Achievements in forest tree genetic improvement in Australia and New Zealand 7: Maritime pine and Brutian pine tree improvement programs in Western Australia

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Summary

Maritime pine (*Pinus pinaster*) is an important plantation species in Western Australia. The area now planted is about 50 000 ha, but this will increase significantly because of the planned establishment of more than 150 000 ha in medium-rainfall areas of the wheat belt to reduce salinity while providing a commercial tree crop.

A breeding program was begun in 1957 in Western Australia to ameliorate defects in *P. pinaster* for plantation wood production on impoverished sands in high-rainfall areas of the Swan Coastal Plain. The priority was to improve stem straightness while maintaining dominant vigour; reducing branch angle and branch size were secondary requirements. Eighty-three progeny trials covering 160 ha with 186 100 trees were planted from 1965 to 1991, and 25 ha of clonal seed orchards were established. The program has provided substantial gains in tree growth, and stem and branching form, since 1971. The new cultivar available for deployment to tree farms is about 80% more productive than the original stock, as well as being much straighter and smaller limbed.

A second phase of the breeding program started in 1996. This was designed to take the developed, diverse breeding population to new sites in medium-rainfall areas of the wheat belt, and to test the suitability of the genotypes available for deployment. Over the subsequent decade some 32 progeny trials testing 843 families with 81 380 progeny were established on an area of 55 ha. Tolerance to drought and strong apical dominance on fertile, medium-rainfall sites were identified as new traits important to the breeding objective. New seed orchards were developed for these major traits.

Brutian pine (*Pinus brutia*) has potential for high-evaporation, medium–low-rainfall areas because of its inherent ability to survive severe water stress and display apical dominance. The breeding of this species was stepped up in 1999 using old progeny trials at Yanchep as a base population. The objective was to improve the early growth and establishment of the species, and to examine its potential as a hybrid with *P. pinaster*.

Keywords: breeding programs; genetic improvement; genetic resources; races; provenance; hybrids; traits; drought resistance; history; *Pinus pinaster*; *Pinus brutia*; Western Australia

Introduction

There are more than 4 million ha of *Pinus pinaster* forest in south-western and Mediterranean Europe and northern Africa. The species consists of five major races, distinguished by vigour and phenotypic appearance (Destremau *et al*. 1982):

- Atlantic coast, occupying the coastal plains and seaboard from Lisbon (Portugal) to Nantes (France)
- Mediterranean coast, from Tarragona (Spain) to Tivoli (Italy)
- Corsican group, restricted to the islands of Corsica and Sardinia
- Continental group, of the Iberian mountain regions, including the Atlas Mountains in Morocco
- North Africa coast, in Algeria and Tunisia.

Pinus pinaster was first planted in trials in Western Australia (WA) in 1896 and in plantations on the northern Swan Coastal Plain near Perth from 1923 using seed originating in France. Maritime pine grows well on poorer soils unsuited to *P. radiata*. Provenance trials were planted in 1926 using seed from Portugal (Leiria), France (Landes and Esterel) and Corsica. These were conclusive in showing that *P. pinaster* from Leiria had the best growth rate and reasonable form for south-western Australian conditions (Perry 1940, 1949). Since 1942, all *P. pinaster* plantations have used seed derived from the forest of Leiria in Portugal. Subsequent testing of seed from Portugal, Spain, France, Corsica, Italy and Tunisia has confirmed the superior vigour of the Leirian provenance (Hopkins 1960; Hopkins and Butcher 1993).

Nicholls *et al*. (1963) assessed wood properties of Leirian, Landes, Corsican and Esterel races of *P. pinaster* and concluded that the Leirian population had higher basic density and good fibre length. Based on a glasshouse study, Hopkins (1971) showed the seedlings derived from Leiria to have good drought tolerance. Hopkins and Butcher (1993) confirmed this result in field trials.

Hopkins (1960) reported that in early plantations of Portuguese origin less than 13% of trees had acceptable vigour and form for a commercial crop, and only 2% became ideal plantation trees. Thus to permit selection of a final crop of 250 trees ha^{-1}, the planting of about 2500 trees ha^{-1} would be necessary.

Table 1. Genetic resources of *Pinus pinaster* in Western Australia

Race or provenance and population[a]	Source[b]	No. parents	No. cloned	No. in tests
Leiria				
G0	WA	86	72	55
	Portugal	85	79	85
	S. Australia	3	3	3
	WA_S96	200	133	109
	S. Africa	55	0	17
G0_total		429	287	269
G1	WA_cp	634	402	279
	WA_op	182	117	81
	S. Africa	55	43	0
G1_total		871	562	360
G2	WA_cp	37	37	0
Other provenances	Corsica	37	11	19
	Landes	19	6	19
	Tunisia	24		24

[a]G0 = generation zero; G1 = generation 1, etc.
[b]cp = controlled pollinated; op = open pollinated

Resultant nursery, establishment and thinning costs would be high, and a large volume of poor quality logs would have to be placed on the market in order to obtain the desired final crop sawlogs.

Wide spacing was essential on the marginal soils owing to the limited availability of soil water (Butcher and Havel 1976; Butcher 1977). This accentuated the importance of branch size, as the high cost of pruning large branches to obtain sawlogs of acceptable quality was a major concern of managers.

A breeding program was initiated by Hopkins in 1957 with the objectives of (a) improving stem quality in the population to allow wider plantation spacings and thus lower establishment and tending costs, and (b) increasing the volume of the stand that could be commercially utilised (Hopkins 1969). The priority was to improve stem straightness while maintaining dominant vigour; reducing branch angle and branch size were secondary requirements. The selection traits were described by Hopkins and Butcher (1994).

Base breeding population for the Leirian provenance

In 1957 WA plantations, older than 30 y, were searched for plus trees. The age constraint limited the search area to only 400 ha. Because this initial search yielded insufficient trees suitable for immediate use in a clonal orchard, the search was extended to plantations aged 23–30 y. Fifty-four plus trees were selected, of which only five were considered to be outstanding and another 11 to be of sufficient quality to go into the first seed orchard at Joondalup.

This inadequate base was overcome by an agreement with the government of Portugal to select plus trees from mature stands in the Leiria forest — a program supported by funding from forest services in South Australia (SA), Victoria and New Zealand, and the Commonwealth Forestry and Timber Bureau. Outstanding phenotypes in the Leiria forest were selected by WA forester Dick Perry in an intensive search during 1965 and 1966 (Perry and Hopkins 1967). Only the better stands, ranging in age from 30 to 136 y, were examined; most of the trees chosen were 50–80 y old. Following recommended practice at the time, only the best of the numerous candidate trees were ultimately used; the selection intensity was estimated as one plus tree per 250 000 trees.

Scion material and seed from the best 85 phenotypes were dispatched to collaborating tree breeding centres as part of the agreement. However, grafting failed at these centres, though not in WA. Subsequently, scion material was sent from WA to collaborators and to South Africa.

Additional local plantations were searched in 1972–1974, and again in 1996, increasing the number of local selections to 286. Scion material from three plus trees selected in SA was imported in 1965. Pollen and seed was also exchanged with the South African breeding program (Table 1).

The base population for the breeding program consists of 429 G0 (generation zero) selected parents (Table 1) of which 287 have been grafted and planted in archives. Some 816 G1 (next generation) clones have been selected from 900 full sib (WA_cp) and half sib (WA_op) families by index selection in progeny trials of the G0 (Table 2, trials 1965–1991). Next-generation trials of 360 G1 parents (Table 1) in 843 families (Table 2) were planted in 1997–2005. G2 selection and cloning has commenced in these new trials.

Table 2. Genetic resources in progeny trials in Western Australia

Date of planting	No. trials	Area (ha)	No. trees	No. families
1965–1991	83	160	186 106	900
1997–2005	32	55	81 380	843

Progeny testing

Progeny tests were duplicated on shallow grey sands extending to the watertable at Gnangara and on deep yellow sands at Yanchep (Fig. 1). These were the site types commonly planted with *P. pinaster* (Havel 1968). Rainfall is relatively uniform over the area (Butcher 1986). Sites in the south-west marginal to *P. radiata* growth were also used. Pedigree seed was also sent to other Australian states, New Zealand and South Africa for trialling to determine the adaptability of these progenies over a wide range of conditions (Hopkins and Butcher 1994).

Some 85 progeny trials based on controlled pollination, and covering an area of 158 ha with 183 400 trees, were established in WA from 1965 to 1991 (Table 2). The progeny tested in the program were produced by three different types of mating (Hopkins and Butcher 1994):

- tester mating to estimate the general combining ability (GCA) of genotypes and their ranking for use in seed orchards
- factorial mating to estimate GCA/SCA (specific combining ability) effects
- random pair mating to produce a large number of unrelated families from which a future breeding population could be selected.

There has been no new open-pollinated testing of local parents in the program, though this was the means for the early evaluation of the trees selected in Leiria. Open-pollinated tests also served as a major selection population for the next-generation (G1) population (Table 1, WA_op).

Black cockatoos devour immature cones on trees and have been a serious problem in the controlled-pollination program. All control-pollinated cones have had to be bagged to prevent their loss.

Early trials have been revisited in recent years for later-age assessment, validation of selected trees and selection of new trees with new information and emphasis on different traits. These 20–30-y-old assessments have shown:

- juvenile–mature correlation for diameter and form has been very stable
- SCA effects are not significant
- the stem and crown form standards at early-age assessment for reselection were set too high for coastal plain plantations, but will be required for more fertile sites
- the superiority of pedigree trees over ‘routine’ ones generally increased with all forms of trial management
- while tree growth has been substantially increased, the stem and crown form of pedigree trees has given *P. pinaster* a new appearance (Fig. 2).

Deployment I: The first clonal seed orchards

Western Australia’s first *P. pinaster* clonal seed orchard was planted at Joondalup, near Perth, in 1962–1963 on an area of 10.5 ha using ramets of 16 locally selected but untested parents. Ramets of 41 parents selected in Portugal were inter-planted in 1966 to enrich the genetic composition of the pollen and

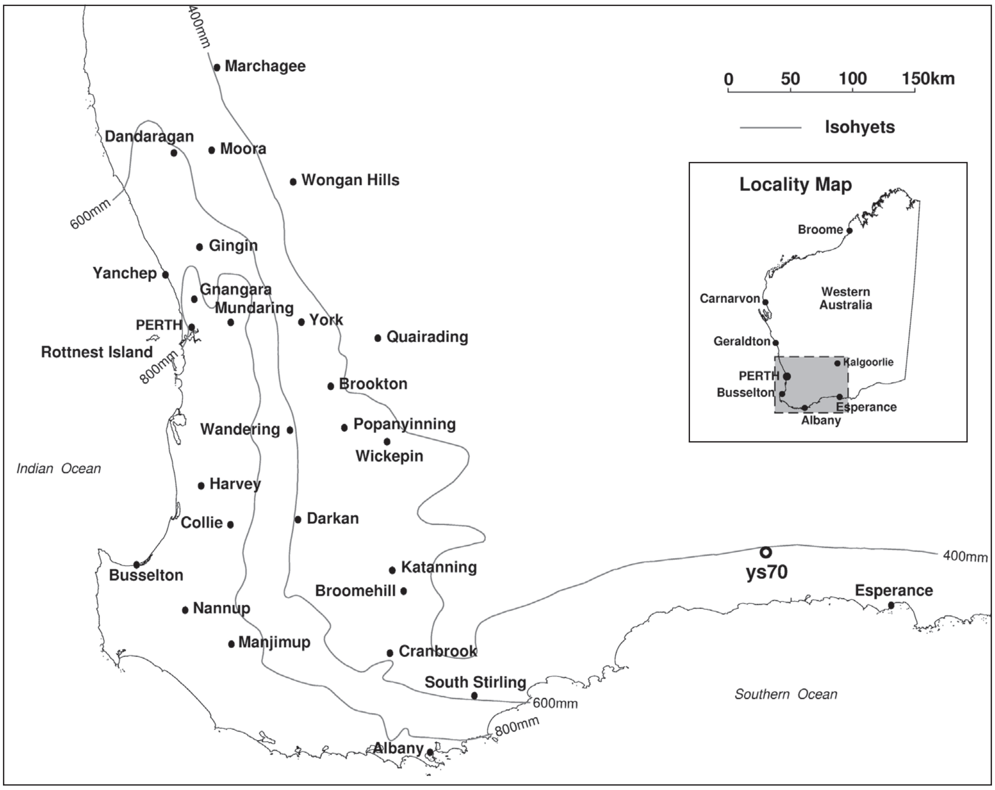

Figure 1. Location of breeding trials in Western Australia

Figure 2. LHS: 37-y-old unimproved *Pinus pinaster*; RHS: 34-y-old improved *P. pinaster*; both at Nannup Arboretum, same site and identical silviculture

thus the genetic worth of the seed produced. The first harvest was made in 1968 and production peaked in 1971 with a seed yield of 24.5 kg ha^{-1}. The last major cone collection from this orchard was in 1976. A total of 1083 kg was collected from Joondalup orchard between 1967 and 1976. Yield trials were established at Gnangara and Yanchep in 1973 and included the Joondalup orchard as a major seed source treatment. Results were reported in Butcher and Hopkins (1993).

A second seed orchard was planted at Mullaloo, also near Perth, between 1969 and 1972. It contained 7816 ramets of 96 parents, 55 from Portugal and 41 from Australia, on an area of 10.1 ha. A maximum seed yield of 28 kg ha^{-1} was achieved in 1981, some 10 y after planting of the ramets. Yields have fluctuated depending on culling status and cockatoo damage to cone crops. A total of 1704 kg of seed was collected from Mullaloo orchard from 1975 to 1994. This site is now part of the Edith Cowan University, Joondalup Campus. It was heavily thinned in 1995 as parkland at the centre of the campus and to serve as a clonal archive of these best original parents.

Genetic gain trials

Butcher (1978) presented the first results from the WA *P. pinaster* breeding program. The use of improved seed gave large gains when compared with unimproved seed. For example, there were 42% more straight trees and 68% more trees with acceptable branch diameter, and height growth was 15% greater. Use of Joondalup orchard seed allowed initial stocking in plantations on the Swan Coastal Plain to be reduced from 2240 trees ha^{-1} to 1140 trees ha^{-1} while still giving better selection for the final crop. Similar large gains have been reported from genetic gain trials planted in 1973 at Gnangara and Yanchep. Eighteen-year-old trees from Joondalup orchard seed gave 36% more volume when compared with the routine unselected source, and the large gains achieved in stem form and branch quality significantly increased the utilisable volume (Butcher and Hopkins 1993).

Some early trials have been remeasured for tree height and diameter at about harvest age (30 y). Mean annual volume increment (MAI) from eight trials (planted 1966–1968) averaged 9 m^3 ha^{-1} for improved *P. pinaster* compared with 6.4 m^3 ha^{-1} for unimproved. Actual values are low because of the low-stocking silviculture and poor site quality. The difference in growth is 40%, which is consistent with all other data from the first-phase progeny trials of the breeding program and gain trials. Most of the trials were on the Swan Coastal Plain but also include trials on water-gaining sites (Busselton, Manjimup), fertile sites (Collie, Nannup, Mundaring), other states (Victoria, New South Wales (NSW)) and other countries (South Africa, Portugal, Morocco).

Gains from the first-phase work are encapsulated in Figure 2. Prior to first thinning at age 11 y, improved tree diameter was 21.5 cm compared with unimproved 17.6 cm, and improved tree height 12.1 m compared with 10.7 m.

Wood density

Kingston and Risdon (1961) found samples of unimproved maritime pine from WA had a mean air-dry density of 596 kg m^{-3}

and basic density of 490 kg m^{-3}. Nicholls *et al.* (1963) assessed wood properties of the four major provenances of *P. pinaster* and concluded that the Leirian provenance had higher basic density and good fibre length compared with the others. No values were quoted but a graph in the report indicates a basic density of 500 kg m^{-3} was achieved by age 10 y. Perry and Hopkins (1967) give basic density data for each of the 85 selected Leirian trees, and a mean of 500 kg m^{-3}.

Wood density was a minor consideration in the breeding program, although it was expected that the high value already evident in the species would be maintained. Hopkins and Butcher (1994) screened parents used for the next generation of breeding (G1), showing an average basic density of 430 kg m^{-3} for juvenile wood (rings 1–8) and 480 kg m^{-3} for mature wood (rings 9–12). Hill (2000) used the genetic gain trial at Yanchep, planted in 1973, to compare the wood density of adjacent improved and unimproved *P. pinaster*. Basic densities were 458 kg m^{-3} and 454 kg m^{-3}, and air-dry densities 557 kg m^{-3} and 550 kg m^{-3} respectively. Although average ring width of the improved trees was greater than that of the unimproved, the proportion of earlywood to latewood was similar, resulting in similar density. This confirmed that wood density was being maintained even though there were significant increases in wood volume from the breeding program.

Interim and future seed supply

Most of the *P. pinaster* plantation had been located on the northern Swan Coastal Plain above the Gnangara Mound aquifer, which provides over 40% of Perth's water supply. Land use objectives of potable water and quality sawlogs are compatible if the pine forest is maintained at a prescribed low stand density (Butcher 1979). Large gains in tree form, branching and growth from the breeding program made this possible. However, stand volume production was compromised by the requirement to grow trees at a low stocking because of the water production objective. Against this background, clearing of native vegetation for plantations became a major environmental issue and new planting on the northern Swan Coastal Plain ceased. The breeding program was placed on a maintenance basis in the early 1980s.

Planting of *P. pinaster* was then restricted to second-rotation and potential new sites on the south coast. A new, replacement seed orchard was designed for Manjimup to meet land use objectives for second-rotation stands on the Swan Coastal Plain. Breeding traits were cylindrical volume and form of the 10-m sawlog, and reduced limb size to minimise rainfall interception. Because stem and branch diameter are correlated, gains in volume were expected to be reduced.

Western Australia had a basic seed requirement to replace the existing 20 000 ha of plantation, that is, 500 ha y^{-1} over a 40-y rotation. About 70 kg of seed was needed annually for this program. *Pinus pinaster* seed yields in the orchards close to Perth averaged 13 ± 5 kg ha^{-1}, so a new orchard of 7 ha was required. The Plant Propagation Centre at Manjimup was chosen as the site; it was well located for management and had less pressure from cockatoos, and there were indications that higher rainfall and cooler temperatures could ensure maximum seed yields.

The Manjimup orchard was planted between 1986 and 1990 with 157 parents, 133 of which were new selections from progeny trials. This was an unusually large number of clones for a production seed orchard. Orchard clones are a subset of the breeding population, and usually only 20–30 outstanding, tested clones are used. However, the future role of *P. pinaster* in the state's timber strategy was uncertain (Department of Conservation and Land Management 1987), and it was expected that the importance of traits could change in the future. With this uncertainty, the strategy was to use a large number of selections, each with the greatest number of desirable genes. This also allowed more flexibility in culling, as the flowering potential of the new clones was unknown. The genetic contribution from each of the clones in the orchard pool was calculated using our tree breeding information management system (TBIMS; Butcher 1993). Ninety-one of the original genotypes are in the orchard, but their contributions are not equal. The top decile group of nine genotypes provides 31% of the orchard genes and these have high breeding values for stem form, branching and diameter. All clones used in the orchard have been evaluated for wood density. The first harvest was made at age 5 y; the yield was 22 kg ha^{-1} by age 8 y and 33 kg ha^{-1} at age 9 y.

Silvicultural policy was changing in 1990. Planting density was increasing and first thinning delayed to give higher yields and to control branch size. The objectives were still the same — to optimise quality sawlog production from plantations and potable water from the Gnangara mound aquifer — although there was an increasing emphasis on the production of industrial wood from thinnings. To further increase wood yields, the economic weighting of traits was changed for selections for a new seed orchard at Nannup and additions to the Manjimup orchard (unit 2). As vigour is weakly negatively correlated with form traits of *P. pinaster*, emphasis on form traits, as applied for the first Manjimup orchard, was reduced and weighting for tree vigour increased. For the orchards planted at Nannup (3 ha) and Manjimup (2 ha) in 1992, genetic gain in diameter was calculated to increase to 15%. This was 50% more than the gain from the first seed orchard.

Breeding strategy

Development of the next generation of *P. pinaster* was outlined in the WA Strategy Plan[1]. Essentially it is to:

- divide the breeding population into five sublines, using TBIMS, so that there is no co-ancestry between lines
- subdivide each subline into elite and breeding populations to maximise gains from breeding while maintaining diversity
- maintain line pedigree by controlled pollination
- rank genotypes by crossing with a pollen mix from other lines
- expand the base population by an extensive search within unimproved Leirian *P. pinaster* plantations in WA

[1]WA Strategy Plan (1995) Tree breeding strategy for *Pinus pinaster* in Western Australia. Internal report, Department of Conservation and Land Management, Perth, Western Australia, 42 pp.

Table 3. Esperance progeny trial YS70, planted in 1999 and assessed in April 2007

Seed source	No. trees	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})	Stem[a] (%)	Stem[b] (%)	Branch[a] (%)	Branch[b] (%)
Unimproved	105	17.9	57	33	8	36	7
Improved	4406	23.4	79	57	21	54	16
Top quintile	892	25.1	86	66	25	60	17

[a]Fraction of trees with good stem straightness or branching
[b]Fraction of crop trees with very good stem straightness or branching

- introduce new improved genetic material, as scion, pollen or seed, from breeding programs in South Africa, Morocco, Spain, Portugal and France.

Successive generation selections were first made following the age 9 y assessment of trees in progeny trials. In the early phase of the program, best trees were selected from the families best for tree form and growth, and selections were then screened for wood density. The retained selections were grafted and planted in archives and orchards. All genetic information and economic trait weighting is now used to construct selection indices (Cotterill and Dean 1990). Readily available software such as LSMLMW (Harvey 1988) and ASReml (Gilmour *et al.* 2002) is used to calculate genetic parameters, and all breeding program information is integrated using TBIMS (Butcher 1993). Line crossing commenced in 1994 and is continuing.

Pinus pinaster progeny trials close to rotation age on the Swan Coastal Plain have been revisited and measured. The data on vigour have allowed checking of early-age selections and immature–mature correlations for our breeding strategy. A subset of trials (44 ha) had been left unthinned, and assessment of health and vigour in these has provided good information on tolerance to extreme water stress (Butcher and Chandler 2007), a trait particularly important for enhancing drought tolerance in the breeding population.

Breeding population bases made up of more than 300 individuals are routinely accepted as necessary to sustain breeding programs over a number of generations. The first phase of our work included 191 G0 selections (Table 1: WA, Portugal, SA and South Africa — n = 17) and might be considered inadequate for moving the species into new environments. Large areas of mature plantations in WA were still available in 1996 to expand the genetic base of *P. pinaster* for future breeding. Two hundred new selections (stem form, branching and vigour) were made in Gnangara and Yanchep unimproved stands in 1996 (Table 1, WA_S96). Scions were collected and grafted for planting in archives at Manjimup and Wandering. Few cones were collected from ortets because of cockatoos; this deficit would later be overcome by bagging immature cones in the archive.

Improved genetic material can also be obtained from other tree breeding programs. The author visited Portugal, Spain, France, Morocco and South Africa on a Winston Churchill Fellowship in 1997 to study *P. pinaster* breeding programs (Butcher 1999). Collaboration was discussed and projects initiated (see national and international collaboration, below).

Maritime pine project: The salinity action plan

Western Australian rural areas are faced with huge salinisation problems, the result of broad-scale clearing of woodland for agriculture since European settlement. The Premier of Western Australia, late in 1996, announced the Maritime Pine Project as a significant component of the Salinity Action Plan (Western Australia Department of Agriculture and Department of Conservation and Land Management 1996). The government, in partnership with private landowners, planned to establish 60 000 ha of *P. pinaster* over the following 10 y to demonstrate the commercial viability of the species as an alternative land use. The Salinity Action Plan recognised the need to establish perennial crops to use soil water and re-establish hydrological balance. Commercial tree crops would be used to draw down water tables to give both environmental benefits and a commercial return to the landowner (Shea 1998).

This initiative provided a stimulus to the *P. pinaster* breeding program, and a new round of selection and breeding for medium–low-rainfall sites was undertaken. The improved breeding population of the Leirian race, developed for high-rainfall areas of the coastal plain, had to be tested on much drier, ex-farmland sites. Fortunately a broad and diverse genetic base had been chosen for new-generation orchards.

In 1997, progeny trials of 210 op parents were planted at Moora, South Stirling and Popanyinning, initiating extensive trials across a range of sites in medium–low-rainfall agricultural areas.

Natural Heritage Trust (NHT) project 983194 funding was used over the period 1999–2002 to create a new-generation breeding population by controlled pollination of parents selected for drought tolerance, growth rate and tree form. Twelve NHT trials were established and occupy an area of 39 ha, testing 380 new cp families with 43 000 trees. These mostly had excellent establishment, with 95% survival or better[2]. These trials provide the opportunity to identify families and individuals with the best survival, form and growth. Problems are expected with drought tolerance, particularly in the northern wheat belt where rainfall is low and evaporation high.

In a decade, 32 progeny trials were established on 55 ha (Table 2) from Moora to Esperance testing 843 families, 512

[2]Butcher, T.B. (2003) Improvement of drought tolerance of commercial tree crop species. Final Report Project No. FFP 983194, Natural Heritage Trust.

of which were created by controlled pollination. Progeny trials usually included 80–200 families plus 3–4 unimproved seedlots, with a minimum of 24 progeny per family planted in plots of 4 trees. Incomplete block designs were used for all trials (Williams *et al*. 2002) and trials were repeated on 3–4 sites, one of which was a second-rotation *P. pinaster* site.

The first trial, planted in 1997 at Moora — with rainfall 462 mm y^{-1} and evaporation 2300 mm y^{-1} — was assessed at age 8 y. Drought death, 12% of trees, was found in one corner of the trial, but the mortality had a low heritability because of its uneven disposition across the trial site. Basal area was 12 m^2 ha^{-1} for improved trees and 9 m^2 ha^{-1} for unimproved trees. There were 30% more straight stems, 50% more trees with smaller branches and 16% more healthy trees among the improved stock.

The trials at Esperance showed that *P. pinaster* has huge potential in this region (rainfall 400 mm y^{-1} and evaporation 1700 mm y^{-1}). After 4 y, heights averaged 3.9 m for unimproved compared with 4.4 m for improved trees, while best families were 5.2 m and best trees were 6.6 m. Malformation was minimal on this site. At age 8 y, improved trees have 39% more volume, almost double the number with acceptable stem form and branching, and two to three times more crop grade trees (Table 3). The best 16 families (the top quintile group) combined for growth, stem form and branching indicate even greater gains can be achieved.

An unforeseen challenge was stem malformation or lack of apical dominance on certain fertile sites with available soil moisture. Hopkins[3] related this to Lammas growth typical of the Leirian provenance. Malformation is associated with changes in leader dominance and not with bends, crooks or sweeps, and results from the development in summer–autumn of the terminal resting bud of the leading shoot. Physical damage to leaders results in similar defects, making assessment for purposes of selection difficult. A very detailed assessment, tracking development of the leading shoot, was carried out on 4-y-old trees. Apical dominance had a low to moderate heritability, and family breeding values were consistent across sites (Carpenter 2003). Information from the assessment was used to plan special seed collections within seed orchards and pollinations for the cuttings program. A new seed orchard was grafted in 2003–2004 to provide stock with improved apical dominance.

While trees of Leirian provenance are susceptible to abnormal late-season growth, those of Corsican provenance are not. Hybrids between these provenances had been first created in 1969 and planted in field trials in 1974. An assessment in 2000 found the hybrid trees had less malformation and were significantly more vigorous than Corsican trees. The Forest Products Commission is collaborating with AFOCEL in France to develop such hybrids; 15 elite Corsican parent trees were imported as pollens in 2001 and included in the controlled pollination program. A progeny trial was planted in 2004 near Broomehill.

Deployment II: Advanced-generation seed orchards

An additional 15 ha of advanced-generation clonal seed orchards were established in the Manjimup region in 1995–1997. A number of strategies were used. Small clonal blocks were planted with prolifically flowering parents having good breeding values for volume and tree form. These ramets were hedged at a young age and used immediately for controlled pollination using pollens with very high breeding values. Conventional orchards were also planted with clones having very high breeding value but unknown flowering potential. As research has shown that seed yield can be increased by 30% by applying $GA^{4/7}$ hormone, this is now routinely used on ramets at Manjimup. Calculations indicate that these new orchards may increase the diameter of progeny by 22% (equivalent to a 70% gain in volume). This is twice the genetic gain achieved from the first seed orchards; gains in tree form will be maintained.

Another 2.2 ha unit was added to the Manjimup orchard in 2000. This addition consisted of selections from old unthinned progeny trials that had suffered continued drought deaths (Butcher and Chandler 2007). Seed from this unit will be deployed to plantations north of Brookton.

Information from the assessment of malformation of progeny trials was used to add a 4.7 ha unit at Manjimup in 2004–2005, using parents with the best apical dominance as the principal trait and drought tolerance as a secondary one.

Black cockatoos have been an increasing problem to the Commission seed orchards at Manjimup. Initially these birds were not a threat, but numbers have increased as the area of orchards has expanded. Scare guns were effective at the early Joondalup and Mullaloo orchards and to a limited extent at the isolated Manjimup Court orchard. Immature cones on malformation-resistant parents were bagged for a couple of years, but this protective measure was expensive and time consuming. A radar-based bird deterrent system with inflatable colourful dolls has been put in place at Manjimup orchards to protect the valuable seed and the Maritime project. Eventually orchards will be covered with netting to protect the cone crop; a 3 ha orchard unit was netted in 2004.

Vegetative multiplication using juvenile cuttings was another deployment option[4]. This had the advantage of immediately multiplying the area of plantation that could be established from improved seed, the supply of which was insufficient for the new 4000 ha y^{-1} planting program. Another advantage was that families selected for specific traits — tolerance to drought and malformation — could be rapidly deployed. Pollination programs in 1999–2000 concentrated on making elite crosses to provide replacement stock for the hedges of mother plants. A problem with *P. pinaster* cuttings is the difficulty of maintaining juvenility and the high associated costs. Mother plants of this species age rapidly compared with those of *P. radiata*; aging reduces rooting success and growth in the nursery and

[3]Hopkins, E.R. (1996) Stem disorders in *Pinus pinaster*. Internal report, Department of Conservation and Land Management, Perth, Western Australia.

[4]Barbour, E. (2001) Development of *Pinus pinaster* genetic deployment. Project Final Report No. FFP 973844, Natural Heritage Trust.

limits selection for field planting. AFOCEL was producing one million cuttings each year at the end of the 1980s but stopped production in 1991 because of the high cost of cuttings and the difficulty of maintaining juvenility of the donor hedges (Alazard and Kadio 1984). Large-scale production of cuttings in WA was abandoned in 2003, although research continues.

National and international collaboration in improving *P. pinaster*

Australia

The Australian Low Rainfall Tree Improvement Group (ALRTIG) was formed with the objective of ensuring that only material of the best genetic quality was used for afforestation projects with a commercial potential (Boardman *et al*. 2002). ALRTIG funding was used to establish improved breeds of *P. pinaster* from the WA program in ten genetic gain trials across southern Australia in 2000. The trial sites were in NSW, Victoria, Tasmania, SA and WA. These plantings will demonstrate the usefulness of the improved species in medium–low-rainfall areas.

Portugal and Spain

Success of our program is underpinned by the early collaboration and introduction of best genotypes from the Leiria forest. More recently, yield trials of improved trees from WA have been established in Portugal and northern Spain. *P. pinaster* does not naturally occur in the dry regions of Alentejo or Algarve in southern Portugal (Roulund *et al*. 1988), although there are scattered small plantings. The seed source for these is probably Leiria, and they are of interest to WA as the trees have been growing for 30 y or more in arid conditions. Butcher (1999) visited plantations at Barrancos and Sines and considered they could make a valuable contribution to the WA plan. Early glasshouse tests at Madrid show that some of the southern low-rainfall provenances have good drought tolerance (Fernandez *et al*. 2000). The breeding program in WA could benefit from infusion of genes of the Cazorla provenance and of selections from dry areas of Portugal.

France

AFOCEL has an active breeding program using the Landes and Corsican races (Illy 1966; Alazard 1983, 1989). Pollen from elite Corsican trees was imported to WA from the AFOCEL program and used in 2001 to create inter-racial hybrids. The hybrid Leiria × Corsica will have better apical dominance than Leirian parents. Pollen from WA improved Leiria trees was exported to AFOCEL in 2007 in time for crossing with Landes parents. Earlier Leiria × Landes hybrids in France showed better vigour and stem form than Landes trees, and better frost tolerance than Leirian trees (Butcher 1999).

South Africa

Key breeding trials in South Africa (Steyn 1991) with 22-y-old trees of Leirian *P. pinaster* were assessed in 1998 as part of NHT983194 project[2]. Trees with the best breeding value for diameter, stem form and branching form were selected. Forty-three G1 parents were successfully introduced to WA through grafting (Table 1). These were in quarantine for 3 y, released in September 2003 and planted in archives. The new clones will supplement the breeding program for tree form.

Morocco

An essential part of the maritime pine project is to enhance drought tolerance. An important gene source area is the mature-age Mechra el Kettane *P. pinaster* plantation of Morocco (Bellefontaine and Raggabi 1978). Climate of the Moroccan coastal lowlands is very similar to medium–low-rainfall, agricultural areas of south-western WA. Long-term average rainfall at Mechra el Kettane is 420 mm y^{-1}, but in the 5-y period 1993–1997 rainfall averaged only 280 mm y^{-1}. This drought caused severe mortality in the 50-y-old Leirian stand. Butcher (1999) saw this as an excellent opportunity to select healthy, vigorous and well-formed trees with a demonstrated capacity to survive prolonged, severe drought. Pollen from the drought-resistant Tamjout provenance is also being sought. Improved resistance to drought is a desired characteristic for *P. pinaster* plantation programs in both Morocco and Australia. Negotiations are continuing to accomplish the necessary selection and importation. Family trials using genetic material from WA were successfully planted in Morocco in 2002.

Long-term breeding strategies for *P. pinaster*

The initial goal of our breeding was to meet land use objectives of the Swan Coastal Plain, namely compatible sawlog and potable water production. Breeding traits were cylindrical volume and form of the 10-m sawlog, reduced branch size to minimise rainfall interception and the maintenance of wood density. Tolerance to drought is important in the medium-rainfall, high-evaporation region and is now a major selection criterion, together with apical dominance, and so the breeding objective has been appropriately revised.

Advanced-generation breeding populations will be managed with controlled pollination and sublining to maintain genetic diversity whilst achieving maximum gains through the various seed orchards. The efficient testing of families on a range of sites and efficient selection of parents for deployment and breeding populations, using all available information, will be essential. Archiving of clones on a minimum of three separate sites, for long-term protection, is another important requirement.

The breeding program follows the classical model of recurrent selection within the Leirian population, and second-generation (G2) selection is in progress (Table 1). As material from Corsica may be added to increase apical dominance, a separate small program will be maintained on this race. Inter-specific hybridisation with *P. brutia* is another option being pursued to enhance drought tolerance.

Brutian pine (*Pinus brutia*) tree improvement program

Pinus brutia has the potential to be an important commercial softwood species in the medium–low-rainfall zones of WA. It is very tolerant of shallow, alkaline and acid soils and can survive in areas of very low rainfall. It also appears to have good control of apical growth on fertile sites at Collie and Mundaring.

This species is native to the north-eastern areas of the Mediterranean. It was trialled, along with *P. pinaster* and *P. radiata*, on a range of sites in the early to mid-20th century. Although there were no early provenance trials, the Cyprus seed source has been recommended for WA since 1946. Harris (1957) reported on exotic conifers in WA and, following his discussions with the Cyprus Conservator of Forests, an intensive search for the best trees was carried out in natural stands by the Cyprus Forests Commission. Seed from 40 plus trees was collected in April 1962 and seed, a phenotypic record and a photograph of each tree were sent to WA.

Overall 77 seed lots, mostly from Cyprus, were imported and planted on an area of about 40 ha between 1926 and 1999. A conifer arboretum planted from 1968 to 1997 included other provenances of *P. brutia* (Fremlin *et al.* 1985).

Trees of the Cyprus provenance generally have good form, branching, apical dominance, vigour and drought tolerance. This was well demonstrated in the Yanchep '100 acre' plot planted in 1952 on shallow yellow sands with outcropping limestone. The unthinned stand had negligible mortality, and growth was reasonably comparable to that of adjacent *P. pinaster*. The ability to survive at high stocking on shallow soils, and with rainfall as low as 500 mm y^{-1} and high evaporation, indicates substantial drought tolerance.

Breeding *P. brutia* started in 1961 with the selection of five outstanding phenotypes from a 12-ha stand which had been planted at Sommerville, near Perth, in 1931. These were grafted and planted in a clonal archive at Mundaring and in 1965 as a clonal seed orchard at Rottnest Island. Seed was also earlier collected from the thinned Sommerville stand and used to plant the '100 acre' plot at Yanchep.

The first progeny trials were planted at Yanchep in 1964 and 1969. As for most *P. brutia*, management of the trials was neglected because of the very slow early growth of trees — they were left unpruned while adjacent *P. pinaster* and *P. radiata* trees were pruned and later thinned. These progeny trials assumed importance with planting in the state moving to medium–low-rainfall areas and the need for greater drought tolerance. Trees in the trials were measured in 1999 for diameter, height, stem form and branching form, and the best cored for wood density. Survival had varied, but apparently this was due to establishment losses as there was no evidence of recent deaths. The average MAI for volume in the trial was 6 m^3 ha^{-1} while the best families reached 11 m^3 ha^{-1}, and basic density was 523 kg m^{-3}. In the adjacent heavily thinned *P. radiata* stand, diameters were comparable but trees were shorter and had stems split from sunscald. Improved *P. pinaster* in a nearby provenance trial had an MAI for volume of 12 m^3 ha^{-1} (Butcher and Chandler 2007) but was suffering from deaths due to drought (Butcher and Havel 1976).

The best trees for volume, stem form and branching form in the families with average or better performance in the two progeny trials were grafted in 2000 with 56% success. The best phenotypes from plots of known provenance were also grafted. The Commission's second *P. brutia* seed orchard was planted on 1.6 ha at Manjimup during 2001–2005 using 48 parents; the best 24 clones were represented at twice the frequency of the remainder. The first new-generation progeny trials were planted in 2001 at Dandaragan and Esperance. At age 6 y, Dandaragan average height was 3.0 m and best family, 3.9 m. Ortet trees in the breeding program were again climbed in January 2001 to bag immature cones (to provide protection from cockatoos), cones were collected in August 2001, seed sown in November 2001 and progeny trials planted in July 2002 at three sites (Marchagee, Brookton and Esperance). Genetic resources now consist of an area of 11 ha with 9 progeny trials.

The orchard at Rottnest Island has continued to be the major source of seed for recent annual plantings of 20–50 ha. It is now retained for bulk pollen collection; the pollen is used for supplementary pollination of young ramets at Manjimup.

For plantations north of Brookton, drought tolerance is a major breeding objective. This could be achieved by using *P. brutia* as a pure species or as a hybrid with *P. pinaster*. This hybrid would combine the drought tolerance and apical dominance of *P. brutia* with the vigour and rapid establishment of the improved *P. pinaster,* and would be suitable for lighter soils. Hybrid crosses were made in 2002 at the Rottnest Island *P. brutia* clonal seed orchard. Hybrid and pure species seedlots, plus special provenance seedlots, imported from Turkey in 2003, were sown at Manjimup in December 2004. The species hybrid trial was planted in July 2005 east of York. Survival at 1 y was 88% for the hybrid and was similar for *P. brutia* and *P. pinaster*. Hybrid crossing is continuing.

Pinus brutia was selected for genetic improvement under the ALRTIG program (Boardman *et al*. 2002) because of its extreme hardiness and good form in select provenances. It complements *P. pinaster*, being suitable for planting at the dryer end of the rainfall spectrum, and on shallow soils. The ALRTIG plan was to select the best trees in plots scattered across southern Australia and in provenance trials at Jerilderie, NSW and Bundaleer, SA (Spencer 1985). Open-pollinated seed was collected from plus trees and used to plant ALRTIG progeny tests at Brookton in 2002 (1.2 ha, 64 families, 2427 trees). The best 45 ALRTIG plus trees were grafted in WA in 2000–2002 for clonal seed orchard planting at Glenoran, near Manjimup (0.8 ha) and in SA and Canberra.

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Eric Hopkins initiated the breeding program for *Pinus pinaster* in 1957 and was responsible for its direction and management over the next 15 y. Dick Perry was nearing retirement when he went to Portugal to select the best trees for the WA program in 1964–1965. These special trees form the basis of the WA breeding population as well as other breeding programs throughout the world. Alex Malajczuk and Joe Stritof were senior technical officers involved from the start at Wanneroo and committed their careers to the breeding program; their thoroughness and dedication underpinned the program. Mike Cully is the current field manager and started as technical officer with the breeding program in 1990. Trevor Butcher succeeded Eric Hopkins in the management and direction of the *P. pinaster*

and other breeding programs in 1971. This has been a single career commitment. A Winston Churchill Memorial Fellowship in 1997 enabled him to visit Europe and Africa to study tree improvement programs of *P. pinaster*.

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