CLIMATE – READY REVEGETATION IN THE UPPER SHOALHAVEN LANDCARE DISTRICT

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Report for Upper Shoalhaven Landcare

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1. INTRODUCTION AND RATIONALE FOR THE PROJECT

This study commences research into climate-ready revegetation for the Upper Shoalhaven Landcare District (USLD), drawing on work done by the Yass Area Landcare Network (YAN), Adapt NSW, and Macquarie University's work on building resilience in species and ecosystems in response to a rapidly shifting climate. Bushfires that ravaged the district in 2019-2020 provided impetus for revegetation and species recovery projects across USLD. Selection of species resilient to modelled future climate scenarios is crucial to the long-term survival of revegetation projects. The aim of this initial research into climate-ready revegetation is to understand how well indigenous plants of the Braidwood region are projected to survive under changing climatic conditions, to shortlist resilient species for propagation in local nurseries, and recommend a strategy to bolster genetic diversity of species (especially those with a restricted local population and corresponding limited gene pool) to increase species' resilience to climate change.

1.1 Background

"*Human induced climate change, including more frequent and intense events, has caused widespread impacts and related losses and damages to nature and people beyond natural climate variability…this includes increased drought-related tree mortality."* (Intergovernmental Panel on Climate Change (IPCC) 2022, p.11).

In the Action Summary in the same IPCC report, the importance of ecosystem restoration to mitigate climate change impacts is highlighted:

"Conservation, protection and restoration of ecosystems…reduce the vulnerability of biodiversity to climate change. The resilience of species, biological communities and ecosystem processes increases with the size of natural areas, by restoring degraded areas and by reducing non-climatic stressors. To be effective, conservation and restoration actions will increasingly need to be responsive to ongoing changes at various scales and plan for future changes in ecosystem structure, community composition and species distribution, especially as 1.5^{0}C warming is approached and even more so if exceeded." (IPCC 2022, p. 26).

This study addresses concerns about current and future tree mortality as a result of climate change, suggests species most likely to be resilient to projected climate change projections (and conversely, species currently in the district unlikely to survive in the mid - long term), and outlines a potential species selection strategy to support restoration actions.

In response to successive IPCC reports, Adapt NSW was established by the New South Wales Government to help its citizens take action on, and adapt to climate change, and to build a more resilient, low emissions future for this and future generations. Part of its remit includes:

- Providing practical actions to help individuals and different sectors of society adapt to the impacts of climate change: and
- Giving the people of NSW the tools to access localised climate change and hazard information (https://www.climatechange.environment.nsw.gov.au/about-adaptnsw; accessed 26.04.2022).

The Research Hub of AdaptNSW, led by Macquarie University and the Department of Planning and Environment, provides the community with the research tools and expertise to access and interpret local climate change modelling, and use this to inform revegetation and other adaptation and mitigation projects. The methodology used in this study is drawn from one of the Research Hub's publications, the *Climate-ready Revegetation Guide* ("the Guide"; Hancock *et al.,* 2018). The Guide provides online tools to assist the nursery industry, Landcarers and other natural resource managers to adapt to the changes and uncertainties inherent in global warming when planning revegetation activities. The authors' rationale is as follows:

> "…*the Guide is based on the premise that survival and resilience will be enhanced for species and local populations with large, genetically diverse populations. Species differ in their vulnerability to climate change. Species that cannot evolve and adapt to new environmental conditions in-situ as fast as the climate changes, or disperse to more suitable climes, will be more vulnerable than those with the evolutionary potential and/or the capacity to disperse. In theory, plants with wide distributions are more likely to cope with climate change than those with narrow distributions. However, even if a species' distribution indicates that it is able to tolerate a broad range of climate conditions, survival of local populations is not guaranteed."*

In a departure from previous received wisdom (e.g. Ralph 2003) about restricting revegetation to local provenances, the authors note that small populations with a limited gene pool may require incorporation of non-local genetic material to increase their capacity to adapt to a rapidly changing environment (Prober et al., 2015; Hancock *et al.,* 2018). While the emphasis in this study is on local species' ability to adapt to overriding changing climatic factors (temperature and rainfall, and potential changes in rainfall distribution), there are many other factors which influence a species' ability to survive and thrive, such as landscape position, soil factors, community structure and ecological interactions.

This project relied on both the Guide and a subsequent landmark study by the Yass Area Network of Landcare associations (YAN) utilising methodology in the Guide to inform species and provenance selection for community nurseries across the network. YAN members generously shared detailed methodology and insights which informed our efforts.

1.2 Aims

The aims of the study are to:

- provide detailed information on likely climate scenarios for the district around Braidwood
- assess local species likely to survive into the future, through analysing climate scenarios and plant species information as detailed in NSW Nichefinder and the Atlas of Living Australia
- produce a short list of climate-ready native plant species for future propagation in community nursery/ies
- provide recommendations for potential climate ready strategies to inform nursery production and revegetation in the USLD, and
- determine suitable provenances to incorporate into nursery production and local plantings to increase the genetic diversity and resilience of future plantings across the district.

1.3 Selection of species for consideration

Plants for consideration in this study comprise major overstorey trees in the district, dominant shrub species, and species used widely for Landcare and other revegetation plantings in the district (Lyn Ellis, pers. comm.). Species in the USLD listed under the *Final National Prioritisation of Australian Plants Affected by the 2019-2020 Bushfire Season* (Gallagher 2020) were also included in the study, as they were severely impacted by the 2019-20 fires, and are a focus for recovery actions. Several of these species are endemic to the USLD, so a local focus on propagation and revegetation will be crucial to restoring viable populations of these threatened species. Two non-indigenous native species which are well-established in local plantings but not invasive were also included. Groundcover species, species occurring predominantly in National Parks and Wildlife Estate, and species with recovery projects under the *Saving our Species* program were excluded as being too specialised for consideration for an establishing community nursery. A total of 76 species were selected. A list of the species analysed for likely resilience to projected long- to medium term climate scenarios is provided in Appendix 1. These include major overstorey and mid-storey species in each of the four sub-regions identified below.

1.4 Upper Shoalhaven Landcare District & its subregions

The Upper Shoalhaven Landcare District (Figure 1) is bounded by the ACT border to the west and Budawang and Morton National Parks on the east. The northern boundary includes Lake George, Currawang, Mount Fairy and Nerriga. The southern boundary extends as far as Snowball.

Major geographical features within the USLD include the Great Dividing Range, which bisects the region on a north-south axis, and the coastal escarpment. Each of these features affects climatic patterns in the USLD.

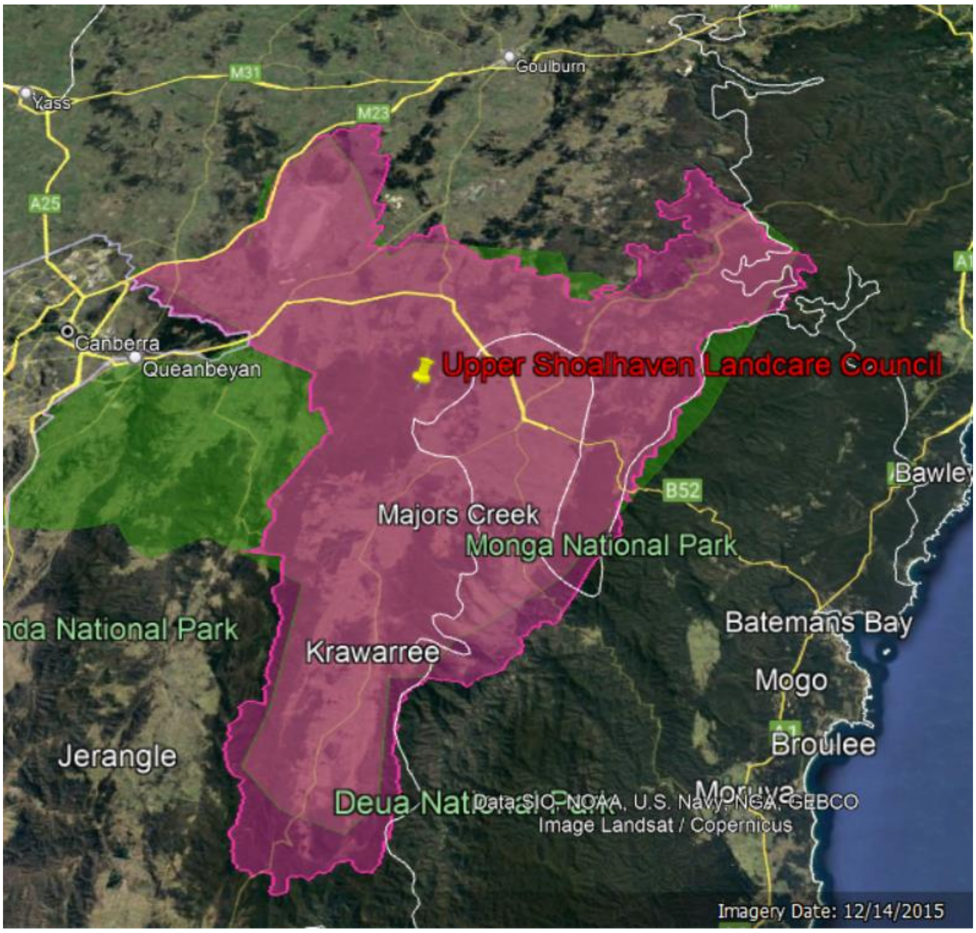

Figure 1. Map of Upper Shoalhaven Landcare District (Google Maps)

Distinct differences in vegetation aligned to geographical features, climate and geology/ soils are found in the region, which has informed nursery production and species composition in revegetation plantings (Lyn Ellis, pers. comm.). For this reason, the USLD was subdivided into four different sub-regions: Braidwood, West of Divide, Coastal Scarp and the Araluen Valley. This is partially explicable in terms of the *Interim Biogeographic Regionalisation for Australia (IBRA),* which classifies Australia's landscapes into geographically distinct bioregions based on common climate, geology, landform, native vegetation and species information (Thackway & Cresswell, 1995). The Araluen Valley is part of the South-East Corner (SEC) Bioregion; the Coastal Scarp forms part of the Sydney Basin (SYD) Bioregion within the USLD, while the rest of the USLD is part of the South-eastern Highlands (SEH) Bioregion.

Within the USLD, west of the Divide, the median of average precipitation is more than 50mm lower than that of the Braidwood district. Largely due to higher elevation on the Divide and a low, frost-prone plain in the Bungendore/ Lake George area, minimum and maximum temperatures for this subregion are one to two degrees Celsius below temperatures experienced further east in the Braidwood district. This is reflected in differing vegetation communities and/ or species composition within common Plant Community Types (PCTs). For this reason, areas west and east of the Great Divide within the SEH bioregion were regarded as distinctly different. Each of the four subregions (Figure 2) and distinctive vegetation communities within each are described briefly below.

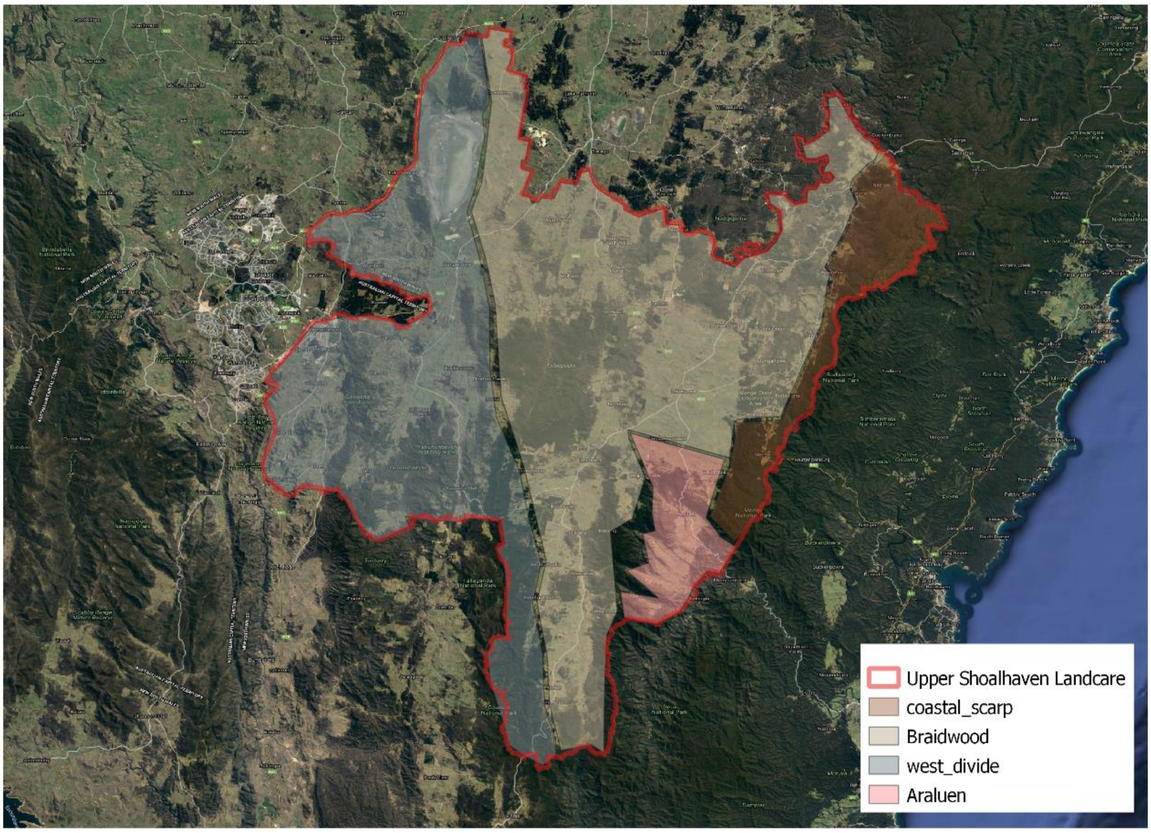

Figure 2. The Upper Shoalhaven boundary, marked in red, and the four subregions developed for the purpose of analysis: Coastal Scarp, Braidwood, Araluen, West of divide (Map made using QGIS)

1.4.1 Araluen

The Araluen Valley is known to be milder than much of the Upper Shoalhaven Region, and its vegetation communities are quite distinct. Several are also listed as endangered ecological communities (EECs) under the BC Act. These include *Eucalyptus tereticornis – Angophora floribunda – E. globoidea* grassy woodland (Araluen Scarp Endangered Ecological Community, NSW *Biodiversity Conservation Act 2016* (BC Act)); *Eucalyptus maidenii – E. melliodora – E. tereticornis* Grassy open forest (Lowland Grassy Woodland Endangered Ecological Community, BC Act); River Oak open forest of major streams, and River Peppermint - Rough-barked Apple - River Oak herb/grass riparian forest of coastal lowlands, southern Sydney Basin Bioregion and South East Corner Bioregion (River Flat Eucalypt Forest on Coastal Floodplains EEC); and small remnants of *Ficus rubiginosa - Pittosporum undulatum* dry rainforest (Dry Rainforest of the South East Forests in the South East Corner Bioregion EEC; (Umwelt, 2015)).

1.4.2 Braidwood

The Braidwood subregion includes Braidwood and the area between the eastern fall of the Great Dividing Range and the Coastal Scarp. Vegetation communities include Broad-leaved Peppermint-Brittle Gum shrubby open forest on the eastern tablelands, South Eastern Highlands Bioregion; Ribbon Gum – Snow Gum grassy open forest; Snow Gum – Candlebark woodland (Monaro or Werriwa Tableland Cool Temperate Grassy Woodland Critically Endangered Ecological Community (CEEC) BC Act); Silvertop Ash- Narrow-leaved Peppermint on ridges of the eastern tableland; and a local variant of the White Box – Yellow Box – Blakely's Red Gum CEEC (BC and EPBC Acts).

1.4.3 Coastal Scarp

This subregion includes Budawang, Morton and Monga National Parks, and contains a complex mix of vegetation communities, ranging from heathland to warm, cool and dry rainforest types. Mallee vegetation is found on plateau, with species including *Eucalyptus stricta, E. moorei, E. sclerophylla* and *Banksia ericifolia.* At lower altitudes, vegetation consists of eucalypt forests and woodlands. Wet sclerophyll associations include *Eucalyptus fastigata, E. fraxinoides, E. viminalis, Corymbia maculata* and *E. tereticornis*. Open forest areas are dominated by *Corymbia gummifera, E. sieberi, E. agglomerata, E. globoidea and E. consideniana.* Other significant vegetation types include *Eucalyptus saligna/ E. botryoides/ Syncarpia glomulifera* forest with rainforest understorey; *Eucryphia moorei/ Dicksonia antarctica* cool rainforest, and River Oak Coastal Forest dominated by *Casuarina cunninghamiana, Tristaniopsis laurina* and *Eucalyptus elata* (NPWS 2001). A large proportion of this subregion occurs within National Parks estate.

1.4.4 West of Divide

This subdivision covers areas on the western fall of the Great Dividing Range, including Bungendore, Queanbeyan and Captains Flat. Major vegetation communities include Red Stringybark – Brittle Gum – Inland Scribbly Gum dry open forest, Yellow Box – Blakely's Red Gum grassy woodland CEEC (BC and EPBC Acts), Brown Barrel – Narrow-leaved Peppermint moist tall open forest, Monaro and Werriwa Cool Temperate Grassy Woodland CEEC (BC Act) and Natural Temperate Grassland of the South East Highlands Bioregion CEEC (BC and EPBC Acts).

1.5 South East Climate Snapshot

Climate forecasts for NSW have been published in a series of regional documents (AdaptNSW, 2014), providing succinct 'snapshots' of expected climate scenarios across regional NSW. While detailed climate modelling is described and used to analyse species' responses to climate change (see Methods), a 'snapshot' of the trends for the far future (2070 – the most realistic timeframe in terms of tree longevity) is useful background to the analysis.

Annual average temperature in the south east and tablelands region is predicted to increase by around 2°C by 2070. The greatest increases are expected over spring (+2.15 °C) and summer (+2.28°C). The current number of hot days above 35°C is currently around 10 per year. This is expected to increase annually by 8.2 days on average. Predictions for the southern tablelands are expected to increase to 30 days per year over 35°C. While rainfall is expected to increase by 1.4% over this time period, the seasonal distribution of rainfall is expected to change markedly, with large increases over autumn (+11% of present precipitation) and summer (+8.8%), and deficits in spring (-11.2%) and winter (-4.1%), with the probability of extreme events (flood, drought) increasing. The number of cold nights (<2 °C) is expected to decrease by 35 nights per year on average, with the most marked decline in winter (-16.9 nights).

1.6 Potential strategies for selecting provenances likely to survive projected climate change

Provenance is considered the geographic/ genotypic origin of the seed material. Different provenances are assumed to be genetically different. An increase in genetic diversity within a population by incorporating different provenances potentially gives the population greater ability to adapt to change, and directly introduces genetic traits more likely to cope with hotter, dryer or wetter conditions.

Incorporating propagation material from areas where the existing climate is similar to the projected local climate scenario reduces the risk of future failure of revegetation plantings based solely on germplasm collected locally. The Guide (Hancock et al, 2018) identifies five provenance selection strategies: climate-adjusted, local provenance, composite, admixture and predicted.

Climate-adjusted includes non-local and local provenances to increase genetic diversity and thus adaptive potential. Non-local provenances are sourced from areas currently experiencing climatic conditions similar to the projected local climate. This is incorporated with local provenance adapted to local soils and biota to maximise adaptability within the area of interest.

Local provenance is restricted to germplasm collected in the local area, which is adapted to local soils, biotic factors and past, relatively stable climate. This has been the standard approach for revegetation plantings over many years. Especially in over-cleared areas and fragmented landscapes, there is a risk that this approach may not have sufficient genetic diversity to adapt to rapidly changing climatic factors.

A *Composite* approach mixes small proportions of genotypes from high quality and genetically diverse populations with local germplasm to restore a more diverse and adaptable gene pool and reduce inbreeding depression.

An *Admixture* approach is useful where there is a high degree of uncertainty about the scale and rate of climate change. This strategy incorporates germplasm from a wide range of provenances with the aim of maximising the genetic diversity of propagation material and building evolutionary resilience. It differs from the composite approach in not specifically favouring local germplasm.

A *Predictive* strategy sources germplasm from a source population that is the best match for the projected climate in the revegetation site, excluding local provenances deemed to be less climatically suitable. This strategy is appropriate where there is reasonable certainty about future climatic trends.

Strategies are illustrated schematically in Figure 3.

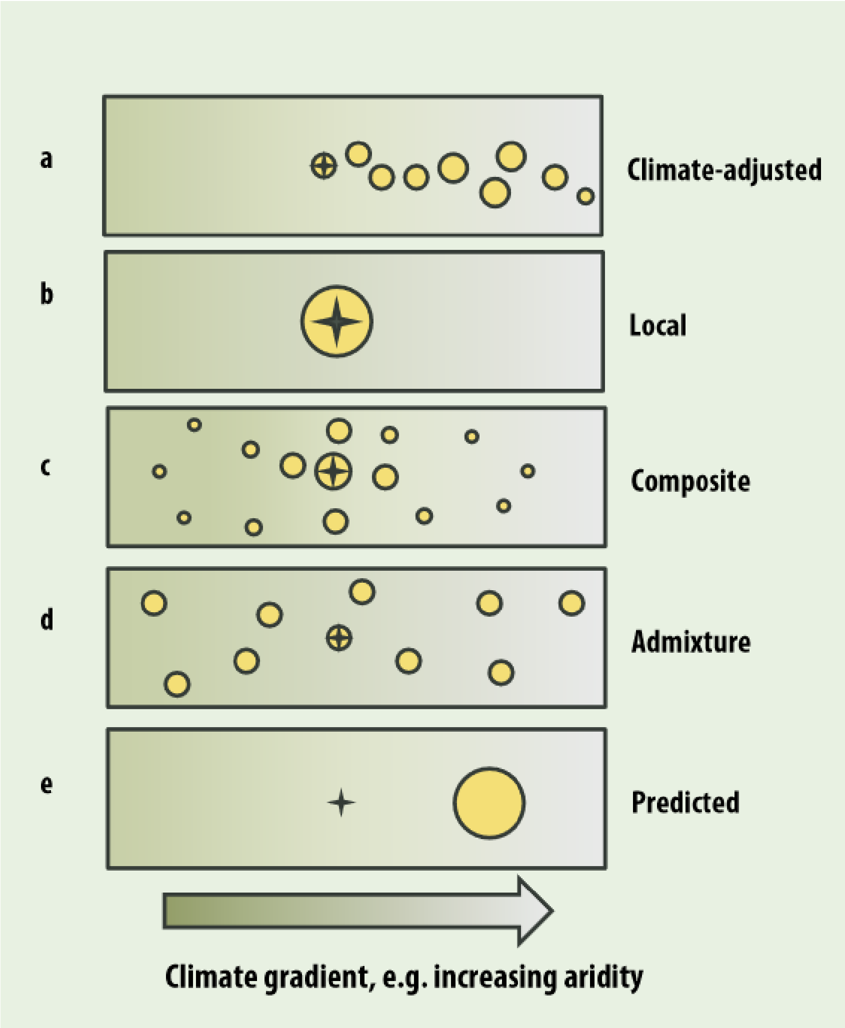

Figure 3. Provenance strategies for revegetation. The star indicates the proposed revegetation site, and the yellow circles represent populations of the species. The size of the circles indicates the relative quantities of germplasm included from each population for use at the revegetation site. Climate change is represented as increasing aridity but other dimensions (e.g. increasing temperature) could be used. Figure reproduced from Climate-ready revegetation. A guide for natural resource managers. Hancock et al. 2018.

A ***climate-adjusted strategy*** was chosen to select suitable provenances. The rationale for choosing this strategy is that it combines advantages of local provenances (finely tuned adaptation to local non-climatic factors (soil, biota etc.) and climatic factors (such as frost)), with adaptive potential conferred by non-local provenances in suitable climate analogue areas to withstand predicted hotter and seasonally disrupted climates (i.e. wetter summers, drier winter and spring). In addition to this, climate adjusted provenancing takes into account the considerable work done on climate modelling, and the general consensus among models to predict climate trends.

The composite strategy, while also incorporating advantages of finely tuned local adaptations, ignores major climate modelling trends. A predictive provenance strategy relies entirely on future climate modelling, and has the disadvantages of losing local adaptive capacity, and lack of flexibility in the case of climate uncertainty. The spread of modelled predictions used in the analysis would suggest that this would be imprudent.

An admixture approach, while including local provenance, takes less account of trends in modelled climatic factors, instead capitalising on capturing a wide range of climatic adaptability. While this is a suitable strategy for a highly unpredictable future climate, trends are clear in terms of warming temperatures and seasonality of rainfall.

Restricting seed sources to local provenance retains adaptation to non-climatic factors, but risks inbreeding depression, especially in small endemic populations, and in species where climate change is likely to cause decline in, or is already affecting, populations (Prober et al. 2015). While temperature increase is an established trend, rainfall is less predictable, with drought and flood cycles influenced by El Niño and La Niña events respectively. Plants therefore need to be adapted to both a drying climate but able to withstand periodic flooding events.

2. METHODS

2.1 Climate suitability analysis

2.1.1 Upper Shoalhaven Region Future climate projections

This work used data derived from the NSW and ACT Regional Climate Modelling (NARCliM) 1.0 project and provided by the Government of New South Wales, Australia (Evans, et al., 2014).

Data was obtained for each of the four subregions within the Upper Shoalhaven region for historical climate (baseline; 1990 – 2009), and projected climate for the near future (2020 – 2039) and far future (2060 – 2079), for 12 different models from NARCliM v1.0 (NSW and ACT Regional Climate Modelling) (4 GCMs with 3 RCMs), at a SRES A2 emission scenario (comparable to RCP8.5, or worst case / business as usual). Data was provided by Jamie Love and Jojo Jackson, DPIE, NSW Government.

Data was collected for the following variables:

- Annual mean temperature;
- Annual precipitation;
- mean temperature of coldest quarter;
- mean temperature of warmest quarter;
- precipitation of wettest quarter; and
- precipitation of driest quarter.

NARCliM v1.0 was published in 2014 and used an earlier generation of climate model projections. As such it is considered a conservative approach. NARCliM v1.0 uses 'SRES' (Special Report on Emissions Scenarios), published by IPCC in 2000 (Intergovernmental Panel on Climate Change, 2000). The SRES has four different scenarios of population, economic growth and greenhouse gas emissions. SRES A2 assumes high greenhouse gas emissions and strong economic development (Intergovernmental Panel on Climate Change, 2000).

NARCliM v1.5 has adopted Representative Concentration Pathways (RCPs), which addresses four pathways for greenhouse gas concentrations and the resulting warming expected by the end of the century. Of the four scenarios (2.6, 4.5, 6.0, and 8.5), SRES A2 is considered to be most aligned with RCP8.5, the worst-case scenario (Walsh, et al., 2014).

The analysis used four GCMs (General Circulation Models): CCCMA, CSIRO mk3.0, ECHAM, MIROC. The GCMs use a horizontal and vertical grid over the earth's surface to simulate interactions between the atmosphere, oceans, land surface and ice (Flato, et al., 2013).

Three RCMs (Regional Climate Models) were used to downscale each GCM, based on weather research and forecasting, which are at a higher resolution than the GCMs and provide more specific regional observations at a smaller scale (Flato, et al., 2013).

2.1.2 Future climate suitability analysis

The climate suitability analysis mostly followed the methods used by the Yass Area Network team, for the Climate-Ready Revegetation in the Yass Area Network Landcare Region, provided by Elizabeth Goodfellow (Duus, Goodfellow, Hall, McGuirk, & McIntyre, In prep) and AdaptNSW (Isobel Cummings, pers comm). Methods are summarised below.

For each species in question, the distribution and climate envelope were investigated using NicheFinder (http://www.nswnichefinder.net), by downloading species distribution climate data, as listed above. We then generated three scatter plots for each species, as follows:

- Annual mean precipitation versus annual mean temperature
- Precipitation of the driest quarter versus mean temperature of the hottest quarter
- Precipitation of the wettest quarter versus mean temperature of the coldest quarter

Melicytus dentatus, which did not have data available on NicheFinder, was assessed using data retrieved from the Spatial Portal in the Atlas of Living Australia (https://www.ala.org.au/).

The climate data was downloaded for each species, and then plotted with the current (baseline) average climate, and the minimum and maximum climate projections for the 12 NARCliM models, for each of the four subregions, using Microsoft Excel (2019).

Only the far future (2060-2079) data was analysed, since this is most relevant for tree/shrub plantings.

2.2 Interpretation of climate graphs

Each graph shows the species' current climatic range, the future projected climatic range and the current average for the region in question (Figure 4). If the current species climatic range extends across the range of the future projected climate, then we can consider the species suitable for the future projected climate.

Graphs initially included climate project data for South East NSW, however the range in projected climate change for the whole region (stretching from Wollongong to Kosciuszko, and from the coast to the south western slopes) is so broad it provided no useful information in the analysis and was removed for the remaining analyses.

Distribution for each species according to NicheFinder was carefully assessed for outlier and false information, using our own understanding of the species, Euclid (https://apps.lucidcentral.org/euclid), and Atlas of Living Australia (https://www.ala.org.au/). Often errors in GPS coordinates or place names can result in a species being placed in the wrong area. Species records may also be included from other states, including from garden specimens and botanic gardens. Whilst these records may provide some information about climate tolerance, they might be watered, and possibly grown in a particular niche to aid survival, so these records were dismissed. False record location was cross checked on NicheFinder, and if they resulted in data points in the extreme hot, wet or dry then they were noted and disregarded during analysis.

To assist graph interpretation, on each graph a box was placed around the minimum and maximum future climate predictions (Figure 4). Because the temperature is expected to increase in the future, only the hottest section of the species envelope was assessed, focusing on hot/wet and hot/dry (Figure 4). If the current species tolerance range included up to the hottest future projected climate (the right end of the box), the species tolerance was marked as 'yes'. Where the current species tolerance range extended over 1^{o}C, the species tolerance was marked as 'yes+'. If the current species tolerance range included almost up to the hottest future projected climate, the species tolerance was marked as 'marginal'. Graph interpretation focused on hot/dry for 'precipitation driest quarter vs mean temperature hottest quarter', and hot/wet for 'precipitation of wettest quarter vs mean temperature coldest quarter', so a negative result was disregarded if it occurred in the contrasting. More weighting was placed on the annual temperature versus annual precipitation graph than the quarterly graphs.

Each species was further assessed as to its predicted tolerance to hot/dry (bottom right section of the boxed area in the graph) and hot/wet (top right section of the boxed area in the graph) (Figure 4). However, given the uncertainty around rainfall in the future climate predictions for south-east NSW (AdaptNSW, 2014), a tolerance for only one extreme did not affect the final decision outcome for that species.

Results that were considered marginal were assessed based on how far from each extreme they were. If species records were from areas more than 1 degree C from the maximum projected temperature, and rainfall more than 50mm from either maximum or minimum projected precipitation, the species were considered not tolerant to the future projected climate. This was based on observations that a difference in average temperature of 1 °C, or a difference in annual rainfall of 50mm, would result in a change of vegetation community when looking across the landscape (E. Goodfellow, pers comm.). Species were also considered marginal if points were few and scattered in hottest part of the species climate envelope. For the purpose of preparing a species list for the nursery, species that were considered to have a marginal tolerance of the future projected climate for all four subregions in the Upper Shoalhaven region were disregarded for further analysis.

Interpretation of the graphs to some level requires judgement calls, which can differ from person to person. For this reason, all species were assessed by both authors, and any disagreements discussed. Results were also shared with an external source (Meredith Cosgrove), and differences discussed.

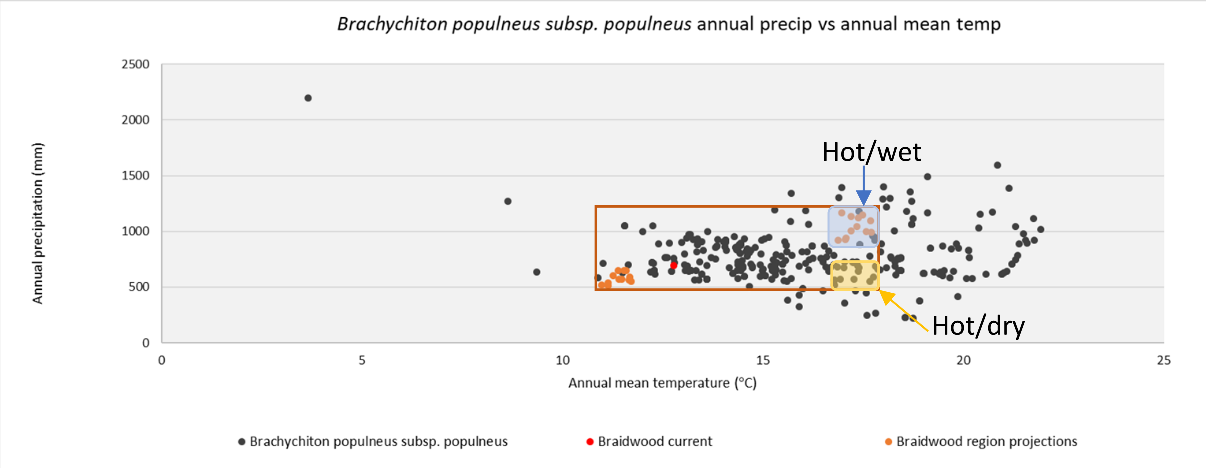

Figure 4. Example of a species climate assessment graph, showing annual precipitation versus annual mean temperature for Braidwood subregion baseline climate and the current distribution of *Brachychiton populneus* subsp. *populneus*, and the minimum and maximum far future (2060 – 2079) predicted climate. The areas of graph assessed for a species' potential tolerance to projected hot/wet and hot/dry conditions are highlighted. In this case, *B. populneus* subsp. *populneus* is shown to be able to tolerate hotter temperatures and increased and decreased precipitation than predicted for the Braidwood subregion, and is considered suitable for further analysis as a climate ready revegetation species.

2.3 Climate adjusted seed provenance site selection

Seed provenance analysis followed a combination of the methods developed by the Yass Area Network team for the Climate-Ready Revegetation in the Yass Area Network Landcare Region, provided by Elizabeth Goodfellow (Duus, Goodfellow, Hall, McGuirk, & McIntyre, In prep), and methods provided by DPIE, NSW Government (Isobel Cummings, pers comm.). Methods are summarised below.

2.3.1 Geographical boundary of seed collection sites

Due to expected differences in geology and logistical difficulties in sourcing seed, it was decided to exclude potential seed sources in South Australia, Western Australia, Tasmania and northern Queensland. A map was prepared to guide seed sourcing sites within south-eastern Australia using the CSIRO climate analogues tool (https://www.climatechangeinaustralia.gov.au/en/projections-tools/climate-analogues/analogues-explorer/), which indicates areas in Australia that have a similar climate to the predicted projected climate for a given location. Climate analogues were mapped for the far future (2090), under the maximum emissions scenario (RCP 8.5), for three scenarios: hottest and driest (worst case), least hot/warmer and wettest (best case) and maximum consensus (warmer and drier; the outcome the majority of models suggest). Two localities, Queanbeyan and Batemans Bay, were chosen as representative of the tablelands subregions (Braidwood and West of Divide) and subregions with a coastal influence (Coastal Scarp and Araluen) respectively.

2.3.2 Target future climate

The range of predicted far future (2060 – 2079) climate extremes (minimum and maximum) were tabulated for each of the four subregions in the Upper Shoalhaven region, and from this a consensus range of annual temperature and annual precipitation across the whole region was decided on to guide climate adjusted seed provenance analysis. This included the minimum to maximum range of annual precipitation, to cover dry and wet future scenarios. Annual temperature was assessed as the current mean to the maximum, as it is agreed that all future scenarios will involve an increase in annual temperature. An overall mean across the four regions was also calculated.

2.3.3 Target species selection

All species that were assessed as 'yes' (suitable for future projected climate conditions) and 'mixed' (some subregions suitable for future projected climatic conditions) were investigated for seed availability in Victoria, New South Wales and Queensland, using information available from Project Phoenix (see https://www.greeningaustralia.org.au/projectphoenix/). Species with minimal or few known seed collectors were excluded from further analysis. The resulting list was assessed further to create a shortlist of species for seed provenance analysis. Criteria used to determine the shortlist were based mainly on the spread of species likely to be in high demand in the proposed community nursery. These included:

- 'Yes' and 'Yes+' species across the entire region
- Species with a suitable spread of climatically suitable populations, according to the climate suitability graphs (i.e. species in hotter range not too few or disjunct)
- widespread species common in many plant community types (*Eucalyptus viminalis, Bursaria spinosa, Acacia melanoxylon*)
- species which are dominant in threatened ecological communities in subregional localities (*Eucalyptus melliodora* and *E. tereticornis*)
- species which are important habitat, especially for threatened fauna (*Allocasuarina littoralis, Bursaria spinosa, Hakea dactyloides, Callistemon* sp.), and
- riparian species (*Callistemon sieberi, Leptospermum brevipes*).

2.3.4 Seed provenance selection

Each species considered suitable for climate adjusted revegetation was entered into NicheFinder (http://www.nswnichefinder.net/), and the annual precipitation data plotted against the annual mean temperature. Focussing on the area of the scatterplot within the minimum and maximum annual precipitation, current mean temp and maximum projected temperature (as discussed above), a minimum of 11 locations were recorded, aiming for low temperature increase, midrange temperature increase and high temperature increase, at low, moderate and high annual precipitation for each temperature range, as well as a further two geographically separated locations representing the median climate projections.

All resulting locations (recorded as latitude and longitude) were then mapped using Google My Maps (https://mymaps.google.com), and highlighted on the species climate envelope graph prepared for the climate suitability assessment for each species, in each of the four subregions. The climate parameters used in the climate suitability assessment were recorded for each location. The resulting map, table and graphs were then visually assessed to ensure that suitable seed provenance sites had been located to represent the range indicated by the climate analogues map, and across the range of the future predicted precipitation and temperature. If geographical regions or particular precipitation or mean temperature ranges were not represented further points were selected from the NicheFinder scatterplot to ensure appropriate representation.

3 RESULTS

3.1 Upper Shoalhaven Region Future climate projections

Baseline climate data (1990 – 2009) and future projected climate data were obtained for the four subregions in the Upper Shoalhaven region (Table 1). Table 1 lists averages for the far future (2060 – 2079) from 12 NARCliM models, however it should be noted that each model produces a range of estimates. Detailed future climatic projections for the four subregions are presented in Appendix 2. The analysis used the range (maximum and minimum, presented in Appendix 2) for each model to display and assess the uncertainty in the future climate predictions.

The mean annual temperature for each subregion is predicted to increase by 2°C (Table 1). The average temperature for the warmest and coldest quarters are also predicted to rise by up to 2°C. Average rainfall is predicted to decrease in the driest quarter and increase in the wettest quarter, with the exception of the subregion 'west of divide', for which the mean figures show the opposite trend. However, there is a large amount of variation in the rainfall predictions across the 12 NARCliM models, as shown in the detailed climate prediction data (Appendix 2) and the analysis graphs (Appendix 3).

Table 1. Average climate projections for four subregions in the Upper Shoalhaven region. Baseline represents records 1990-2009. 2070 represents climate predictions 2060-2079. Note that these are average predictions from 12 NARCliM models.

	Araluen		**Braidwood**		**Coastal Scarp**		**West of Divide**	
	Baseline	**2070**	**Baseline**	**2070**	**Baseline**	**2070**	**Baseline**	**2070**
Annual temp. (°C)	14.16	16.12	12.78	14.77	12.73	14.68	12.40	14.44
Annual rain (mm)	761.97	777.47	696.44	698.30	868.63	870.33	640.66	656.48
Warmest quarter temp (°C)	19.80	21.60	18.90	21.18	18.38	20.59	18.87	21.25
Coldest quarter temp (°C)	8.39	10.07	6.57	8.20	6.98	8.59	5.94	7.56
Driest quarter rain (mm)	150.23	127.88	132.80	122.77	180.24	149.18	111.86	117.95
Wettest quarter rain (mm)	238.43	262.71	211.16	227.57	259.01	283.33	258.33	210.51

Future climate suitability analysis

A total of 76 species were shortlisted for the climate suitability analysis (Appendix 1), consisting of native trees and shrubs.

Each of the 76 native plant species were assessed against the predicted future (2060-2079) climate for four subregions in the Upper Shoalhaven region, to determine potential tolerance to hotter and drier/wetter conditions (Table 2). Detailed results for each species, including potential tolerance of hot/dry conditions and hot/wet conditions are included in Appendix 4. Thirty five species were considered unlikely to tolerate future projected climate change across the Upper Shoalhaven region based on their current distribution (Table 2). Thirty two species were considered likely to tolerate the future predicted climate change across the Upper Shoalhaven region (Table 2). A further nine species have varied climatic tolerances, resulting in a mixed overall decision (Table 2). These species all indicated tolerance to the future projected climate in the subregion 'west of divide', and varied tolerances to the remaining three subregions. It should be noted that the analysis focused on maximum temperature, and both maximum and minimum precipitation, focusing on extremes. Species that showed no evidence of coping with extremes were rejected.

Whilst considering projected climates and species response over four subregions provides a very detailed analysis, and might be considered to be beyond the requirements of the end purpose (a community nursery), the four regions were maintained for analysis purposes, as it might provide important detail for seed provenance sites in the future. The variation in average temperature and rainfall (Table 1) for each subregion was enough to consider that there is sufficient climatic variation across the subregions to treat them separately. This was further supported in analysis, where many species recorded different results across the four subregions (Table 2). It is also supported by anecdotal evidence regarding survival of revegetation species in different parts of the Upper Shoalhaven region (Lyn Ellis, pers. comm.).

*Table 2. Results for 76 native plant species of potential tolerance to far future (2060 - 2079) projected climate change. Results are included for each of the four subregions, and an overall decision for the species to guide seed provenance investigation. Species underlined are considered as post fire species of concern and/or listed as threatened species. Species marked with * are non-local native species commonly used in local plantings.*

SPECIES	ARALUEN	BRAIDWOOD	COASTAL SCARP	WEST OF DIVIDE	OVERALL DECISION	SEED PROVENANCE ANALYSIS
Acacia covenyi	No	No	No	No	**No**	
Acacia dealbata subsp dealbata	Marginal	Marginal	Yes	yes	**Yes**	No
Acacia decurrens	Yes +	Yes +	Yes +	Yes +	**Yes**	yes
Acacia falciformis	Yes	Yes	Yes	Yes	**Yes**	yes
Acacia genistifolia	No	Marginal	Marginal	Yes	**Mixed**	No
Acacia implexa	Yes +	Yes +	Yes +	Yes +	**Yes**	Yes
Acacia mearnsii	Marginal	Yes	Yes	Yes	**Yes**	Yes
Acacia melanoxylon	Yes+	Yes+	Yes+	Yes+	**Yes**	Yes
Acacia parramattensis	Marginal	Marginal	Marginal	Yes	**Mixed**	No
Acacia rubida	Marginal	Marginal	Yes	Yes	**Yes**	Yes
Acacia siculiformis	No	No	No	Marginal	**No**	
Acacia terminalis	Yes	Yes	Yes	Yes	**Yes**	No
Acacia trachyphloia	No	No	No	No	**No**	
Allocasuarina littoralis	Yes	Yes	Yes	Yes	**Yes**	yes
Allocasuarina nana	No	No	Marginal	No	**No**	
Allocasuarina verticillata	Yes	Yes	Yes	Yes	**Yes**	yes
Angophora floribunda	Yes +	Yes +	Yes +	Yes +	**Yes**	yes
Banksia ericifolia subsp ericifolia	No	No	Marginal	No	**No**	
Banksia marginata	Yes	M	Yes	Yes	**Yes**	yes
Brachychiton populneus subsp. populneus	Yes +	Yes +	Yes +	Yes +	**Yes**	yes
Bursaria spinosa subsp. lasiophylla	Yes	Yes	Yes	Yes	**Yes**	yes
Callistemon citrinus	Yes	Yes	Yes	Yes	**Yes**	yes

Callistemon pityoides	No	No	Marginal	Yes	**Mixed**	No
Callistemon sieberi	Yes	Yes	Yes	Yes	**Yes**	yes
Callistemon subulatus	No	No	No	No	**No**	
Callitris endlicheri	Yes	Yes	Yes	Yes	**Yes**	yes
Callitris oblonga ssp corangensis	No	No	No	No	**No**	
Cassinia longifolia	M	M	Yes	Yes	**Yes**	No
Casuarina cunninghamiana subsp. cunninghamiana	Yes	Yes	Yes	Yes	**Yes**	yes
Eucalyptus agglomerata	Yes	Yes	Yes	Yes	**Yes**	No
Eucalyptus aggregata	No	No	No	No	**No**	
Eucalyptus bosistoana	No	No	Marginal	No	**No**	
Eucalyptus bridgesiana	Marginal	Marginal	Yes	Yes	**Yes**	No
Eucalyptus cinerea subsp. cinerea	No	No	No	No	**No**	
Eucalyptus cypellocarpa	No	No	Marginal	No	**No**	
Eucalyptus dalrympeana	No	No	No	No	**No**	
Eucalyptus dives	No	No	No	Marginal	**No**	
Eucalyptus elata	No	Marginal	M	Yes	**Mixed**	No
Eucalyptus eugenioides	Yes	Yes	Yes	Yes	**Yes**	yes
Eucalyptus fastigata	No	No	Marginal	No	**No**	
Eucalyptus fraxinoides	No	No	No	No	**No**	
Eucalyptus globoidea	Yes	Yes	Yes	Yes	**Yes**	No
Eucalyptus globulus* subsp. *maidenii	N	N	N	N	**No**	
Eucalyptus goniocalyx	No	No	No	Yes	**No**	
Eucalyptus kartzoffiana	No	No	No	No	**No**	
Eucalyptus macarthurii*	No	No	No	No	**No**	
Eucalyptus macrorhyncha subsp. macrorhyncha	No	No	Marginal	Yes	**Mixed**	No
Eucalyptus mannifera subsp. mannifera	N	N	N	N	**No**	
Eucalyptus melliodora	Yes	Yes	Yes	Yes	**Yes**	yes

Eucalyptus moorei subsp. moorei	N	N	N	N	**No**	
Eucalyptus nicholii*	N	N	N	N	**No**	
Eucalyptus obliqua	Marginal	Marginal	Yes	Yes	**Yes**	No
Eucalyptus ovata	N	N	N	N	**No**	
Eucalyptus parvula	N	N	N	N	**No**	
Eucalyptus pauciflora subsp. pauciflora	No	No	Marginal	Marginal	**No**	
Eucalyptus radiata subsp. radiata	No	No	NO	Marginal	**No**	
Eucalyptus rossii	No	Marginal	Yes	Yes	**Mixed**	yes
Eucalyptus rubida subsp. rubida	No	No	No	No	**No**	
Eucalyptus sieberi	Yes	Yes	Yes	Yes	**Yes**	yes
Eucalyptus stellulata	No	No	No	No	**No**	
Eucalyptus tereticornis subsp. tereticornis	Yes+	Yes+	Yes+	Yes+	**Yes**	yes
Eucalyptus viminalis	No	No	Yes	Yes	**Mixed**	yes
Grevillea arenaria subsp. arenaria	Marginal	Marginal	Marginal	Yes	**Mixed**	No
Grevillea juniperina ssp villosa	N	N	N	N	**No**	
Hakea dactyloides	Yes	Yes	Yes	Yes	**yes**	yes
Hakea eriantha	Yes	Yes	Yes	Yes	**yes**	yes
Hakea macraeana	N	N	N	N	**no**	
Hakea microcarpa	M	Marginal	M	Yes	**Mixed**	No
Leptospermum brevipes	Yes	Yes	Yes	Yes	**Yes**	yes
Leptospermum lanigerum	No	No	Yes	No	**No**	
Leptospermum morrisonii	Marginal	Marginal	Yes	Yes	**Yes**	No
Leptospermum myrtifolium	No	No	Marginal	Marginal	**No**	
Leptospermum obovatum	No	No	Marginal	Marginal	**No**	
Melaleuca parvistaminea	No	No	No	Marginal	**No**	
Melicytus dentatus	Yes	Yes	Yes	Yes	**Yes**	No
Telopea mongaensis	No	No	No	No	**no**	

3.2 Climate adjusted seed provenance site selection

We assessed 25 species to determine the ideal locations for climate adjusted seed provenance sites. These species were selected out of 41 species considered suitable for the future projected climate across all or some of the four subregions delineated in the Upper Shoalhaven region (Table 2).

3.2.1 Geographical boundary of seed collection sites

The climate analogue map created to guide seed provenance sites indicated that the most appropriate areas in which to target populations for seed ranged from Wangaratta (Vic) and Bega (NSW) in the South, Griffith, Condobolin and Gilgandra (NSW) in the west, Camden and Taree (NSW) in the east and Kingaroy (QLD) in the north (Figure 5). Sourcing seed from within these boundaries will prevent logistical and potential growing difficulties that might be encountered if sourcing seed from geographically distant areas, such as Western Australia, South Australia and far north Queensland.

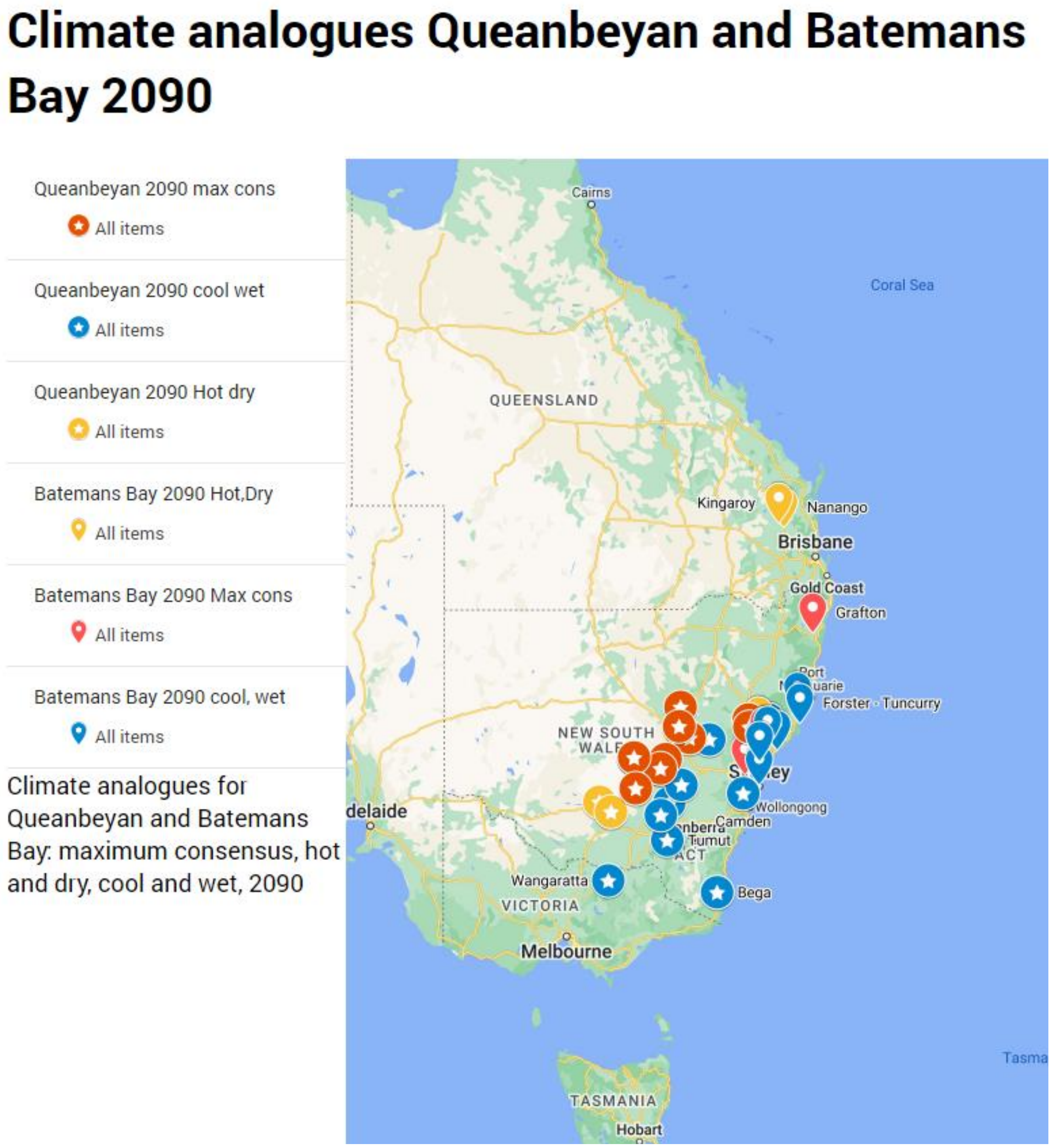

Figure 5. Climate analogues for Queanbeyan (representing climate in West of Divide and Braidwood subregions) and Batemans Bay (representing climate in Araluen and Coastal Scarp subregions). Climate analogues identified using the CSIRO's climate analogue tool (https://www.climatechangeinaustralia.gov.au/). Map produced using Google My Maps (https://mymaps.google.com).

3.2.2 Target future climate

Predicted future precipitation and annual temperature were assessed across each of the four subregions to develop a range from which to target seed provenance sites (Table 3). To simplify the seed provenance selection process, the same climatic range was used to represent the entire Upper Shoalhaven region. This has resulted in the climate suitability graphs for the warmer subregions – particularly Araluen, displaying a selection that slightly resembles the 'admixture' seed selection strategy. Whilst this is not the intended seed selection strategy, and the 'climate adjusted' seed selection strategy is preferred, this ensures that the predicted temperature increases for the cooler subregion, specifically "west of divide" (Bungendore region) are incorporated. Cooler seed source sites can be excluded from warmer planting regions if desired, provided all nursery plantings are carefully labelled. However, maintaining all seed source sites at a planting site is still expected to increase the genetic variation and the adaptive potential of a species within a site, and it may still be an advantage to retain all seed sites.

Table 3. Projected annual temperature and precipitation for four subregions in the Upper Shoalhaven region, based on twelve models as described in the methods section, and the temperature and precipitation range used to select seed provenance sites.

2060 – 2079 CLIMATE PROJECTIONS	RANGE OF ANNUAL PRECIPITATION (MM)	MEDIAN ANNUAL PRECIPITATION (MM)	RANGE OF ANNUAL TEMP (ºC)	MEDIAN ANNUAL TEMP (ºC)	BASELINE (1990 – 2009) ANNUAL MEAN TEMP (ºC)
ARALUEN	601.17 – 1147.49	777.47	12.68 – 17.99	16.12	14.16
BRAIDWOOD	511.88 – 1169.74	698.3	10.97 – 17.70	14.77	12.78
COASTAL SCARP	644.14 – 1385.92	870.34	12.10 – 17.01	14.68	12.73
WEST OF DIVIDE	498.57 – 1152.09	656.48	10.34 – 16.28	14.44	12.4
RANGE USED FOR SEED PROVENANCE ANALYSIS.	**500 - 1200**	**750**	**13 - 18**	**15**	**13**

3.2.3 Target species selection

Species information for eleven seed suppliers that collect from south-east Australia was collated (Appendix 5). This resulted in 34 species with a suitable spread of seed collectors to justify further investigation.

A total of 25 species were selected for seed provenance analysis. These included species considered to be priority species for local revegetation projects, such as key species in threatened local vegetation communities, species common across multiple local vegetation communities, and riparian species. *Leptospermum brevipes* was included in the seed provenance analysis despite limited seed collectors, as the majority of *Leptospermum* species are not considered suitable for the future projected climate, and they are important riparian species.

3.2.4 Seed provenance selection

Seed provenance analysis for 25 native species in the Upper Shoalhaven region are included in Appendix 6. For each species, a table of locations is provided, detailing the six climate variables used for the climate suitability assessment, for each suggested seed source site (Table 4). The information in this table is used to ensure that the sites cover a range of temperature and precipitation measures that represent potential predicted climate change (between 500mm and 1200mm annual precipitation and between 13°C and 18°C annual mean temperature). This information is also visualised on each of the three species climate tolerance graphs (Figure 6). A map has been prepared for the suggested seed provenance sites for each species, to confirm the sites are within the climate analogue envelope (Figure 7), and represent a range of sites across south eastern Australia.

Whilst specific locations are provided, seed provenance will always be limited by available seed being collected at any one time. As such, the locations should be considered a guide as to where to aim to source seed from. If seed is sourced from the general areas indicated then the future change in climate should be represented.

It should be noted that local seed is not represented in any of the seed provenance results, as it is assumed that local seed will also be included in all seed sourcing strategies, as local seed is known to be adapted to the current climate, as well as to non-climate factors such as soil type.

Table 4. An example of a seed source location table. Location information is detailed, along with climate data for the six climate variables used in the climate suitability assessment. Locations include a range of annual mean temperatures from 13°C to 18ºC, and a range of annual precipitation from 500mm to 1200mm.

Recommended seed provenance sites (climate adjusted)								
Brachychiton populneus subsp. populneus								
Seed source	**Longitude**	**Latitude**	**Mean temp of warmest quarter (deg C)**	**Precip driest quarter (mm)**	**Mean temp of coldest quarter (deg C)**	**Precip wettest quarter (mm)**	**Annual mean temp (deg C)**	**Annual precip (mm)**
Granya, Vic	147.267	-36.117	20.02	151.88	6.59	349.08	13.19	972.52
Metz, NSW	151.867	-30.567	19.33	102.39	7.62	298.08	13.71	762.72
Tharwa, ACT	149.067	-35.517	19.79	135.2	6.54	188.2	13.2	650.49
Mount Barney NP, QLD	152.676	-28.273	19.62	135.16	10.25	452.07	15.29	1194.9
Kanangra, NSW	150.250	-34.000	21.35	128.14	9.57	298.95	15.59	815.6
Temora, NSW	147.601	-34.297	23.17	113.12	8.47	167.19	15.7	579.29
Yarras, NSW	152.317	-31.417	22.89	114.99	12.75	504.47	18.08	1219.12
Crows Nest, QLD	152.084	-27.248	22.91	107.49	12.07	351.47	17.95	887.55
Gilgandra, NSW	148.683	-31.717	25.02	120.04	10.21	166.27	17.67	554.52
Douglas Park, NSW	150.720	-34.170	21.87	137.43	11.24	254.68	16.77	785.63
Dubbo, NSW	148.583	-32.117	24.61	128.89	9.85	164.82	17.27	573.95
Clyde River, NSW	150.217	-35.467	21.02	186.79	10.96	322.94	16.14	1064.15
Putty Road, NSW	150.967	-32.717	22.08	109.1	10.53	261.69	16.49	728.11

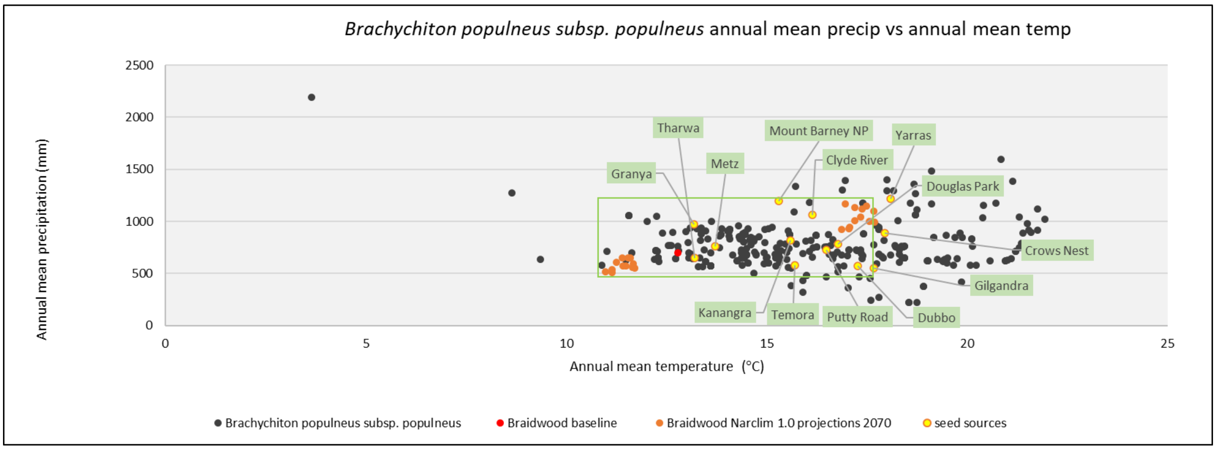

Figure 6. An example of a species climate assessment graph, highlighting the suggested seed provenance locations. Locations represent the range of predicted climate change from the baseline though to potential maximum temperature and precipitation.

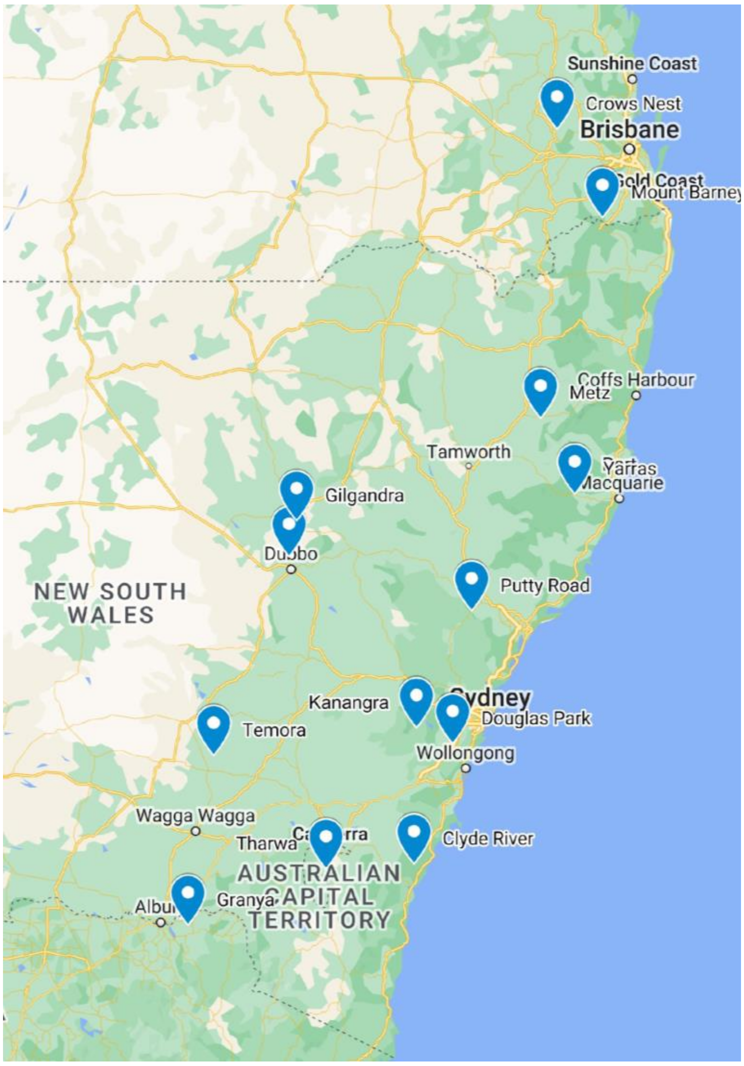

Figure 7. An example of a seed provenance map, showing 13 suggested seed provenance sites for Brachychiton populneus subsp. populneus within south-eastern Australia. The map can be used to guide seed sourcing, by locating seed collectors within an area or bioregion that match to each of the suggested sites.

3.3 Seed sourcing

The eleven seed suppliers across the geographic area suggested by provenance analysis were contacted to determine availability of seed of specific provenances (Appendix 5). Of these suppliers, three were able to supply seed provenances across the range of provenance sites for the 'Yes" and 'Mixed' species.

Greening Australia has recently amalgamated all its eastern states seed operations, and is now able to supply provenance specific seed for a wide variety of species from across eastern Australia. Interestingly, some of the seed harvested is sourced from previous provenance-traced revegetation plantings undertaken by the organisation on farming and other properties (M. Bailey, pers. comm.). Nindethana, a nationwide seed merchant based in Western Australia, will also supply seed of specified provenance given adequate lead time (this can be 18 months or more). Due to Myrtle Rust quarantine restrictions in W.A., no trade in seed of Myrtaceae (eucalypts, callistemons, melaleucas) is possible over state boundaries, however. Royston Petrie in Mudgee collects over a range of provenances, as does Diversity Native Seeds (Coonabarabran), although the latter specifies only biogeographic subregions (e.g. South West Slopes, North Coast). Alessi (Windellama) only supplies local tablelands provenances, which is nevertheless useful as a source of locally adapted seed provenances. Another nearby seed collector potentially of interest for Araluen and Coastal Scarp subregions is Seedworld in Nowra. While they track provenance of their seed, collection occurs over a relatively limited area. Seeding Victoria (which the operator describes as a deposit and withdrawal seedbank) collects seed from a wide variety of provenances from Goldfields, Riverina and Wimmera Regions. The remaining listed suppliers do not specify seed provenance or did not respond to queries.

It should be noted that seed supply is highly variable, depending on season and availability. If a species is no longer in supply, a seed collector will require 12-18 months notice as a minimum to source the required seed. Seed availability is also dependent on the species producing seed in that year.

4 DISCUSSION

On the face of the above analysis, the future looks grim for the survival of nearly half (45%) of species analysed. This includes all but one of the threatened species and species of concern post 2019 – 2020 fires. Only 8 of the 33 eucalypt species native to the USLD were assessed as likely to tolerate projected climate across the region, with another 4 eucalypt species predicted to tolerate conditions in some but not all subregions. This obviously has major implications for both plantings and indeed entire ecological communities across the landscape, as eucalypts are structural dominants in the vast majority of vegetation communities across the USLD. Even riparian communities, where climatic extremes are likely to be less severe, appear to be facing structural losses of dominant shrub species, such as 4 of the 6 common *Leptospermum* species found in the district. Furthermore, NARCliM 2.0 is expected to be released in 2023, and will provide climate projections with finer resolution across the region (https://www.climatechange.environment.nsw.gov.au/). This data, using updated models, is expected to provide a clearer picture of what climate change could look like in the region, and may result in further changes to the expected tolerance of plant species in the region.

However, it should be noted that the analysis used takes no account of factors other than geographic distribution records and broad climatic factors. The vulnerability of species to climate change is more complex than this would suggest. It is a function of interacting factors: the degree of exposure to climatic effects, sensitivity of species to these, and inherent adaptive capacity to withstand a changing environment (Leishman et al. 2016). A consideration of these factors was beyond the scope of this report.

Interpreting data from species with a limited distribution (which includes many endemic and threatened species) is difficult, as this analysis does not take into account a species' physiological capacity to withstand climatic extremes. The Wollemi Pine (*Wollemia nobilis*) is one example. Despite an extremely limited distribution, it has proven highly adaptable to cultivation indoors, outdoors, in a wide range of climates and soils both here and overseas. Another species to consider is Black Gum, *Eucalyptus aggregata.* This species is listed as vulnerable under both BC and EPBC Acts and is known from only a limited number of sites. This results in a restricted climate envelope, and the species was assessed as not likely to withstand climate change. However, it is a staple species in shelterbelt plantings throughout the district, has thrived in a range of harsh, exposed environments, and has survived prolonged drought, frost hollow temperatures below -10^{o}C, waterlogging and periodic flood inundation.

Vulnerability to climate change is most likely in species restricted to habitats exposed to extremes (mountain tops, frost hollows, exposed ridges); species with a narrow range of physiological tolerances (e.g. specific temperatures /stratification for germination); specific ecological interactions (e.g. specialist pollinators, mycorrhizal fungi); very localised habitat (e.g. Corang Pine, Monga Waratah, Bombay Bossiaea); small populations; and the combination of difficulty dispersing across landscapes and inability to adapt to changing conditions *in situ* (e.g. *E. viminalis* across the Monaro (Ross & Brack 2015)). Species which have been assessed as likely to tolerate climate change on the basis of current distribution and climate modelling may still be vulnerable to any of these factors.

It is also important to remember that the climate projection data is over a minimum of 10km square grids in NSW, and creates a broad view of climate, completely disregarding microclimates that may be provided by waterways, mountains, rocky outcrops etc. For this reason, whilst it is important to ensure the most resilient future vegetation, it would be dangerous to completely disregard species and their chance of future survival entirely based on this climate analysis, as some species might be able to survive in suitable pockets of habitat.

The decision to look further into seed provenances beyond the region was informed by the large proportion of species assessed as being unlikely to survive predicted climate change across the region, hence the need to boost adaptive capacity by incorporating climate-adjusted provenances. Limiting nursery stock to plants grown from seed collected locally might significantly limit the range of species and the long-term survival of even climate-resilient species.

Climate adjusted seed provenance provides the opportunity to increase genetic diversity, and potentially resilience within a population, by sourcing seed from healthy populations within multiple areas experiencing the range of climates similar to that projected for the local region (Prober et al 2015). This in turn may give the population the genetic ability to adapt to a changing climate, and improve chances of a species' local survival (Prober et al 2015). There is, however, some risk in introducing genotypes from geographically distant populations, particularly between populations where gene flow has not naturally occurred for extensive periods of time, which may result in outbreeding and unhealthy hybrid plants (Breed at al 2013). This could occur with species that have a disjunct distribution. For example, the Hunter River Valley has been identified as a long-term barrier to dispersal for many plant species (Flores-Renteria et al, 2021; Milner et al, 2012), and species exhibiting a distributional break in this region may also show genetic differentiation either side of the Hunter River Valley. Within this study this might include northern populations of

Leptospermum brevipes, *Hakea eriantha*, *H. macrocarpa*, *H. dactyloides*, *Eucalyptus tereticornis* subsp. *tereticornis* and *E. obliqua.* However, the risk of outbreeding is outweighed by the potential benefits of the climate adjusted seed provenance (Prober et al, 2015), and provided multiple seed sources are used across the distribution of species, the risk is limited.

Maintaining ecosystem function across the landscape in the face of expected widespread vegetation decline due to climate change depends on ensuring continued protection of existing habitat, and revegetation to connect these areas across the landscape (Leishman et al. 2016). Revegetation needs to be done on a landscape scale, with resilient species. This places pressure on seed sources in the wild, and will entail boosting the native nursery industry to cater for anticipated demand (Van Moort, et al. 2021).

The geographic base of seed suppliers (unless specifically interested in local provenance) was of less importance than their provenance sourcing and tracing. For species with a wide range that includes climates more extreme than the climate envelopes predicted for the USLD, it should be relatively easy to source suitable provenances. This is more difficult with rare and endemic species with a more limited distribution.

The 2019-20 bushfires highlighted the need for a sustainable supply of native seed for fire recovery, and to be prepared for future fires and extreme weather events resulting from climate change. Supply is mostly limited by access to seed and land, as well as variability due to seasonal conditions, incomplete information, and lack of seed production beyond wild populations across the sector. This is further limited by climate change, catastrophic disturbance events (e.g. fire and flood) and the fragmentation and deteriorating condition of native vegetation (Van Moort, et al. 2021). While an increasing number of seed merchants do supply seed from specified provenances, availability depends on a network of specialised seed collectors around the country, and factors such as seasonal variation, predation, drought, fire and flood. Seed from threatened populations is strictly licensed, for obvious reasons, hence difficult to obtain. Handling costs for small quantities may also be significant for small, non-profit enterprises (M. Bailey, pers. comm.). As a small community with extremely limited nursery capacity to fill increasing demand, and limited access to suitable seed provenances or capacity to collect beyond the USLD, the establishment of local seed production areas to increase local supply of suitable seed provenances (a long-term investment when considering woody species) should be investigated. This could provide a modest source of farm income.

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APPENDIX 1: SPECIES CONSIDERED IN THE STUDY

COMMON SPECIES	SPECIES OF CONCERN	NON-INDIGENOUS SPECIES
Acacia dealbata subsp. *dealbata*	*Acacia covenyi*	*Eucalyptus macarthurii*
Acacia decurrens	*Acacia trachyphloia*	*Eucalyptus nicholii*
Acacia falciformis	*Callistemon subulatus*	
Acacia genistifolia	*Eucalyptus fastigata*	
Acacia implexa	*Eucalyptus fraxinoides*	
Acacia mearnsii	*Eucalyptus kartzoffiana*	
Acacia melanoxylon	*Eucalyptus macarthurii*	
Acacia parramattensis	*Eucalyptus moorei* subsp. *moorei*	
Acacia rubida	*Eucalyptus parvula*	
Acacia siculiformis	*Grevillea arenaria* subsp. *arenaria*	
Acacia terminalis	*Grevillea juniperina* subsp. *villosa*	
Allocasuarina littoralis	*Hakea macraeana*	
Allocasuarina nana	*Telopea mongaensis*	
Allocasuarina verticillata		
Angophora floribunda		
Banksia ericifolia subsp. ericifolia		
Banksia marginata		
Brachychiton populneus subsp. *populneus*		
Bursaria spinosa subsp. lasiophylla		
Callistemon citrinus		
Callistemon pityoides		
Callistemon sieberi		
Callitris endlicheri		
Callitris oblonga subsp. *corangensis*		
Cassinia longifolia		
Casuarina cunninghamiana subsp. *cunninghamiana*		
Eucalyptus agglomerata		
Eucalyptus aggregata		
Eucalyptus bosistoana (Araluen only)		
Eucalyptus bridgesiana		
Eucalyptus cinerea subsp. *cinerea*		

Eucalyptus cypellocarpa		
Eucalyptus dalrympeana		
Eucalyptus dives		
Eucalyptus elata		
Eucalyptus eugenioides		
Eucalyptus globoidea		
Eucalyptus goniocalyx		
Eucalyptus macrorhyncha subsp. *macrorhyncha*		
Eucalyptus globulus subsp. *maidenii*		
Eucalyptus mannifera subsp. *mannifera*		
Eucalyptus melliodora		
Eucalyptus obliqua		
Eucalyptus ovata		
Eucalyptus pauciflora subsp. *pauciflora*		
Eucalyptus radiata subsp. *radiata*		
Eucalyptus rossii		
Eucalyptus rubida subsp. *rubida*		
Eucalyptus sieberi		
Eucalyptus stellulata		
Eucalyptus tereticornis subsp. *tereticornis*		
Eucalyptus viminalis		
Hakea dactyloides		
Hakea eriantha		
Hakea microcarpa		
Leptospermum brevipes		
Leptospermum lanigerum		
Leptospermum morrisonii		
Leptospermum myrtifolium		
Leptospermum obovatum		
Melaleuca parvistaminea		
Melicytus dentatus (Araluen only)		

APPENDIX 2: UPPER SHOALHAVEN REGION FUTURE CLIMATE PROJECTIONS

Supplementary documents: Historical climate data (baseline; 1990 – 2009), and projected climate for the near future (2020 – 2039) and far future (2060 – 2079), for 12 different models from NARCliM v1.0 (NSW and ACT Regional Climate Modelling) (4 GCMs with 3 RCMs), at a SRES A2 emission scenario (comparable to RCP8.5, or worst case / business as usual), for four subregions in the Upper Shoalhaven region (Araluen, Braidwood, Coastal Scarp, West of Divide). Data was provided by Jamie Love and Jojo Jackson, DPIE, NSW Government. Provided as four excel files.

To request supplementary documentation contact Upper Shoalhaven Landcare Council at 42 Ryrie st Braidwood, NSW 2622 or email upper.shoalhaven@gmail.com.

APPENDIX 3: SPECIES CLIMATE SUITABILITY FILES

Supplementary documents: 76 pdf files, one for each species included in the climate suitability assessment. Attachments include 35 'no' files and 41 'yes' or 'mixed' files.

To request supplementary documentation contact Upper Shoalhaven Landcare Council at 42 Ryrie st Braidwood, NSW 2622 or email upper.shoalhaven@gmail.com.

APPENDIX 4: DETAILED SPECIES ASSESSMENT RESULTS

Detailed results for 76 native plant species of potential tolerance to far future (2060 - 2079) projected climate change, including predicted tolerance to hot/dry and hot/wet future conditions. Results are included for each of the four subregions, and an overall decision for the species to guide seed provenance investigation.

SPECIES	ARALUEN	BRAIDWOOD	COASTAL SCARP	WEST OF DIVIDE	OVERALL DECISION
Acacia covenyi	No	No	No	No	No
Acacia dealbata subsp dealbata	M hot/dry No hot/wet	No hot/dry M hot/wet	Yes hot/dry No hot/wet	yes	Yes
Acacia decurrens	Yes +	Yes +	Yes +	Yes +	Yes
Acacia falciformis	Yes	Yes	Yes	Yes	Yes
Acacia genistifolia	No	M hot/dry No hot/wet	M hot/dry no hot/wet	Yes hot/dry M hot/wet	Mixed
Acacia implexa	Yes +	Yes +	Yes +	Yes +	Yes
Acacia mearnsii	M hot/dry No hot/wet	M hot/dry Yes hot/wet	Yes	Yes	Yes
Acacia melanoxylon	Yes+	Yes+	Yes+	Yes+	Yes
Acacia parramattensis	M hot/dry No hot/wet	No hot/dry M hot/wet	M hot/dry no hot/wet	M hot/dry yes hot/wet	Mixed
Acacia rubida	Marginal	Marginal	Yes hot/dry No hot/wet	Yes	Yes
Acacia siculiformis	No	No	No	No hot/dry M hot/wet	No
Acacia terminalis	M hot/dry Yes hot/wet	No hot/dry, Yes hot/wet	Yes	M hot/dry, Yes hot/wet	Yes
Acacia trachyphloia	No	No	No	No	No
Allocasuarina littoralis	Yes	Yes	Yes	Yes	Yes
Allocasuarina nana	No	No	No hot/dry M hot/wet	No	No
Allocasuarina verticillata	Yes hot/dry M hot/wet	Yes	Yes hot/dry M hot/wet	Yes	Yes

Angophora floribunda	Yes +	Yes +	Yes +	Yes +	Yes
Banksia ericifolia subsp ericifolia	No	No	No hot/dry M hot/wet	No	No
Banksia marginata	M hot/dry yes hot/wet	M	Yes hot/dry no hot/wet	Yes	Yes
Brachychiton populneus subsp. populneus	Yes +	Yes +	Yes +	Yes +	Yes
Bursaria spinosa subsp. lasiophylla	Yes hot/dry No hot/wet	Yes hot/dry No hot/wet	Yes hot/dry No hot/wet	Yes hot/dry No hot/wet	Yes
Callistemon citrinus	No hot/dry yes hot/wet	M hot/dry yes hot/wet	Yes	M hot/dry yes hot/wet	Yes
Callistemon pityoides	No	No	M hot/dry no hot/wet	No hot/dry yes hot/wet	Mixed
Callistemon sieberi	Yes	no hot/dry Yes hot/wet	Yes	Yes	Yes
Callistemon subulatus	No	No	No	No	No
Callitris endlicheri	Yes	Yes	Yes	Yes	Yes
Callitris oblonga ssp corangensis	No	No	No	No	No
Cassinia longifolia	M	M	yes hot/dry no hot/wet	yes hot/dry no hot/wet	Yes
Casuarina cunninghamiana subsp. cunninghamiana	Yes	Yes	Yes	Yes	Yes
Eucalyptus agglomerata	M hot/dry Yes hot/wet	No hot/dry yes hot/wet	Yes	No hot/dry yes hot/wet	Yes
Eucalyptus aggregata	No	No	No	No	No
Eucalyptus bosistoana	No	No	No hot/dry M hot/wet	No	No
Eucalyptus bridgesiana	M hot/dry No hot/wet	M hot/dry No hot/wet	Yes hot/dry No hot/wet	Yes hot/dry No hot/wet	Yes
Eucalyptus cinerea subsp. cinerea	No	No	No	No	No
Eucalyptus cypellocarpa	No	No	M hot/dry No hot/wet	No	No
Eucalyptus dalrympeana	No	No	No	No	No
Eucalyptus dives	No	No	No	M hot/dry no hot/wet	No
Eucalyptus elata	No	No hot/dry M hot/wet	M	No hot/dry Yes hot/wet	Mixed
Eucalyptus eugenioides	Yes	M hot/dry yes hot/wet	Yes	M hot/dry yes hot/wet	Yes
Eucalyptus fastigata	No	No	No hot/dry M hot/wet	No	No
Eucalyptus fraxinoides	No	No	No	No	No
Eucalyptus globoidea	No hot/dry yes hot/wet	M hot/dry yes hot/wet	Yes	M hot/dry yes hot/wet	Yes
Eucalyptus globulus subsp. *maidenii*	N	N	N	N	No

Eucalyptus goniocalyx	No	No	No	Yes hot/dry No hot/wet	No
Eucalyptus kartzoffiana	No	No	No	No	No
*Eucalyptus macarthurii**	No	No	No	No	No
Eucalyptus macrorhyncha subsp. macrorhyncha	No	No	M hot/dry No hot/wet	Yes hot/dry No hot/wet	Mixed
Eucalyptus mannifera subsp. mannifera	N	N	N	N	No
Eucalyptus melliodora	Yes	Yes	Yes hot/dry M hot/wet	Yes	Yes
Eucalyptus moorei subsp. moorei	N	N	N	N	No
*Eucalyptus nicholii**	N	N	N	N	No
Eucalyptus obliqua	No hot/dry M hot/wet	No hot/dry M hot/wet	Yes hot/dry M hot/wet	Yes	Yes
Eucalyptus ovata	N	N	N	N	No
Eucalyptus parvula	N	N	N	N	No
Eucalyptus pauciflora subsp. pauciflora	No	No	M hot/dry no hot/wet	M hot/dry no hot/wet	No
Eucalyptus radiata subsp. radiata	No	No	NO	No hot/dry M hot/wet	No
Eucalyptus rossii	No	M hot/dry No hot/wet	Yes hot/dry no hot/wet	Yes hot/dry M hot/wet	Mixed
Eucalyptus rubida subsp. rubida	No	No	No	No	No
Eucalyptus sieberi	No hot/dry yes hot/wet	No hot/dry yes hot/wet	No hot/dry yes hot/wet	No hot/dry yes hot/wet	Yes
Eucalyptus stellulata	No	No	No	No	No
Eucalyptus tereticornis subsp. tereticornis	Yes+	Yes+	Yes+	Yes+	Yes
Eucalyptus viminalis	No	No	yes hot/dry No hot/wet	yes hot/dry no hot wet	Mixed
Grevillea arenaria subsp. arenaria	M hot/dry No hot/wet	Marginal	M hot/dry No hot/wet	M hot/dry yes hot/wet	Mixed
Grevillea juniperina ssp villosa	N	N	N	N	No
Hakea dactyloides	No hot/dry yes hot/wet	No hot/dry yes hot/wet	M hot/dry yes hot/wet	M hot/dry yes hot/wet	yes
Hakea eriantha	Yes	no hot/dry yes hot/wet	Yes	no hot/dry yes hot/wet	yes
Hakea macraeana	N	N	N	N	no
Hakea microcarpa	M	No hot/dry M hot/wet	M	Yes hot/dry M hot/wet	Mixed
Leptospermum brevipes	Yes hot/dry M hot/wet	No hot/dry yes hot/wet	Yes hot/dry M hot/wet	No hot/dry yes hot/wet	Yes
Leptospermum lanigerum	No	No	Yes hot/dry M hot/wet	No	No
Leptospermum morrisonii	No hot/dry M hot/wet	No hot/dry M hot/wet	No hot/dry yes hot/wet	No hot/dry yes hot/wet	Yes

Leptospermum myrtifolium	No	No	M hot/dry no hot/wet	M hot/dry no hot/wet	No
Leptospermum obovatum	No	No	No hot/dry M hot/wet	No hot/dry M hot/wet	No
Melaleuca parvistaminea	No	No	No	M hot/dry no hot/wet	No
Melicytus dentatus	M hot/dry yes hot/wet	No hot/dry Yes hot/wet	Yes	M hot/dry Yes hot/wet	Yes
Telopea mongaensis	No	No	No	No	no
				No	35
				Yes	32
				Mixed	9
				total	76

APPENDIX 5: SEED AVAILABILITY

Availability of seed for ‘yes’ and ‘mixed’ species as a result of the species climatic envelope assessment in south-east Australia.

Climate-ready species	GA Capital Region	Nindethana (GA – Aust wide)	Alessi (local)	Seed World (Nowra)	Ausseed (Blue Mtns)	Royston Petrie (Mudgee)	Goldfields (Central Victoria)	Harvest Seeds & Native Plants (Terrey Hills)	Seeding Victoria (various sites – searchable by provenance location)	Diversity Native Seeds (Coona-barabran) - listed by NSW subdivisions	Queensland Native Seeds (Sth Burnett)
***Acacia** dealbata*	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	x
A. decurrens	Y	Y	Y	Y	Y	Y	x	Y	x	Y	x
A. falciformis	Y	Y	Y	Y	Y	Y	x	Y	x	Y	Y
A. genistifolia	Y	Y	Y	x	Y	Y	Y	Y	Y	Y	x
A. implexa	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
A. mearnsii	x	Y	Y	Y	Y	x	Y	Y	Y	Y	Y
A. melanoxylon	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	x
A. parramattensis	Y	Y	Y	Y	Y	Y	x	Y	x	Y	x
A. rubida	Y	Y	Y	Y	Y	Y	Y	Y	x	Y	x
A. terminalis	Y	Y	Y	Y	Y	Y	x	Y	x	x	x
***Allocasuarina** littoralis*	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
A. verticillata	Y	Y	Y	x	Y	Y	Y	x	Y	Y	x
***Angophora** floribunda*	x	x	x	Y	Y	Y	x	Y	x	Y	Y

Banksia *marginata*	x	Y	Y	Y	Y	Y	Y	Y	x	Y	x
Brachychiton *populneus*	x	Y	Y	Y	Y	Y	Y	Y	x	Y	Y
Bursaria *spinosa*	x	Y	Y	Y	Y	Y	Y	Y	x	Y	x
Callistemon *citrinus*	Y	x	Y	Y	Y	Y	x	Y	x	Y	x
C. pityoides (**M**)	x	x	Y	x	Y	x	x	Y	x	x	x
C. sieberi	x	x	Y	Y	Y	Y	Y	Y	Y	Y	x
Callitris *endlicheri*	x	x	Y	x	Y	x	Y	Y	x	Y	Y
Cassinia *longifolia*	x	x	Y	x	Y	x	Y	Y	Y	x	x
Casuarina *cunninghamiana*	x	Y	Y	Y	Y	Y	Y		Y	Y	Y
Eucalyptus *agglomerata*	x	x	Y	Y	Y	Y	x	Y	x	Y	x
E. bridgesiana **M**	Y	x	Y	Y	Y	Y	x	Y	x	Y	x
E. elata **M**	x	Y	Y	Y	Y	Y	Y	Y	x	Y	x
E. eugenioides	x	x	Y	Y	Y	Y	x	Y	x	Y	x
E. globoidea **M**	x	x	Y	Y	Y	Y	x	Y	x	Y	x
E. goniocalyx	Y	x	Y	Y	Y	Y	Y	Y	Y	Y	x
E. macrorhyncha	Y	x	Y	Y	Y	Y	Y	Y	Y	Y	x
E. melliodora	Y	x	Y	Y	Y	Y	Y	Y	Y	Y	Y
E. obliqua	x	Y	x	Y	Y	Y	Y	Y	Y	x	x
E. rossii **M**	x	x	Y	Y	Y	Y	x	Y	x	Y	x
E. sieberi	Y	Y	Y	Y	Y	Y	x	Y	x	x	x

E. tereticornis	x	x	Y	Y	Y	Y	x	Y	x	Y	Y
E. viminalis **M**	x	x	Y	Y	Y	Y	Y	Y	Y	Y	x
Grevillea *arenaria*	x	x	x	x	x	x	Y	x	x	Y	x
Hakea *dactyloides*	x	Y	Y	x	Y	Y	x	Y	x	Y	x
H. eriantha	x	x	Y	x	Y	x	Y	Y	x	x	x
Leptospermum *brevipes* **M**	x	x	Y	x	Y	Y	x	x	x	x	x
L. morrisonii	x	x	x	x	x	x	as hybrid x spectabile	x	x	x	x
Melicytus *dentatus*	x	x	x	x	Y	x	Y	x	Y	x	x

APPENDIX 6: SEED PROVENANCE ANALYSIS

Supplementary documents: Seed provenance analysis for 25 species and four subregions in the Upper Shoalhaven region (Araluen, Braidwood, Coastal Scarp, West of Divide). Provided as four excel files.

To request supplementary documentation contact Upper Shoalhaven Landcare Council at 42 Ryrie st Braidwood, NSW 2622 or email upper.shoalhaven@gmail.com.

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Landcare New South Wales

Australian Government

Upper Shoalhaven Landcare Council