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A Strategy to Develop a Low Rainfall Breed of *Pinus radiata*

– the Australian Low Rainfall
Tree Improvement Group

A report for the RIRDC/Land & Water
Australia/FWPRDC
Joint Venture Agroforestry Program

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Foreword

Growing interest in farm forestry in the 400–600 mm rainfall, sheep-wheat belt of southern Australia has prompted a cooperative national effort to select and breed better trees for this region. Tree planting can help control dryland salinity — a result of rising water tables — and reduce soil erosion. Rates of planting are likely to increase if farmers can choose trees that will also provide a worthwhile economic return. Selection and breeding will boost the benefits of tree planting by increasing yields of high quality timber or leaf oils.

This report outlines a strategy to develop a low rainfall breed of radiata pine (*Pinus radiata*). Radiata pine is the most widely accepted species in the timber trade in southern Australia, and forms the raw material for several commercially valuable products. Development of a low rainfall breed would enable expansion of the plantation estate into new areas. The breeding strategy has been developed by the Australian Low Rainfall Tree Improvement Group (ALRTIG). The group is a collaborative undertaking involving researchers from State agencies and CSIRO. ALRTIG aims to speed up the process of tree improvement by coordinating efforts across southern Australia.

This project was jointly funded by the Natural Heritage Trust, and the Joint Venture Agroforestry Program (JVAP), which is supported by three R&D Corporations — Rural Industries Research and Development Corporation (RIRDC), Land & Water Australia, and Forest and Wood Products Research and Development Corporation (FWPRDC), together with the Murray-Darling Basin Commission (MDBC). The R&D Corporations are funded principally by the Australian Government. State and Australian Governments contribute funds to the MDBC. Significant financial and in-kind contributions were also made by the project partners: CSIRO Forestry and Forest Products; Department of Conservation and Land Management, WA; Department of Sustainability and Environment, Victoria; and Primary Industries Trading, New South Wales.

This report, a new addition to RIRDC's diverse range of over 1600 research publications, forms part of our Agroforestry and Farm Forestry R&D program, which aims to integrate sustainable and productive agroforestry within Australian farming systems. The JVAP, under this program, is managed by RIRDC.

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Executive Summary

What the report is about

This report outlines a strategy for developing a breed of low rainfall radiata pine (*Pinus radiata*). The new breed would be suitable for expanding the radiata planting estate into warmer, drier areas than those to which the existing breeds of radiata developed in Australia and New Zealand are currently adapted. The strategy aims to create a new breed possibly based on the previously untapped Mexican island and Cambria provenances.

Who is the report targeted at?

This report will be of use to researchers and forest industry staff interested in the future opportunity to plant radiata pine in low to medium rainfall zones.

Background

Radiata pine wood forms the raw material for several commercially valuable products and it is the most widely accepted species in the timber trade in southern Australia. It is mainly grown in the high rainfall zone (i.e. greater than 650 mm mean annual rainfall), though expansion of the resource in this land base is becoming increasingly restricted due to competing land uses. The natural distribution of *P. radiata* spans a significant range of mean annual rainfall and climatic variation. Although there are five provenances of *P. radiata*, the Australian and New Zealand breeds are based nearly entirely on Monterey and Año Nuevo provenances respectively. This material has proven to be extremely adaptable to a very wide range of climate types, and in Australia, both breeds have been planted on a significant scale for commercial purposes on sites ranging from high rainfall down to less than 600 mm mean annual rainfall in parts of New South Wales, Tasmania, Victoria, South Australia and the Australian Capital Territory. Most successful plantations of the species are in the higher rainfall areas.

Production of a more drought-resistant breed with satisfactory growth rates and yields would allow pine to be grown in low to medium rainfall zones away from the coast, where new tree crops are sought for commercial and environmental purposes. In such drier areas, seasonal dry spells and occasional protracted droughts are likely to be experienced. The Guadalupe and Cedros Island sites have the lowest mean annual rainfall of the five provenances and Cambria the next lowest and so these three drier climate provenances may have traits that are expected to contribute towards a breed with greater drought resistance.

The Australian Low Rainfall Tree Improvement Group (ALRTIG) is a collaborative undertaking involving researchers from State agencies and CSIRO, with supporting funding from the Joint Venture Agroforestry Program. ALRTIG aims to speed up the process of tree improvement for low to medium rainfall zones, by coordinating efforts across southern Australia.

Aims/Objectives

To devise a breeding strategy for developing a new breed of radiata pine, suitable for expanding the estate into warmer, drier areas than those to which the existing breeds are currently adapted. The new breed will have broadly similar wood properties and end-uses to the existing breeds, and will be suitable for processing by existing infrastructure.

Methods used

In developing the strategy, the ALRTIG softwood technical committee reviewed the literature regarding radiata pine's adaptability, genetic variation, drought tolerance and provenance performance. A strategy was then developed which outlines the source material to be used, and the timing and sequence of breeding work to select for low-rainfall tolerant traits.

An important initial assumption is that material from *radiata*'s drier Mexican provenances (Cedros and Guadalupe) and Cambria, in California, might be a good source of drought resistant material for integrating into the low rainfall breed. The likelihood of this assumption being valid is discussed based on an examination of the literature on other pine species that have been grown in plantations in low rainfall environments.

Results/Key findings

Within-species variation in physiological and growth response to drought has been found in most conifers studied. Drought tolerance (rather than drought avoidance) is a variable trait in some *Pinus* species at both the provenance and family-within-provenance levels. Few trials have tested all five *P. radiata* island provenances on sites below 700 mm mean annual rainfall in Australia. In higher rainfall sites in New Zealand the two northern provenances (Año Nuevo and Monterey) grew best followed by Cambria. In a trial at Wirrabara north of Adelaide, Guadalupe families ranked highly for size and vigour compared with other provenances. Cedros provided a low proportion of dominant trees, but was by far the most resistant to *Ips* attack. The review concluded that *P. radiata* would appear not to be strongly variable between provenances in drought tolerance, but had not extensively studied. Therefore, trials to test for family and provenance variation in drought tolerance and/or drought avoidance were a high priority.

The strategy which has been developed will involve a number of components:

- preliminary screening of a selection of material for genetic variation in drought resistance;
- establishment of longer-term field trials on target site types;
- formation of a breeding population using stored seed and controlled-crosses using existing stands, and
- later on, possible integration of new drought resistance genes through interspecific hybridisation.

Results from early-established trials will guide the strategy as time progresses.

The breeding program will be based on recurrent selection, and managed as a separate breed from the existing New Zealand and Australian genetically improved populations.

Implications for relevant stakeholders

The strategy is intended as a starting point for a program that will take significant time and effort to implement. Preliminary work has been undertaken as part of ALRTIG to implement the strategy, including establishment of trials and controlled crossing.

Recommendations

Initial work is to concentrate on establishing a breeding population, selection from existing conservation stands of *P. radiata* provenances showing promise, establishment of trials for drought tolerance/avoidance, and controlled crossing.

The strategy should be reviewed periodically as results from early screening work and longer-term field trials become available.

1. Background

Radiata pine (*Pinus radiata*) wood forms the raw material for several commercially valuable products and it is the most widely accepted species in the timber trade in southern Australia. Most radiata pine plantations exist in the high rainfall (i.e. greater than 650 mm) mean annual rainfall (MAR) zone, within which capable and suitable land is becoming increasingly expensive. Also, other land-uses including irrigated and rain fed agriculture, urban development and hardwood (particularly *Eucalyptus globulus*) plantation developers are targeting parts of the high rainfall potential radiata land-base.

In addition, climate models (e.g. CSIRO 2001) predict warmer temperatures and lower rainfalls in south-western Western Australia and much of south-eastern Australia. A few existing plantations (e.g. at Longford, Victoria, near Naracoorte, South Australia and at Kowen, Australian Capital Territory) show radiata pine can grow profitably in areas with less than 600 mm MAR and that it should be possible to extend the boundary of the zones where the species will grow successfully further into the dry country.

What is needed is a new breed of radiata pine, better adapted to longer dry periods than the existing, genetically improved, routinely deployed Australian and New Zealand germplasm. The new breed could be used to extend the southern Australian softwood estate beyond the existing warm-dry climatic limits and/or maintain the existing estate in the advent of adverse climate-change.

The Southern Tree Breeding Association (STBA) in Australia and the New Zealand Radiata Pine Breeding Company (NZRPBC) have both focused on breeding radiata suited to the better quality sites but not for the lower rainfall sites. The opportunity to develop a new breed suited to lower rainfall sites was identified by ALRTIG (Australian Low Rainfall Tree Improvement Group) which is a partnership between State and Commonwealth Government forestry organisations and the Joint Venture Agroforestry Program (JVAP). ALRTIG has the brief to develop genetically improved seed and make it available for growing in low rainfall areas. As part of this, it will embark on a program to develop radiata pine suited to sites with <650mm MAR. An update on ALRTIG progress with genetic improvement for a range of low rainfall species is provided in Bush et al. (2007).

2. Strategy overview

The proposed strategy is to create a low rainfall breed of radiata pine. The following issues are dealt with in subsequent sections:

- 2.1. Characteristics of the new breed
- 2.2. Why not use another species?
- 2.3. Adaptability of radiata pine
- 2.4. Genetic variation in drought-hardiness in *P. radiata* and other pines
- 2.5. Relative performance of provenances of *P. radiata*
- 2.6. How will the new breed relate to existing genetically improved radiata?

2.1. Characteristics of the new breed

The new low rainfall (LR) breed of radiata will be physiologically better adapted to handle longer periods of water stress than other Australian radiata. This adaptation is expected to be through increased physiological drought resistance¹, which is a result of either drought avoidance or drought tolerance. Genetic variation for the latter has been observed in radiata pine (Sands *et al.* 1984) and differences in seasonal growth patterns have also been observed (Matheson *et al.* 1995, D. Kain, unpublished Honours thesis, ANU). This means that the prospects for successful selection are favourable in the field trials we propose as part of this breeding strategy. We note that if avoidance is the principal means of adapting to drought, it will result in reduced growth. We plan to be pragmatic, selecting individuals for further breeding that combine superior growth and survival in field trials established on dry sites representative of the target planting zone.

In other respects, we expect LR radiata to have broadly similar characteristics to radiata routinely grown in Australia. We envisage that the LR radiata will be grown primarily for sawlogs, with residual wood being sold for pulpwood and production of fibre products. This will allow similar silvicultural management regimes and integration of LR radiata feedstock into existing radiata processing infrastructure and markets.

2.2. Why not use another species?

Alternatives to *P. radiata* for low rainfall country are being pursued by ALRTIG and others. ALRTIG has commenced domestication and breeding of a number of hardwood (*Corymbia maculata*, *Eucalyptus camaldulensis*, *E. cladocalyx*, *E. occidentalis*, *E. tricarpa*, *E. sideroxylon*, and one softwood species (*P. brutia*) and have also tested *P. pinaster* bred by Forest Products Commission Western Australia across a range of low rainfall sites in southern Australia. These species are all known to be intrinsically drought-hardy. This has allowed concentration of breeding effort on accumulation of genetic gain in growth, form and apparent disease resistance traits, without having to try to breed for drought stress resistance. This is a considerable advantage to tree breeders, as growth, form and even wood property traits (to be examined later in the abovementioned species) are relatively simple to measure and select for, compared with traits such as drought avoidance, drought tolerance and water use efficiency, which might be associated with overall ‘drought-hardiness’.

However, there are a number of down-sides to starting with these intrinsically drought-hardy species:

¹ Drought stress resistance is defined here *sensu* Levitt (1980). Drought resisting plants are sub-defined as: (1) drought avoiders, those that avoid low Ψ_{cell} (cellular water pressure) by mechanisms such as stomatal closure and; (2) drought tolerators - those plants that tolerate some degree of tissue desiccation caused by low Ψ_{cell} through various mechanisms.

1. Growth rates are nearly always lower than species such as *P. radiata* and *E. globulus* on sites suitable for these species;
2. Many of the species have serious form problems that will need to be significantly improved to make commercially acceptable breeds (*Corymbia maculata* is an exception and *P. pinaster* has been very significantly improved already); and
3. Very little is known about the commercial acceptability of many of the species, particularly the hardwoods. Sawing properties, solid wood stability and high density are particular issues that might have to be addressed. While *P. pinaster* and *P. brutia* are sawn commercially overseas and *P. pinaster* in Western Australia, they are not as widely acceptable to Australian industry as *P. radiata*.

ALRTIG has therefore decided to pursue the creation of a low rainfall breed of *P. radiata* as well as the strategy common to the already drought hardy species. It is envisaged that a low rainfall breed of *P. radiata* would be readily adopted by industry which already has suitable processing facilities, particularly at the warm-dry fringe of the existing radiata plantation estate.

2.3. How adaptable is radiata pine?

Most of what we know about the adaptability of radiata pine is based on plantings of Australian and New Zealand material. This has a narrow genetic base compared with the entire base population. The full range of material from the base population has not been extensively tested in low rainfall environments. However, we assume that we are likely to be able to create a new breed of radiata pine that is better adapted to low rainfall environments and will yield products similar to existing radiata pine. The rainfall zone being targeted is the 500-650 mm rainfall zone.

There are only five natural provenances of radiata pine (*Pinus radiata* D. Don); Año Nuevo, Monterey and Cambria in California and the Mexican islands of Guadalupe and Cedros. Introductions into Australia and New Zealand during the 19th century led to landraces consisting predominantly of Monterey in Australia (although there is some Año Nuevo as well) and Año Nuevo in New Zealand (although there is some Monterey as well). These are called landraces because they have been subject to both natural and artificial selection away from their natural range. Existing breeding efforts have been based on selected descendents of these two provenances imported about 1860; breeders have largely avoided the broader genetic material available in the species as a whole (Moran and Bell 1987). Material from all five natural provenances as well as from improved populations is available (Eldridge 1978) to form a suitable base population for selection and breeding for drier areas.

The Australian and New Zealand landraces of radiata pine, consisting of Año Nuevo and Monterey provenance material have proven to be extremely adaptable to a very wide range of climate types. In Australia, both landraces have been planted on a significant scale for commercial purposes from high rainfall, greater than 1500 mm MAR in Tasmania and Victoria, down to less than 600 mm MAR in parts of Victoria, South Australia and the Australian Capital Territory although most successful plantations of the species are in the higher rainfall areas.

The natural distribution of *P. radiata* spans a significant range of MAR. However, it never occurs more than a few kilometres from the Pacific Ocean. The cold waters of southward-flowing currents result in high humidity, moderate temperatures, and summer fogs. The Guadalupe and Cedros Island sites have the lowest MAR of the five provenances and Cambria the next lowest (Table 1) and so these three drier climate provenances may have traits that are expected to contribute towards a breed with greater drought resistance. Mean daily temperatures along the Californian coastline increase towards Mexico, which would also

tend to drive pan evaporation up and water availability down. The trees on Guadalupe Island occur at high altitude (1200 m above sea level), which is likely to counter this effect to some extent.

Table 1. Climate data for P. radiata provenances

Provenance	MAR (mm)	Pan evaporation (mm per annum)	Temperature (mean max. hottest/coldest month) °C
Año Nuevo (Santa Cruz)	756	1270	25.1/14.7
Monterey (Del Monte)	450	1270	22.2/14.7
Cambria (San Luis Obispo, Poly)	540	1400	25.3/16.8
Cedros Island (San Fernando, Ensenada 200 km N. of Cedros Is.)	96	1888	35.2/20.9
Guadalupe Island (marine garrison, S. tip of island.)	124	No data	24/19

The overall interaction of fog drip - that can be so significant as to form pools (Eldridge 1978) – rainfall, temperature and other microclimatic and soil physical property variables is difficult to ascertain from the available data. However, the island provenances are likely to be growing in harsher environments than the Californian mainland ones. The pine stand on Guadalupe Island occurs on an almost bare volcanic rockfield with rather depauperate vegetation; the vegetation on Cedros Island is an extension of the Sonoran desert flora (see Rogers *et al.* in press).

None of the natural provenances have been extensively tested in the target rainfall zone and selection of trees for the previous breeding programs was based on trials in higher rainfall locations. No Cambria or Cedros material and only one Guadalupe tree is included in the current highly selected breeding populations or seed orchards or mass produced cuttings. It is also possible that trees in the Año Nuevo and Monterey base populations that were not selected for the previous breeding programs may contribute genes to suit our purpose and some elite trees themselves may have high tolerance to drought.

2.4. Genetic variation in drought resistance in *P. radiata* and other pines

An important element of this strategy is based on the assumption that radiata material sourced from places that are drier than the original sources of the existing Australian and New Zealand base populations will be a potential source of genes on which to base a new breeding population. What is the evidence for intraspecific genetic variation in drought hardiness within *P. radiata* and other conifer species?

2.4.1. Drought avoidance

Drought avoidance is a common form of drought resistance in conifers: stomatal control is the most commonly reported mechanism. Lebourgeois *et al.* (1998) contend that drought avoidance as evidenced by stomatal closure in response to Ψ_s (soil water potential) is a common feature of Mediterranean pines including *P. uncinata*, *P. pinaster* and *P. sylvestris*. Buxton *et al.* (1985) also report drought avoidance in North American boreal conifers (*Picea glauca*, *P. mariana* and *Pinus banksiana*), though the onset (in terms of needle water pressure deficit) varies between species.

Relatively little research has been directed towards assessing drought hardiness parameters in *P. radiata*, perhaps because there have been, up until recently, relatively abundant sites available in Australia and New Zealand free from significant drought. Dean and Sands (1983) measured drought avoidance characters in five, one year-old, pot-grown families of *P. radiata*. The families were selected to represent the wet and dry ends of the species' range:

two were from Guadalupe, two from Point Año Nuevo and one was from the Australian landrace. Parameters studied included stomatal resistance (r_s) and needle water potential (Ψ_n) in response to induced soil water deficit (Ψ_s – which was lowered from -0.01 MPa to -1.0 MPa) and varying vapour pressure deficit. There were no between-family differences in r_s response, though the Australian landrace family had significantly lower Ψ_n than the other families at both well-watered and low Ψ_s conditions. The study did not, therefore, support the hypothesis that seedlings from the drier Guadalupe provenance had greater drought avoidance ability relative to Año Nuevo material.

In contrast to this finding, Calamassi *et al.* (2001) found that Ψ_n response to levels of Ψ_s ranging between 0 and -1.6 MPa was closely related to the climatic origin of eight provenances of *P. halepensis* seedlings under test. Plants from four more-xeric provenances initially had lower Ψ_n values than the four from milder climates (values ranged from -1.26 to -0.7 MPa; c.f. Dean and Sands (1983) result for *P. radiata* which was -1 MPa under equivalent conditions). However, in the four xeric provenances, Ψ_n dropped less in response to drought (i.e. when Ψ_s was decreased below -1.2 MPa). Interestingly, the drought avoidance response was not fully evident in this species at less severe Ψ_s values above -1.2 MPa: Dean and Sands (1983) used a single value of Ψ_s = -1.0 MPa in their study on *P. radiata*. Further investigations would be needed to confirm whether *P. radiata* provenances have a differential response to pressure deficits similar to that recorded by Calamassi *et al.* (2001).

The drought avoidance strategy identified for *P. halepensis* has also been recorded in *P. nigra* ssp. *laricio* (black pine). Lebourgeois *et al.* (1998) studied drought avoidance in two varieties, *P. nigra* ssp. *laricio* var. *Corsicana* and *P. nigra* ssp. *laricio* var. *Calabrica*. Both of these varieties originate from hot, dry, Mediterranean climates. They found no differences in response to drought between the two varieties, but confirmed that both did exhibit a drought avoidance strategy, with Ψ_n dropping in response to drought stress in much the same manner as was reported by Calamassi *et al.* (2001) for *P. halepensis*, though the response onset at lower stress levels in the *P. nigra*.

2.4.2. Drought tolerance

A number of studies have investigated genetic variation in drought tolerance of *Pinus* spp. Generally, the evidence suggests that selection of genetic material sourced from drought-prone provenances can be a successful strategy for breeding material which will survive on drought-prone plantation sites. The fact that it has been possible to select material that survives well without sacrificing growth also implies that drought tolerance (as distinct from drought avoidance) is a variable trait in some *Pinus* spp. at both the provenance and family-within-provenance levels.

Loblolly pine

Zobel and Goddard (1955) and Goddard and Brown (1959) studied *P. taeda* (loblolly pine) from the species' natural range at seven droughty sites in east Texas. They found that material from the “Lost Pines” region (a population 160 km disjunct from the relatively dry, westerly part of east Texas) significantly outperformed provenances from higher rainfall ecotypes, and had equivalent growth. Van Buijtenen (1966) found that there was significant family-within-provenance variation in seedling drought tolerance of open-pollinated families from the Lost Pines, as indicated by an experiment whereby field-grown seedlings were deprived of rain by the erection of shelter until the onset of mortality. Subsequently, material from the Lost Pines population was incorporated into the *P. taeda* breeding population for use in the droughty western fringe of the east Texas loblolly pine planting zone (Rahman *et al.* 2003). The finding

that drought tolerance variation exists between and within provenances for loblolly pine, and that the more drought tolerant families are sourced from the drier ecotypes is encouraging for the strategy of selection from the drier provenance of *P. radiata* proposed here.

Maritime pine

Maritime pine (*P. pinaster*) originates from diverse climates in south-western Europe and Africa. Hopkins (1971) conducted a series of studies on the effects of soil moisture deficit on seedlings from a range of *P. pinaster* provenances, genetically improved *P. pinaster*, and *P. radiata*, *P. brutia* and *P. elliottii*. The studies showed that *P. pinaster* from hotter, drier climates (Corsica, Tunisia and Leiria, Portugal) was more drought resistant than that from the relatively mild French Atlantic coast. He also confirmed that *P. brutia* was by far the most drought resistant, followed by *P. pinaster*, with *P. radiata* and *P. elliottii* being markedly less resistant. An interesting finding was that the most drought resistant of the *P. pinaster* was the genetically improved material (mostly sourced from Leiria). Hopkins and Butcher (1993) confirmed and expanded Hopkins' earlier findings through a large series of provenance trials: under Western Australian plantation conditions, *P. pinaster* exhibits marked variation between provenances in a variety of characters, including growth, stem form, apical dominance and resistance to drought and cold stress. Drought resistance was determined by analysis of the provenance trials across a range of sites in a severe drought year which caused a mortality differential between provenances. They found that the Leirian provenance (from Portugal) is significantly more vigorous and more drought resistant than either Corsican or Landes material, a finding that may indicate a drought tolerant physiology. Once again, the Leirian-based genetically improved material was shown to be the most drought resistant. This finding may well indicate a drought tolerance mechanism in *P. pinaster*, whereby growth is not impaired by periods of moisture stress.

Corroborative evidence for between-provenance variation in *P. pinaster* water use comes from Fernandez *et al.* (1999), who showed that Landes material from the Atlantic race uses water more profligately early in the growing season than provenances from the Continental race (Spanish provenances), leaving it less able to cope with summer drought. Other research on this species has sought to identify water stress-responsive genes using molecular genetic screening techniques, with some encouraging early success (Dubos *et al.* 2003).

Ponderosa pine

P. ponderosa is the most widely distributed pine species in North America, and studies have shown significant variation between provenances and ecotypes (e.g. Van Haverbeke 1986) and that selection of material from appropriate ecotypes (e.g. dry, cold ecotypes for dry, cold plantation sites) is a successful strategy for ensuring survival and acceptable growth (Van Deusen 1980). However, Cregg (1994) found that while there was significant within and between-provenance variation in survival of *P. ponderosa* seedlings in response to experimentally induced drought stress, this was poorly correlated with climatic indices of the seed sources.

2.4.3. Conclusion – drought resistance

Within-species variation (both between and within provenance) in physiological processes and growth in response to drought has been found in most conifers studied (particularly those commercial species, most of which have quite wide natural ranges, for which breeding programs exist). While *P. radiata* has not been extensively studied, it would appear not to be strongly variable (between provenances) in drought avoidance as indicated by measurements of Ψ_h at low to moderately high levels of soil moisture deficit. However, no specific experiments on drought tolerance variation between provenances appear to have been conducted. Such experiments in other important commercial species (e.g. *P. taeda* and *P. pinaster*) have shown that drought tolerance is variable both between and within

provenances, and that the low rainfall provenances generally seem to be the source of the most drought tolerant material. There are apparent discrepancies, for example the case of *P. ponderosa*, where field studies support the generalisation, but seedling-based experiments contradict it.

One of the difficulties with interpreting the practical significance of studies which involve potted, seedling, or hydroponically grown material is interpreting how levels of imposed stress relate to mature trees growing on the actual site conditions of interest. While plants are often characterised as drought avoiders or drought tolerant, these terms must be taken in a relative context. In fact, all conifers will close stomata, and all will tolerate some level of tissue desiccation both prior to stomatal closure and after. While it may be possible to screen seedlings and identify physiological drought resistance mechanisms through such experimentation, the best indications can come only from survival and growth measurements of genetics trials established on a trial site throughout a rotation length. The Hopkins and Butcher (1993) report of opportunistic measurements of Western Australian provenance trials that had been established on target plantation sites and that experienced a severe drought at age 15 is one of the few reported results that fall into this category. The establishment of such trials for *P. radiata* is therefore a high priority. However, there may also be value in conducting preliminary screening studies (following on from Dean and Sands 1983) to determine whether any indications of drought tolerance and/or drought avoidance can be identified.

2.5. Performance of the provenances

Most of what is known about the performance of *P. radiata* at the provenance level has been determined through provenance and/or provenance-progeny trials carried out on high rainfall sites representative of the plantation base where plantations are currently established. Between 1933 and 1994, 67 provenance trials and genetic resource plantings were established using seed collected from the five native provenances (Eldridge 1998b). Results from New Zealand suggest that the two northern mainland provenances (Año Nuevo and Monterey) grow best there, followed by Cambria with the two Mexican island populations growing slowest (Burdon *et al.* 1992). Less comprehensive results from Australia confirm this, particularly for the three mainland provenances (Garnier-Géré *et al.* 1997, Johnson *et al.* 1997).

Very few provenance trials involving all five of the island provenances have been established on sites receiving below 700 mm MAR in Australia. Boardman and McGuire (1997) report on a provenance-progeny trial at the 'warm-dry limit of the potential range' situated at Wirrabara, north of Adelaide in South Australia where the MAI is 660 mm and pan evaporation is 1900 mm. In this trial, Guadalupe families ranked highly for size and vigour compared with the other provenances and a genetically improved control at eleven years: in fact Guadalupe families provided 50% of the tallest trees. However, while Cedros provided a very low proportion of dominant trees, it was by far the most resistant to *Ips* attack.

Elite trees from the Wirrabara trial (the top 15 based on a P+9-year index selection for vigour and form from 2340 planted) were selected and grafted into Scrimshaw's seed orchard. Open pollinated progeny of these selections were used in family yield trials established at three sites in the upper south-east of South Australia. These trials again showed that certain Guadalupe families can perform well on drier sites. Five years after planting Guadalupe families were ranked equal or better with the genetically improved routine control in terms of volume growth (ForestrySA unpublished data).

2.6. How will the new breed relate to existing genetically improved radiata?

The LR radiata will be managed as a breed separate from the existing New Zealand and Australian genetically improved populations. The Australian and New Zealand populations are owned and controlled by separate breeding organisations, and remain focused on producing genetically improved material for high rainfall plantations. This will allow either or both of two separate strategies to be pursued:

- (1) Deployment of material directly from a LR radiata propagation population
- (2) Hybridising LR radiata with Australian or New Zealand radiata and deploying the hybrids.

These alternatives are discussed further in Section 4 which addresses the Breeding Strategy.

3. Implementing the overall LR radiata strategy

A number of steps need to be taken to create the LR radiata breed. Some steps relate to checking the genetic variation for drought resistance traits in radiata, others to the accumulation of genes conferring drought resistance: the actual breeding strategy. Some of the steps can be implemented immediately and carried out in parallel. Others follow sequentially from predecessors. Some of the activities are optional and could be carried out as the need arises in future. The overall strategy consists of five main activities:

1. Drought resistance screening of young trees

The objective of this activity is to ascertain whether there is within-species variability in drought resistance traits in *P. radiata*. The method of assessment will probably be based on young material grown in pots, and may include the following components:

- (i) Assessment of seedling survival in response to imposed drought
- (ii) Water use efficiency measurements
- (iii) Measurements of physiological parameters such as stomatal control in response to water stress, following on from the work of Dean and Sands (1983).

Drought resistance screening (pot trials measuring response to induced water stress) was successfully used to identify drought resistant genotypes of *P. pinaster* (Hopkins 1971). There are dangers of extrapolating data from pot trials to field situations although results from seedling trials were confirmed in a very general way in long-term trials for *P. pinaster* (Hopkins and Butcher 1993). We advocate reinforcing the data with that from longer-term field performance testing.

Priority: medium-high

Timing: within 2 years of commencement of strategy

2. Drought resistance: field performance testing

The objective of this activity is to field-test various genetic materials over the longer-term to determine whether or not there are differences in drought hardiness. Droughts may occur infrequently at marginal sites situated at the fringes of the existing Australian *P. radiata* estate; perhaps only once per rotation. It will therefore be necessary to examine material over a time frame of more than half a rotation. Such field trials can double as provenance-progeny trials forming part of the *base population* (see section 4.2. for definition of terms).

Priority: high

Timing: initial trials to commence in second year of program

3. Selection and mating

The selection and mating activity is covered in detail in the breeding strategy (next) section of this document. This is essentially the activity that will accumulate genes conferring greater drought resistance and thereby produce the low rainfall radiata breed. This activity will be guided by information sourced from activities 1 and 2 as it becomes available.

Priority: high

Timing: Selection activity to commence immediately; inter-provenance crossing to commence in second year of program

4. Inter-specific hybrid exploration

It may be useful to test the feasibility of hybridising *P. radiata* with other drought resistant species. The aim would be to create a hybrid that has good vigour and wood properties similar to those of *P. radiata*, with drought resistance properties of another parent. The scope for this activity is discussed further in Section 4.8.

Priority: medium

Timing: initial work to test hybrid feasibility to commence within two years: could be delayed.

5. Molecular genetic 'stress gene' identification

Using molecular genetic techniques, it may be possible to identify genes controlling particular aspects of *P. radiata*'s stress physiology response. Such work has already been commenced in *P. pinaster*. This step might be attempted in future, should the financial benefits be likely to outweigh the costs. The results of the work might include ways to rapidly and cost-effectively screen material and/or scope for genetic modification of material.

Priority: lower

Timing: Later. Work from other species could possibly be adapted to *P. radiata* as a cost-effective approach

4. The breeding strategy

4.1. Breeding strategy elements

The breeding strategy is the core of the overall LR radiata strategy. The proposal is to create a new LR breed of radiata. This will be managed separately from existing breeds of radiata (such as the Australian breed and the New Zealand breed), at least initially, but could conceivably interact with these breeds in future.

In summary, the breeding strategy will involve the following steps:

1. Base population definition
2. First LR radiata breeding population developed
3. Short-term seed supply from selected conservation stands of provenances showing promise in field trials (Seed Production Areas).
4. Controlled crosses performed on best-bet selections for creation of improved breeding population
5. Selection from within the first generation breeding population plus infusion of new material from the base and possibly other populations in subsequent generations.

Field trial results (and data from other components of the overall strategy such as physiological data from drought trials) will eventually shape the breeding population. It may also be desirable to integrate material from the breeding populations of existing genetic improvement programs (under agreement with their owners), and/or interbreed LR radiata with other genetically improved radiata for production of the deployment population. In the longer term, it may be possible to introduce useful genes from other species through a program of interspecific hybridisation.

4.2. Definition of terms

Tree improvement programs aim to develop plantation stock superior to their predecessors in one or several key economic traits. In this case, the traits of interest are those related to drought resistance. The overall program is based on an *improvement strategy*, which is implemented through an *improvement plan*. Each is further defined in the following sections (after Eldridge *et al.* 1993).

Improvement strategy (a conceptual plan) - the framework of ideas, the conceptual overview, or philosophy of the management of genetic improvement of a tree species used in plantations. Its essential elements are:

- (a) population improvement by a combination of a particular type of selection and a particular type of mating, starting with a well adapted broad genetic base, and
- (b) an efficient system for mass propagation of outstanding selected individuals either as seed or cuttings.

Improvement plan – the first step is to decide which Breeding Strategy (particular combination of selection and mating) will provide the greatest genetic gain per decade at an acceptable cost for a particular plantation program, and involving appropriate methods of mass propagation. The next step is to prepare a detailed Improvement Plan to implement the Strategy. Typically the plan includes a set of objectives and a flow chart of what is to be done each month for several years ahead and is subject to regular revision, every 2-5 years (Eldridge *et al.* 1993).

As a recurrent process, a breeding strategy accumulates benefits over successive generations of a cycle of testing, selection and mating (Figure 1). Every effective breeding strategy

involves the maintenance of a hierarchy of four major types of population which are summarised as follows:

Base population - The base or gene resource population for *P. radiata* can be considered to consist of two components: the natural forests in California and the Mexican islands, and the *ex situ* plantings in Australia, New Zealand, South America and certain other places in the world. In the first instance, the *ex situ* populations (particularly Australia) will be the primary source of selection, because of difficulty in accessing the native stands and the risk of importing pitch canker (*Fusarium circinatum*) infected seed into Australia. However it may also be possible to broaden the base by raising seed that has been kept in storage from the 1978 collection (Eldridge 1978). These places in which initial selection can be carried out will continue to be a source of a wide range of genetic variation to meet future needs.

Infusion

Introduction of material from the base population into the breeding population after the initial selections have been made is referred to as infusion. It is standard practice to infuse material to ensure adequate genetic diversity and to add new-found superior selections. In the case of LR radiata it may be possible to infuse improved material from the breeding populations of other radiata breeds (under agreement with their owners).

Breeding population – This consists of the selected trees and their progeny in a series of progeny trials and possibly clonal archives in which the breeding cycle of selection and mating will be repeated over many generations. This is the tree breeder's main area of work.

Propagation population – This is the intensively selected trees (commonly fewer than 100 selected trees) propagated in seed orchards or cuttings multiplication areas where the combinations of genes selected in the breeding population are mass produced as genetically improved planting stock.

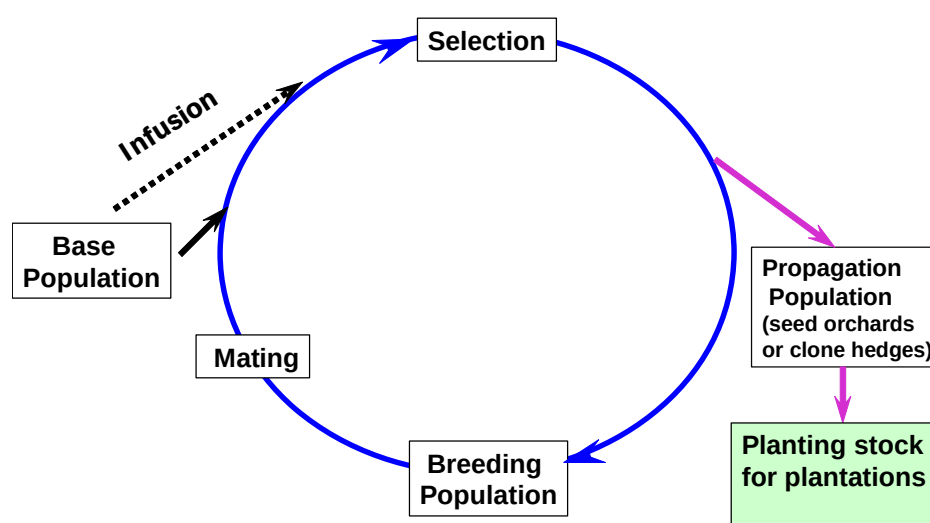
Production population - The major plantation areas established using the improved germplasm constitute the production population.

The process shown in Figure 1 is that used to develop the Australian and New Zealand breeds of radiata, and will be used to develop LR radiata.

Selection and Mating - are key activities in breeding. The process accumulates genes, influencing yield and adaptation over successive generations so that their frequency and that of superior trees continues to increase. Every successful breeding strategy, therefore, requires efficient methods of selecting superior material in the progeny tests and elsewhere, appropriate measurement techniques and selection technology (e.g. selection indices). Mating can be done by open pollination or controlled pollination.

In pursuing the principal functions of efficient selection and mating, a strategy should aim to assess the variation within a species, generate genetic information about it and see that genetic resources for future selection are conserved.

Figure 1. Generalised activity cycle for tree improvement



4.3. Breeding objective

The objective will be to produce a breed of radiata pine to maximise profit per unit area per unit time when grown on sites that are somewhat drier than those where the Australian and NZ landraces are presently deployed. The LR radiata will be physiologically better adapted to such sites (in terms of both survival and wood volume yield per ha) than currently used radiata material. LR radiata will also have stem form suited to production of sawn timber with minimal silvicultural inputs. Maximised production of sawn timber per unit area per unit time with minimised risk of stress-related damage or mortality will be the basis of our overall strategy. We recognise that vigour under dry conditions is likely to be less than elsewhere, even for the LR breed. On the other hand, previous experience suggests that trees grown on low elevation dry sites are straighter, have finer branches and higher wood density than those grown on wetter sites.

Desirable traits, perceived silviculture etc.

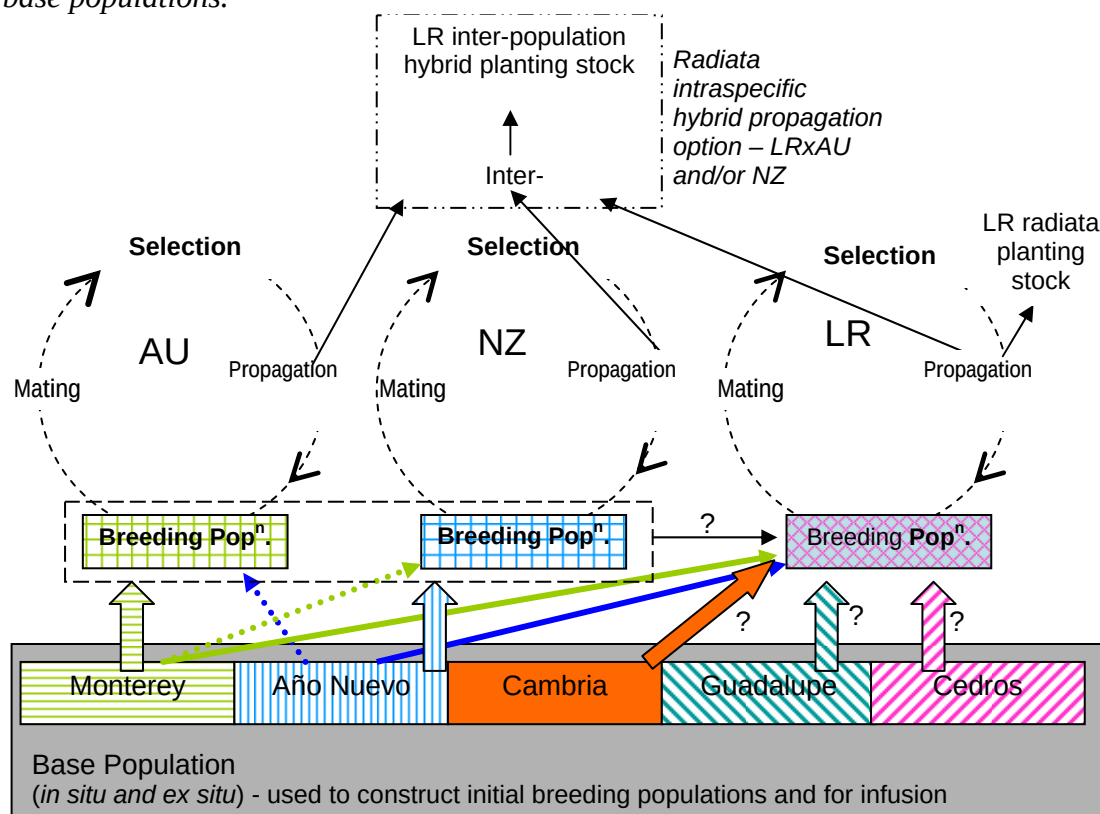
Dry country plantations are likely to be wide-spaced and so fine, multinodal branching will be important. This will reduce the need for expensive pruning and will help minimise costs. Other traits to be included are growth, survival, resistance to sun-scorch, vigour under favourable conditions, stem form and wood quality. Sun-scorch has been a particular problem with the Mexican island provenances in Western Australia, due to the thinner bark, and this will be recognised in the strategy. We are aiming at 25-year rotations.

4.4. Formation of the breeding population

The relationship between the breeding population, base and propagation populations is conceptualised in Figure 2. Initially, the LR breeding population will be formed using selections from all five of the provenances as well as some inclusions of Australian landrace material. The Australian and New Zealand breeding populations on the other hand are composed mainly of Monterey and Año Nuevo respectively (denoted by the thicker arrows leading from the base population to the Australian [AU] and New Zealand [NZ] breeding populations) but a little of Año Nuevo and Monterey respectively (indicated by the dotted arrows). We envisage that the LR breed is likely to contain more of the three relatively dry

provenances (Cambria, Guadalupe and Cedros), denoted by the relatively thick arrows leading from the base to the LR breeding population. It is also possible that, in future, material could be integrated from the Australian and/or New Zealand breeding populations into the LR breeding population (under agreement with the owners).

Figure 2. Overall concept for LR radiata breeding strategy showing relationship to Australian and New Zealand breeding programs and differences in composition of the base populations.



Initially, the breeding population will be formed in two ways: (i) through field trials of open pollinated seedlings and (ii); through control pollinated intraspecific hybrid progeny. These are described in more detail in the following sections:

(i) Open pollinated field trials

Firstly, field trials to test different sources of material (Table 2) will be established, using open-pollinated seeds. It is envisaged that these trials will be undertaken as soon as possible, probably during the second year of the program². Stored seed of native population material (sources 1-3 and 5) with female parent identified is available from CSIRO-FFP for Año Nuevo, Monterey, Cambria and Cedros (Eldridge 1998a). Guadalupe seed is not available in store but may be collected from the conservation stands located at Tantanoola or Tarpeena in South Australia. The Australian landrace (source 6) will be represented by bulked Tallaganda Seed Orchard seed in the Year 2 trial and some GF17 seed of New Zealand origin will represent other select trees (source 7).

² Three trials were established in 2004. Initial controlled pollinations were carried out in 2003, with cones ready for collection in 2005. Refer Bush et al. 2007

(ii) Control pollinated progeny

Selections from the same sources as used in the OP year 2 trials (but not necessarily the same individuals) will be made for the purpose of controlled pollinations using polymix pollen. Trees of native population material (referring to Table 2, sources 1-5) are available in conservation stands at a number of localities and selection should not be difficult (see Eldridge 1998b and 2002).

Table 2. Sources of material for population evaluation and controlled pollinations

Source of material	Purpose	
	Pop ⁿ evaluation trial	Controlled pollinations (numbers of selections)
1. Año Nuevo	Stored seed	Conservation stands (10)
2. Monterey	Stored seed	Conservation stands (10)
3. Cambria	Stored seed	Conservation stands (25)
4. Guadalupe	Conservation stands	Conservation stands (25)
5. Cedros	Stored seed	Conservation stands (25)
6. Australian landrace	Tallaganda SO	From dry areas (10)
7. NZ landrace	GF17	(10)
8. Inter-provenance crosses		Including Guadalupe x Cambria and Guadalupe x Cedros as priorities
9. Other material (later)	?	?

Pollen for interprovenance crosses will be collected initially from Guadalupe, Cambria and Cedros selections made at Sherwood (Australian Capital Territory) and Batlow (New South Wales), Longford (Gippsland, Victoria) and possibly from Scrimshaw's Seed Orchard in South Australia although we plan to use this last source primarily for female parents. Australian landrace selections will be represented by females at Homeleigh (Australian Capital Territory) that were selected for performance at dry sites. The progeny resulting from the CP crosses will be established in field trials as soon as possible, probably in the fourth year of the program.

Later, additions to the breeding population may be sourced from other breeds of radiata

4.5. Selection and mating

The initial basis of the LR radiata breeding strategy will be recurrent selection for general combining ability (GCA). It will be recurrent because it will be designed to continue for a number of generations. It will be based on general combining ability (due to additive effects of genes) in the first instance through estimating breeding values from the polycross trials detailed in Section 4.4. These are derived from a mix of pollen from 6 parents. Breeding values will aim to improve traits that are linked directly to the breeding objective. After the first generation of testing in trials crosses will be undertaken among the individuals with the best breeding values. These crosses will be tested together with interprovenance crosses carried out early in the program. Interprovenance crosses will also be tested in early satellite trials planted after 2004 as they will not be available until after then. It may be possible to take advantage of specific combining ability (SCA) – those due to non-additive effects - later by deploying favourable parental combinations (perhaps interprovenance or inter-breed hybrids) as control-pollinated seed. Non-additive effects can also be captured through cloning, but this can be expensive and the benefits would have to be large to be worthwhile.

Testing after Year 2 will be of polycross (PX) seeds followed by interprovenance (IP) hybrids. Selections will be made in the PX and IP trials and crossed to regenerate the breeding population. Some selections may be made in the Year 2 field trials (open-pollinated – OP).

Crosses to be made will depend on results from the initial round of testing, eg if interprovenance hybrids turn out best, then crosses will concentrate on these.

4.6. Propagation and deployment

Short-term demand for LR radiata can be met by producing CP seed, and/or collecting OP seed from Guadalupe mothers from Scrimshaw's seed orchard (there are preliminary indications that progeny from selections in Scrimshaw's perform well on low rainfall sites – see section 2.5.). Later, conversion of the Year 2 field trials and possibly some 1980s trials to seed production areas by thinning poorer trees out will be an option.

Future deployment will depend on the nature of the best material. If the best material turns out to be interprovenance hybrids, then deployment would be by control-pollinated seed or clones. Pair crosses would be required to identify best parents to produce superior crosses for cloning. If the best material is pure provenance material, then deployment could be open-pollinated seed from provenance seed orchards.

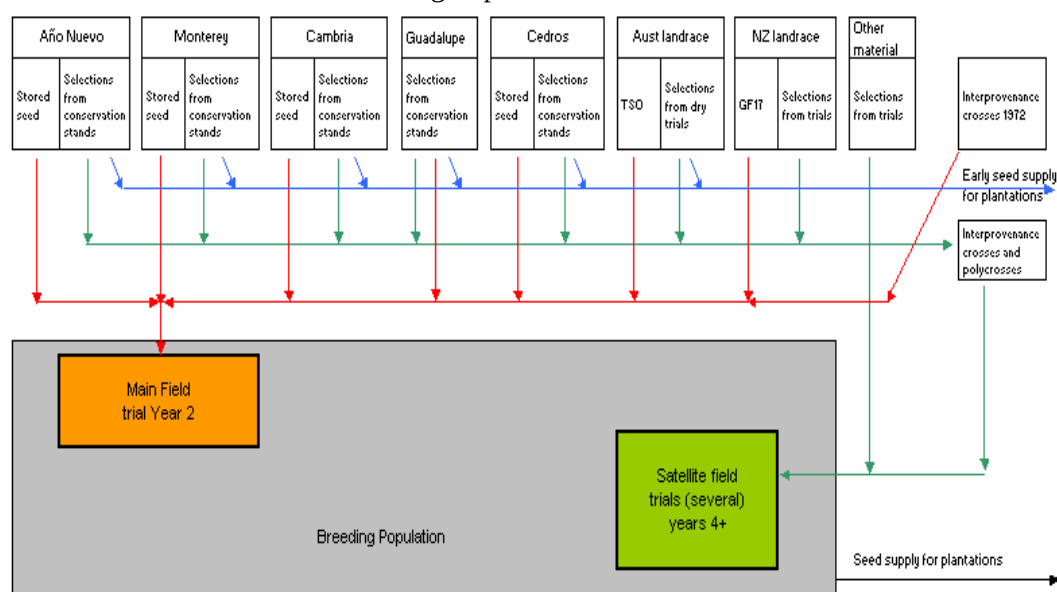
Another option is to interbreed LR radiata with other genetically improved breeds. This is shown as an option in Figure 2. Again, deployment would be by control-pollinated seed or clones.

Avoiding inbreeding in the deployed material can be achieved in several ways, depending on the nature of the best material. It could be by sublining with unrelated sublines and deployment by crosses between them. Or it could be by pedigree control in which crossing between relatives is minimised. Decisions about this cannot be made until after the first results become available.

Monitoring progress is important and so we shall retain considerable amounts of first-generation material for establishing yield trials later.

The strategy is summarised in Figure 3. Review of the breeding strategy will be required at frequent intervals, with the first review due as soon as early results from Year 2 trials become available.

Figure 3. Chart of Breeding Strategy. The Year 2 Main Field Trial and the subsequent Satellite trials will form the Breeding Population.



4.7. Breeding plan to 2004 – establishment of field trials

The plan entails establishment of a large ‘main’ field trial consisting of about 200 families, and a series of smaller ‘satellite’ trials (Table 3). Within trials ‘yield classes’ will be identified based on the 9 classes of material as listed in Table 2. There will be sufficient linkages between trials to allow for genotype x environment analyses to be conducted. Genotype x year interactions are not expected to be significant during the long time-frame that will be required to assess these trials. An exception to this would be a mortality-inducing drought in the first few years (especially the first two years) after planting. Again the common seedlots would be used to identify G x Y effects.

Material for both the main and satellite trials will be assembled and initial sites will be identified during Year 1. The main trial will be established during Year 2, together with two satellite trials. Further satellite trials will be established later, when interprovenance hybrid seeds are available for testing. Radiata landrace selections and other conifer species will be included in all trials as benchmarks.

Table 3. Structure of the field trials to be established during the first two years

Structure	Main trial	Satellite sites
Number of classes	8	8/9
Individuals per class	125	50
Trees	1000	450
Block reps	5	5
Site area	approx 1 ha	approx 0.5 ha
Benchmark seedlots	4	8
Year of planting	Year 2	Year 2 (2); later for the rest

Seedlots for inclusion in the main trial will include seeds from the CSIRO store for the best families in all provenances except Guadalupe for which individual parent seedlots are not available. Seeds will be collected from Guadalupe selections at Batlow (Cpt 777), Longford, Tantanoola and Wirrabara. Seeds from landrace selections are available from the CSIRO (see Eldridge 1998a) and other Partner seed stores. Open-pollinated seed from the 2001 Guadalupe and Cedros collection may become available in the future.

Seeds will be sown in appropriate nurseries in approximately September Year 1 for planting in Year 2. The main trial site will be selected during Spring Year 1 and is intended to be in a dry area that is representative of the target planting zone; perhaps in the Wagga Wagga area. These arrangements need to be finalised early in Year 1. Satellite sites will also be chosen, at least one in South Australia and one in Western Australia to satisfy the same criteria and will need separate nurseries to raise plants.

4.8. Interspecific hybrids

Interspecific hybridisation may be another way of introducing drought resistance genes and/or genes relating to other useful traits into the LR radiata breeding population. While the 90 to 100 species in the genus *Pinus* are not particularly crossable (Critchfield 1966), there may be some possibilities that are worth investigating.

In discussing hybrid possibilities, authors frequently refer to the taxonomic groupings of *Pinus*. The genus is divided into *sections*, *subsections*, and *groups* within subsections: these have been reviewed from time to time. An overview (Dvorak *et al.* 2000) shows that *P. radiata* was originally placed in section *Pinus*, subsection *Oocarpae* by Little and Critchfield (1969), was moved to the *Patula* subsection by Perry (1991), and was then placed in *Attenuatae* by Farjon and Styles (1997) where it remained after a review by Price *et al.* (1998). Various morphological, chemical and other features, including propensity for hybridisation, have been used to define the subsections and groups. More recently, molecular genetic techniques have been used to provide further elucidation. Dvorak *et al.* (2000) calculated genetic distances showing that species in the *Oocarpae* and *Australes* are rather closely related while *Attenuatae* species are somewhat separate, in another cluster.

Most successful pine hybrids have come from within closely related groups of species (Critchfield 1966), while crosses from species between subsections are rarer. Work carried out at Placerville, California during the 1960s investigated a wide range of crosses within the closed-cone pines, *P. radiata*, *P. attenuata* and *P. muricata* (all subsection *Attenuatae*) and with other species. This study showed that while hybrids within the *Attenuatae* were generally successful, hybrids with species in other subsections such as *P. brutia* and *P. halepensis* (both subsection *Halepenses*) were not.

However, there are exceptions to the general rule that inter-subsection hybrids are usually not successful. Various crosses between members of relatively closely related subsections *Oocarpae* and *Attenuatae* have been reported, for example, *P. radiata* x *tecunumanii*. While *P. tecunumanii* generally occurs in higher rainfall locations, the very closely related *P. oocarpa* (according to genetic distances calculated by Dvorak *et al.* 2000) may have good potential as a hybrid in the LR radiata program. The northernmost population of this species is situated in western Mexico at 27° 00'N, mostly at high (1500-2100 m) elevations with quite low summer rainfall (700-1000 mm per year) (Greaves 1979).

5. Program Review

Essential components of genetic improvement programs are regular in-depth review, analysis, evaluation and subsequent revision. The first review should be conducted two years after commencement of the program. A review should also be conducted once the results of water stress trials become available. Further reviews would be conducted at least once every two years. There is sufficient expertise within ALRTIG to carry out the reviews, but it would be desirable for an outside expert not involved in the group to participate in the major reviews.

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