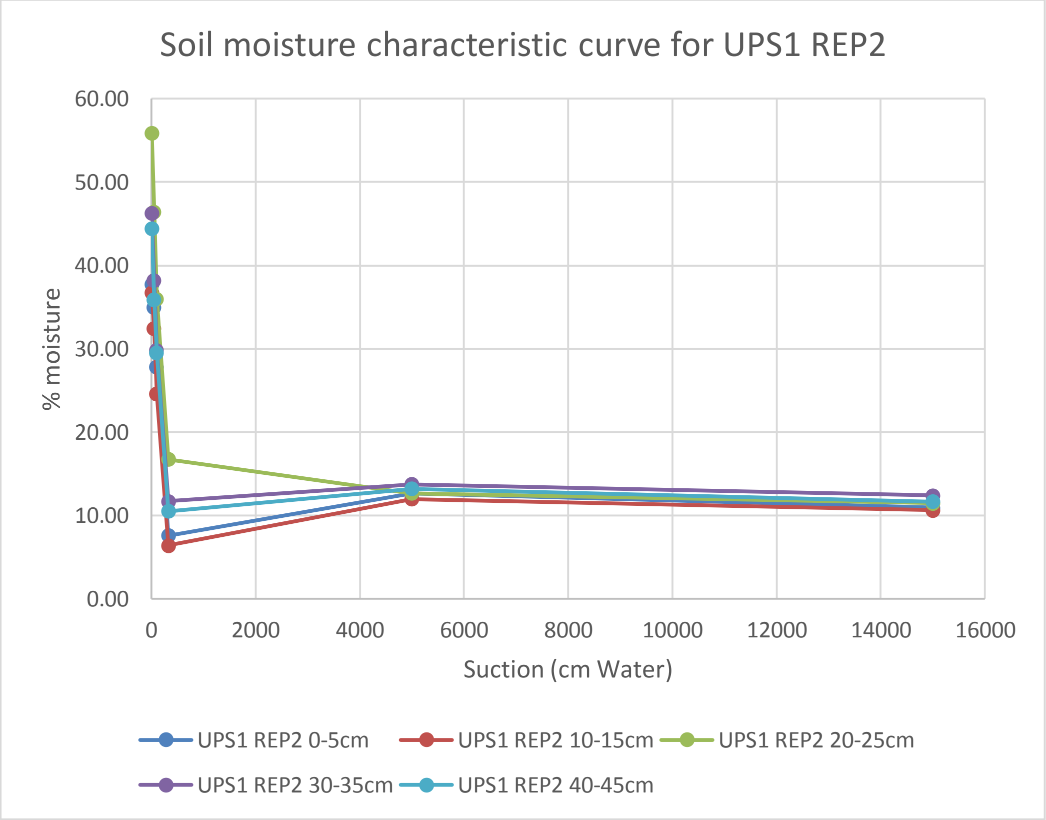
Location	Quadrat	Depth (cm)	EC (µs/cm)	pH
Cowarie Xing	1	0-10	74.9	6.57
Cowarie Xing	1	10-20	51.7	6.39
Cowarie Xing	1	20-30	58.3	6.48
Cowarie Xing	1	30-40	51.2	6.34
Cowarie Xing	1	40-50	53.4	6.72
Cowarie Xing	2	0-10	43.5	6.86
Cowarie Xing	2	10-20	42.2	6.72
Cowarie Xing	2	20-30	44.9	6.67
Cowarie Xing	2	30-40	55	6.69
Cowarie Xing	2	40-50	48.3	6.79
Andrewilla WH	1	0-10	76.4	6.87
Andrewilla WH	1	10-20	71.7	7.19
Andrewilla WH	1	20-30	121.1	7.61
Andrewilla WH	1	30-40	150	7.83
Andrewilla WH	1	40-50	197	8.18
Andrewilla WH	2	0-10	118.8	7.06
Andrewilla WH	2	10-20	129	6.95
Andrewilla WH	2	20-30	129.3	7.07
Andrewilla WH	2	30-40	152	7.13
Andrewilla WH	2	40-50	180.9	7.2

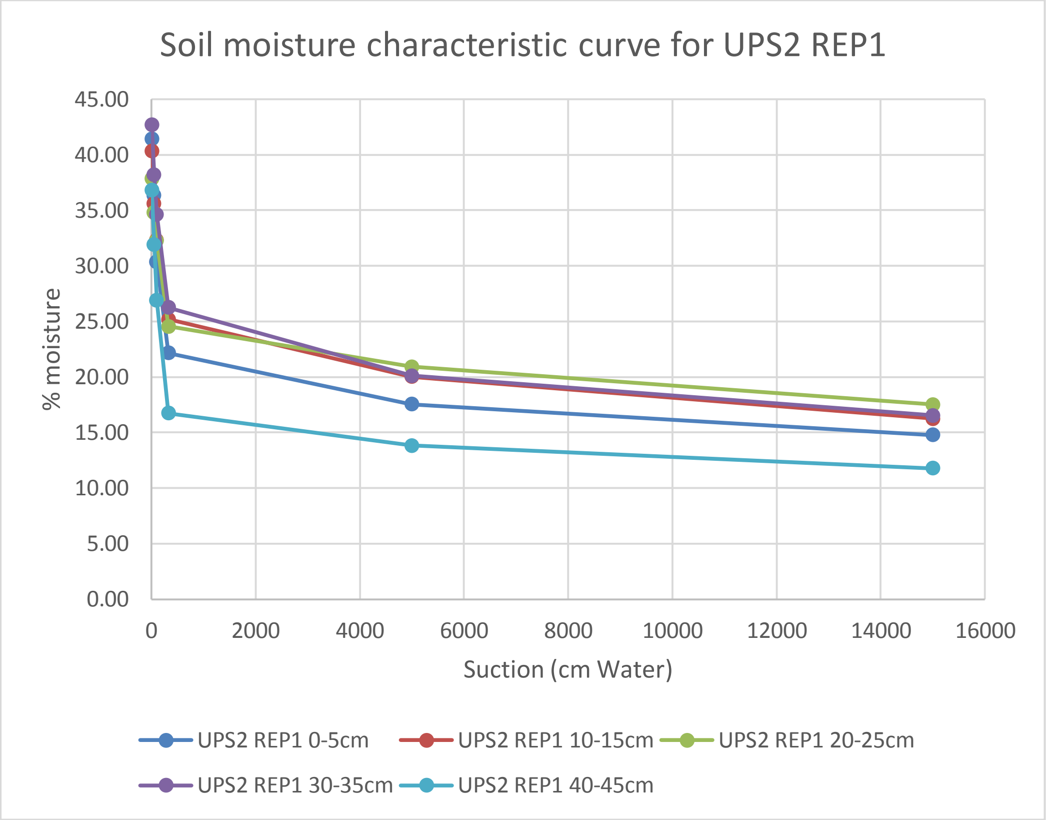
24 Appendix J

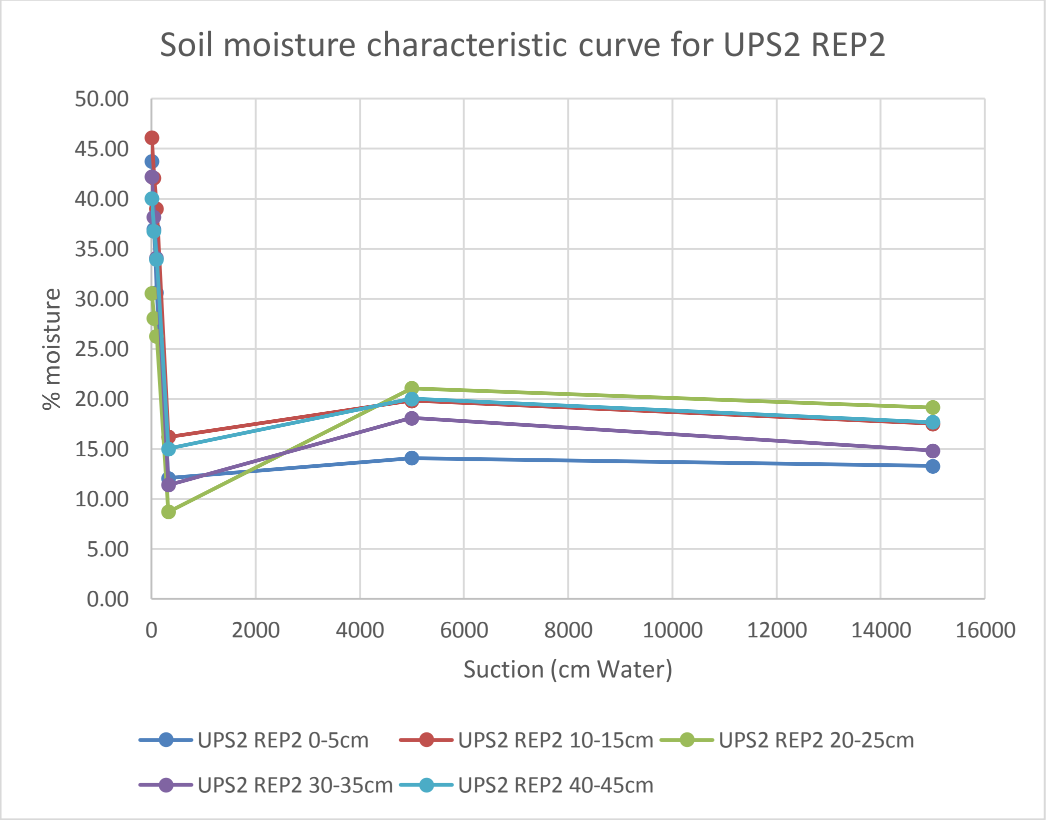
24.1 Soil Analyses Results – Andrewilla Waterhole- Bulk density & Soil Moisture curves

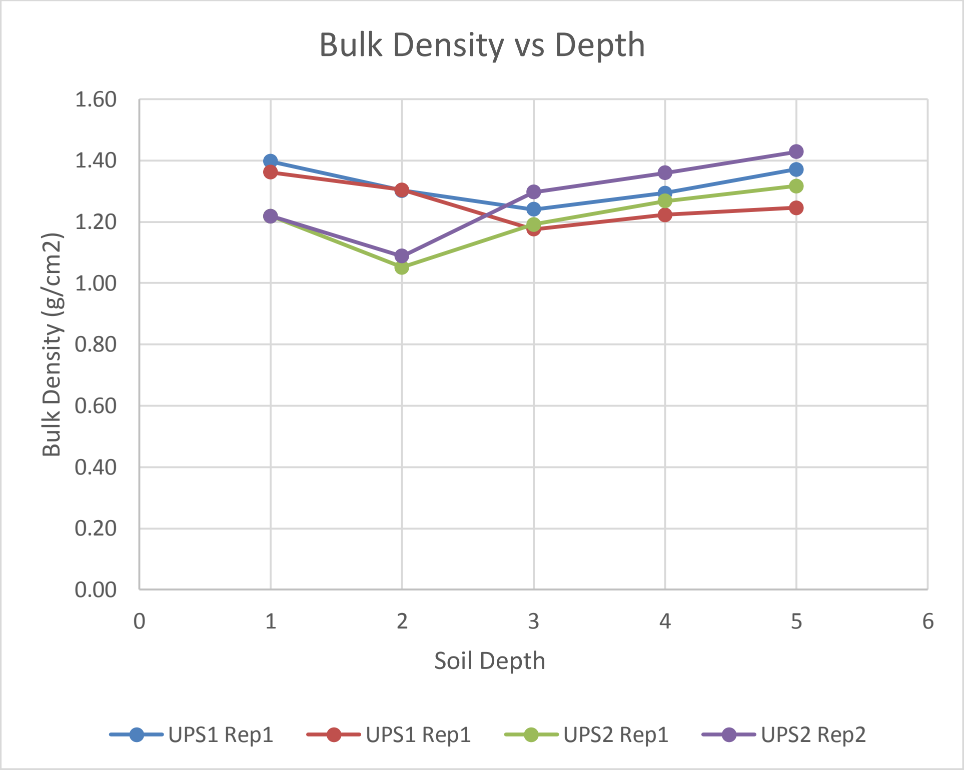
Site	Rep	Depth (cm)	Core No.	Jakes Soil Description	Location	Bulk Density (g/cm2)	10cm suction moisture %	50cm suction moisture %	100 cm suction moisture %	330cm suction moisture %	5 bar moisture %	15 bar moisture %
UPS1	1	0-5	11	SandyLoam	Channel Bank	1.40	38.76	35.06	32.01	14.70	12.12	9.66
UPS1	1	10-15	12	SandyLoam	Channel Bank	1.30	40.21	34.82	26.54	14.80	11.51	9.68
UPS1	1	20-25	13	SandyLoam	Channel Bank	1.24	44.91	36.16	28.49	16.42	13.74	11.24
UPS1	1	30-35	14	SandyLoam	Channel Bank	1.29	39.90	33.79	28.08	16.73	14.27	11.71
UPS1	1	40-45	15	SandyLoam	Channel Bank	1.37	36.82	31.93	26.89	16.74	13.83	11.78
UPS1	2	0-5	16	SandyLoam	Channel Bank	1.36	37.73	35.01	27.79	7.59	12.64	10.92
UPS1	2	10-15	17	SandyLoam	Channel Bank	1.30	36.72	32.44	24.58	6.41	11.96	10.64
UPS1	2	20-25	18	SandyLoam	Channel Bank	1.18	55.90	46.39	36.00	16.73	12.65	11.46
UPS1	2	30-35	19	SandyLoam	Channel Bank	1.22	46.25	38.18	29.86	11.72	13.74	12.38
UPS1	2	40-45	20	SandyLoam	Channel Bank	1.25	44.39	35.87	29.53	10.50	13.21	11.66
UPS2	1	0-5	1	Heavy Clay	Floodplain	1.22	41.41	36.37	30.36	22.15	17.53	14.77
UPS2	1	10-15	2	Heavy Clay	Floodplain	1.05	40.32	35.61	32.33	25.17	20.01	16.24
UPS2	1	20-25	24	Heavy Clay	Floodplain	1.19	37.87	34.76	32.23	24.55	20.91	17.52
UPS2	1	30-35	4	Heavy Clay	Floodplain	1.27	42.68	38.19	34.64	26.24	20.10	16.54
UPS2	1	40-45	5	Heavy Clay	Floodplain	1.32	44.45	41.20	37.11	28.18	20.56	17.23
UPS2	2	0-5	6	Heavy Clay	Floodplain	1.22	43.73	36.96	30.63	12.07	14.08	13.28
UPS2	2	10-15	7	Heavy Clay	Floodplain	1.09	46.09	42.08	38.99	16.20	19.81	17.50
UPS2	2	20-25	8	Heavy Clay	Floodplain	1.30	30.58	28.08	26.24	8.70	21.05	19.14
UPS2	2	30-35	9	Heavy Clay	Floodplain	1.36	42.19	38.18	34.05	11.37	18.09	14.82
UPS2	2	40-45	10	Heavy Clay	Floodplain	1.43	40.05	36.76	33.95	15.01	19.99	17.66
							Uncertain data,possibly faulty suction plate for 330cm.					


Soil moisture characteristic curve for UPS1 REP1
% moisture
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
2000
4000
6000
8000
10000
12000
14000
16000
Suction (cm Water)
UPS1 REP1 0-5cm
UPS1 REP1 10-15cm
UPS1 REP1 20-25cm
UPS1 REP1 30-35cm
UPS1 REP1 40-45cm


Soil moisture characteristic curve for UPS1 REP2
% moisture
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
2000
4000
6000
8000
10000
12000
14000
16000
Suction (cm Water)
UPS1 REP2 0-5cm
UPS1 REP2 10-15cm
UPS1 REP2 20-25cm
UPS1 REP2 30-35cm
UPS1 REP2 40-45cm


Soil moisture characteristic curve for UPS2 REP1
% moisture
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
2000
4000
6000
8000
10000
12000
14000
16000
Suction (cm Water)
UPS2 REP1 0-5cm
UPS2 REP1 10-15cm
UPS2 REP1 20-25cm
UPS2 REP1 30-35cm
UPS2 REP1 40-45cm


Soil moisture characteristic curve for UPS2 REP2
% moisture
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
2000
4000
6000
8000
10000
12000
14000
16000
Suction (cm Water)
UPS2 REP2 0-5cm
UPS2 REP2 10-15cm
UPS2 REP2 20-25cm
UPS2 REP2 30-35cm
UPS2 REP2 40-45cm


Bulk Density vs Depth
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Bulk Density (g/cm2)
0
1
2
3
4
5
6
Soil Depth
UPS1 Rep1
UPS1 Rep1
UPS2 Rep1
UPS2 Rep2