Breeding plan for the development of Douglas-fir *(Pseudotsuga menziesii var. menziesii)* in New Zealand

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EXECUTIVE SUMMARY

Douglas-fir is renowned for its stiff wood and is one of the finest structural timbers in the world. Eighty per cent out of 105,000 hectares planted Douglas-fir in New Zealand is grown in the South Island. Under the changing climate scenarios, breeding for wood production and resilient forests becomes increasingly important in order to boost the interest in growing this species in New Zealand. Since the current breeding plan for Douglas-fir is out-dated, a requirement to update breeding objectives along with selection criteria and operational actions in the breeding programme has been required and is reported here.

Generous genetic resources of Douglas-fir exist in New Zealand ensuring excellent prospects for the future development. Breeding objectives have targeted improved growth and form, and wood stiffness.

New objectives have been defined via the Specialty Wood Products Douglas-fir breeding workshop held in June 2016 for growth and form, wood quality, i.e. stiffness and resistance to Swiss Needle Cast (SNC). The target for growth was a 35 year rotation length and yield of 600 m^3 TRV (total recoverable volume) per ha including 20 m^3 per ha MAI (mean annual increment). Form is an essential selection criteria and the target should be retained at the level of that for tree material at the 1996 progeny trials. The breeding plan will target maintenance of wood stiffness at a minimum level of 8 GPa. SNC is the major limiting factor for growing Douglas-fir more widely in the Central North Island. Consequently, needle retention indicating resistance to SNC is included in the overall objective as a secondary trait and the long-term target was set to needle retention of 3 years.

The current breeding programme is in its second generation and the breeding strategy is to proceed using open-pollinated seed with forwards selection. To mitigate possible effects of genotype by environment interaction (G x E) on genetic gains, a consideration of different breeding zones-seed orchards-deployment areas across New Zealand was endorsed.

Through researching the implementation of new breeding technologies (genomics) and planning of efficient strategy to test tree material, this breeding plan update aims to deliver 30% faster growing, straight, healthy trees with stiff wood for Douglas-fir in New Zealand by 2025.

INTRODUCTION

Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) in New Zealand

Coastal Douglas-fir is the dominant species in the vast forests of the Pacific Northwest of America where it grows from latitude 35º in California all the way up the coast into British Columbia in Canada at latitude 55º.

Douglas-fir trees were first planted in New Zealand on a very small scale in 1859. The New Zealand Forest Service was responsible for establishing about half of the current Douglas-fir estate. Private forest companies did not share the Forest Service enthusiasm for Douglas-fir and its popularity suffered when Swiss Needle Cast (SNC) (*Phaeocryptopus guaemannii*) arrived and reduced its growth rate in the 1970s. However, the presence of a good resource of mature Douglas-fir stands and high international log prices in the early 1990s boosted the production of the species in New Zealand. In the early 1990s, forestry companies from the USA and Asia planted Douglas-fir in Southland and Canterbury on an unprecedented scale, with some of these plantations planted with trees raised from seed imported from the USA. In the 2000s, the discovery of *Nectria* wood rotting fungus in radiata pine and the development of machine stress grading gave Douglas-fir an edge over radiata pine in Southland.

The Forest Service instituted a register of all forest tree seed (Seedlot Register) either collected in New Zealand stands or imported from other countries, which is now maintained in a database at Scion. The Seedlot Register shows that most importations of Douglas-fir seed post 1927 were from Washington state, with very few from Oregon and none from California. Provenance trials were set up in 1955 by Ib Thulin, who imported Douglas-fir seed from the USA and planted provenance trials in 1957. However, the provenances that were obtained were similar to those of previous importations, so a seed collection expedition led by Egon Larsen was mounted in 1956 to fill in gaps in coastal locations as far South as Santa Cruz at latitude 37º. Trials were planted from this seed in 1959.The Douglas-fir co-operative set up another seed collection expedition to the USA in 1993 targeting fog-belt sites near the better performing provenances in the 1959 trial. This seed was sown to supply plants for the provenance and progeny trials that were planted in 1996.

The genetic resources of the species have been utilised to select a breeding population of about 400 trees that will recombine the adaptation and variability of a wide variety of coastal populations. There are preliminary indications from the performance of a few controlled crosses between Oregon and Californian parents planted in the 1996 trial that this outcrossing could generate some hybrid vigour. The concept of three superlines with up to eight sublines within each superline presented in an earlier breeding plan (Low et al. 2009) has been dropped as have attempts to make controlled-crosses for future breeding populations.

The prospects for the future genetic improvement of Douglas-fir in New Zealand are excellent as a result of the diverse gene resources. The emphasis on coastal-fog-belt provenances in the southern part of the species' range reflects the fact that New Zealand's maritime climate is approximated only in those fog-belt areas, and nowhere else in the USA. Selection of parents from populations further inland, and/or from latitudes from northern Oregon northwards, has resulted in poorer-growing offspring. The breeding objectives have been for stiffness, growth and form (Low et al. 2009). Traits of interest in selection criteria has also been for needle retention, the proxy measurement for resistance/tolerance to SNC. Predicted genetic gains in 1996 progeny trials for growth and form were 11 to 12% when selecting the top 20 families across three sites and 9% for needle retention (SNC) in Kaingaroa (Dungey et al. 2012).

The current plantation of area of Douglas-fir in New Zealand is 105,000 hectares, nearly 80% of which is located in the South Island. The species is planted on high country sites where radiata pine suffers wind/snow damage and is prone to low wood density. There is interest in growing more of this species in the North Island, however, SNC is a limiting factor in warmer areas of the country. Globally recognised for its structural timber properties and high stiffness, Douglas-fir would offer a good alternative to wood production compared to other commercial species. Similar to other planted exotic species in New Zealand, Douglas-fir has several characteristics that could be improved through breeding. The potential to use genomic selection in accelerating genetic progress via shorter generation interval and more precise pedigree information should be considered for implementation in the breeding programme. Research on genomic selection in Douglas-fir is on-going and a SNP chip platform to genotype breeding material has been developed at the Oregon State University (Howe et al. 2013). It could provide a further boost for breeding improved tree material for wood production and resilient forests.

The breeding programme is in its second generation and is based on a breeding plan that is out-of-date. Updates to breeding objective, selection criteria and operational actions to achieve targets important to Douglas-fir growers and end users are required. The objective of this report is to collate priorities for the update of Douglas-fir breeding plan. A framework for the breeding targets received from SWP Douglas-fir breeding workshop held in Christchurch in June 2016 will be presented in this report.

RESULTS & DISCUSSION

Breeding Strategy

Breeding objective and selection criteria

The breeding objective for Douglas-fir has been to improve growth and form and timber stiffness. The latest genetics research in the New Zealand Douglas-fir population by Dungey et al. (2012) indicated good genetic gains for the breeding objective traits could be achieved. Genetic gains at three 1996 progeny trials were: for DBH from 9.9 to 13.6%, for stem straightness 8.5 to 22.4%, and for needle retention 9.4% when selecting the top 20 families. Dungey et al. (2013) reported preliminary results for predicted genetic gains for stiffness at Gowan Hill up to 19% and a more moderate genetic gain across all controls of 11% that would deliver an average increase in predicted gains of 12.7GPa (gigapascal) to 15.9 GPa. These genetic gains were for stiffness only and highly stiff tree material is likely to exhibit low growth due to a negative genetic correlation between DBH and acoustic wave velocity (Dungey et al. 2013).Consequently, the breeding strategy must be optimised for selection of both traits simultaneously.

The Specialty Wood Products Programme (SWP) Douglas-fir breeding workshop held in June 2016 discussed a framework for breeding objectives that are important to growers and end-users with the ultimate goal to increase the value of this species in production markets. For growth, the target was a 35 year rotation length and yield of 600 m^3 TRV (total recoverable volume) per ha, as well as targeting 20 m^3 per ha MAI (mean annual increment). Eighty percent of TRV is comprised of saw logs, consequently it can be concluded that growth is actually a surrogate trait for form as well. Deterioration in form should be avoided and the level of quality will be aimed to retain at the average level of that in 1996 trials (Dungey et al. 2012). Selection should be directly for growth and form due to a close to zero genetic correlation between these traits, based on genetic analysis at Beaumont 1999 cross-control progeny trial (Suontama et al. 2015). Estimated heritabilities for stem straightness are good (0.20 to 0.30) based on 1996 trials (Dungey et al. 2012), indicating a great potential to maintain and even improve tree material in this trait. The Douglas-fir breeding workshop held in June 2016 considered branching to be an important trait, however the recommendation was to include it as a culling trait and mainly focus on branch angle. The breeding plan will target maintenance of wood stiffness at a minimum level of 8 GPa using a surrogate trait of acoustic wave velocity. Breeding for stiffness would also be effective, based on estimated heritabilities of 0.49, across three sites in the breeding population (Dungey et al. 2012). Needle retention, a trait that measures resistance to SNC, was targeted at 3 years of needles in the Central North Island where Douglas-fir is most susceptible to the disease.

The breeding strategy of Douglas-fir employs an open-pollinated (OP) progeny testing regime and this breeding strategy was historically based on three superlines that were further divided into seven sublines (Low et al. 2009). These superlines were principally defined as (i) the early range-wide collections (1959 trials), (ii) the Californian and Oregon collections (1996 trials) and (iii) some New Zealand landrace selections, however, the ultimate aim would be to merge these lines to maximise genetic gain (Dungey et al. 2012). An updated strategy therefore suggests consideration of the germplasm in the breeding programme as a single pool and use of the best available tools to maximise the genetic improvement of Douglas-fir in New Zealand. However, consideration of different breeding and deployment zones and seed-orchards to mitigate environmental variation with genotypes, which can result in inaccurate selection outcomes and reduced genetic gains, should be implemented. It is important to emphasise the suitability of germplasm originating from different provenances into the New Zealand environment if the coastal provenances are found to be well adapted to the colder regions in the South Island. Under the current climate change scenarios (Watt et al. 2010), this also raises a question of monitoring needle retention in the breeding programme especially related to SNC and also coastal areas of the South Island (Dungey et al. 2012). Changing climate may increase the range and distribution of the SNC pathogen in New Zealand.

At the Douglas-fir breeding workshop, it was advised that in the USA, SNC is managed using between-population variation as variation within populations is not large. There was also a suggestion to avoid planting provenances from California and focus on specific deployment areas to avoid planting across environments as much as possible. The Northern provenances of Washington and Oregon tend to have a natural resistance to SNC and would be suitable for regions prone to or likely to become prone to SNC. This update proposes that the Douglas-fir breeding strategy be divided into different breeding zones, the North Island and South Island zones. Dungey et al. (2012) reported some G x E interaction for DBH at the provenance level, but this was less observable at the family level. Also G x E interactions were larger between the sites furthest apart but smaller between the South Island sites. As suggested by Dungey et al. (2012), it is proposed that the North Island including the top of the South Island (1) and Southland/Otago (2) be treated as separate deployment areas. This also requires testing of breeding material at several, preferably 4 geographically distinct and environmentally different sites. Different seed orchards for the North Island and South Island would be required for different breeding zones (Dungey et al. 2012).

Douglas-fir is well recognized as structural timber and this is the speciality of this species. Therefore, it will be important to emphasis these traits in an updated breeding plan so that the species does not lose its best qualities. However, capturing the best trees with DBH/SNC correlation breakers that may perform well for other traits would also be useful for the breeding programme. Good phenotyping and application of genomics in the breeding programme were considered to offer the best opportunity for long term mitigation of SNC at the Swiss Needle Cast workshop in 2015 (Suontama and Dungey 2015). Selection of provenances matching different site types as well as implementation of breeding zones could offer greater resistance to SNC as well as improve overall performance of tree material.

Genomic selection

Genomic selection (GS) can accelerate the rate of genetic gain via shorter generation intervals and more accurate pedigrees. For example in loblolly pine, elimination of progeny testing, the most time consuming phase of breeding (typically taking 6-10 yrs), would decrease the breeding cycle significantly and selection efficiency per unit of time could be 53 to 112% higher than with traditional breeding (Resende et al. 2012). To test the efficiency of genomic selection in conifer breeding, a simulation study of *Cryptomeria japonica*, summarized that GS could improve quantitative traits controlled by many small gene effects and was also better than traditional breeding when heritabilities were lower and when marker density was higher (Iwata et al. 2011). Douglas-fir breeding in New Zealand is based mainly on OP-breeding populations, as a result we can expect that accuracy of breeding value estimations will improve as genetic relationships will be known. A SNP chip has been developed for Douglas-fir at the Oregon State University (Howe et al. 2013) which may offer a genotyping platform for implementation of genomic selection in the New Zealand breeding programme. Genomic selection would result in greater accuracy or precision of breeding value estimation and as a result of that, greater gain and delivery of these gains. An extra improvement due to implementation of genomics may come through a shorter generation interval that will further boost genetic gains in breeding population.

A long-term and short-term plan for operational actions

The current breeding programme as described in Figure 1 requires a careful consideration in operational actions to achieve the breeding objectives. Next steps both in the long term and in the short term for selections, breeding assessments, genetic conservation and planning of future breeding trials are therefore described below.

- Phenotypic assessment of breeding trials
  - **Long-term goal:** The first assessment of 2009 progeny trial
  - **2016/17:**The first assessment 2011 progeny trials
  - **Long-term goal:** The first assessment of 2006 & 2007 clonal trials
  - **Long-term goal**: The first assessment of 2012 genetic gain trials
- Preservation of genetic resources
  - **Long-term goal:** 1957 & 1959 provenance trials
  - **Long-term goal:** 1971 & 1972 & 1973 Kaingaroa progeny trials
  - **Long-term goal:** 1996 provenance trials
  - **2016/2017 onwards:** Waikuku material and non-tested genetic material over 100 families from seed-orchards and breeding archives (Waikuku, Proseed)
- Trial establishment
  - **Long-term goal:** Planting genetic resources collected from Golden Downs provenance trial 1959
  - **2017/18:** Establishment of progeny trials from non-tested 100 families in seed-orchards and breeding archives
  - **Long-term goal:** In general, increase the number of breeding trials across a variety of sites
- Research & Collaboration
  - **2016/17:** Optimal structure of next generation trials for breeding and genomics
  - **2016/17 starting:** Implementation of genomic selection in Douglas-fir breeding programme
    - Preference for genotyping platform is SNP chip (Howe et al. 2013)
    - Training population is suggested to be 1996 progeny trials where a good later age phenotypic data is available across multiple sites
  - **2016/17 starting:** Strengthening international collaboration in Douglas-fir genomics research to maximise value delivery and attract international students.

Operational actions 2016/17

Short-term operational actions during the financial year 2016/17 will include phenotypic assessments and quantitative genetic analyses of two progeny trials planted in Kaingaroa and Golden Downs 2011. Genetic resources will be preserved in Waikuku breeding archive to ensure that this genetic material will be available in the future. Testing of genetic material of around 100 non-tested families in seed-orchards will begin 2016/17 by collecting seed and planting into nursery beds at Scion Nursery. Genomics work will proceed in collaboration with international research partners. Collaborations will be seek out from the Oregon State University in the USA, INRA in France, and the BC Ministry of Forestry in Canada.

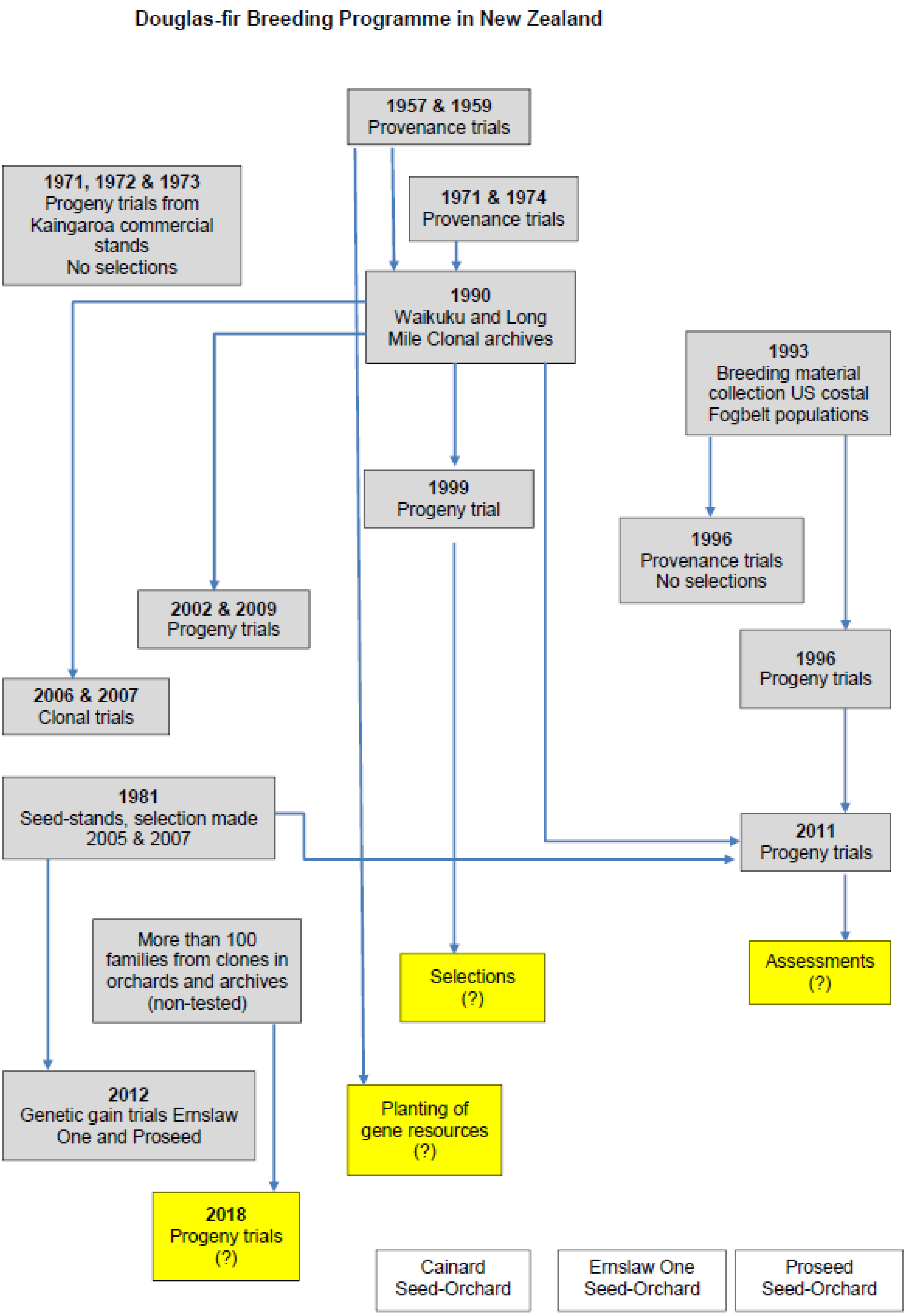

Figure 1. Douglas-fir breeding programme in New Zealand.

Implications

This breeding plan update aims to deliver by 2025, planting stock for New Zealand that is 30% faster growing, straight, healthy with stiff wood. Deployment solutions for exposure, frost, health, stiffness are straightforward and clarified in forest management. Next generation trials have taken place across the country for an additional 20% gain by 2035. The best selections are crossed and bulked up for cuttings via somatic embryogenesis.

CONCLUSIONS

Douglas-fir is well recognised as a species especially suited for structural timber production and offers great potential for higher value specialty wood products in New Zealand markets and elsewhere. The current plantation area of around 105,000 hectares could be increased by breeding for faster growth with a shorter rotation length target of 35 years. Needle retention is one of the major traits for improvement particularly in the Central North Island where the species is most prone to SNC. However, under the current climate change scenarios, it should be expected that more resistance tree material is needed in all parts of New Zealand. Douglas-fir is known for excellent quality timber stiffness, and this trait should be included as the main breeding objectives. Growth, form, and stiffness as primary traits, and needle retention as a secondary trait are the principal breeding targets for Douglas-fir in New Zealand. Breeding would be effective for all these traits based on good heritabilities. As there is no evidence of high favourable genetic correlations between these traits, direct selection for each must be done in the breeding programme. However, genetic correlations between SNC and other selection traits should be estimated to conclude if indirect selection could be employed for improved needle health. Deployment of suitable provenances in different areas of New Zealand and proceeding with a breeding zone scenario in order to mitigate the effects of G x E on genetic gains are considered for inclusion in the current breeding plan. Use of genomic selection may offer faster improvement of tree material through more precise genetic relationship information and therefore faster genetic improvement and delivery to deployment. Genetics research and operational actions in the breeding programme must be planned carefully to optimise the outcomes in the breeding targets.

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