

CLIMATE CHANGE — IMPLICATIONS FOR *PINUS RADIATA* IMPROVEMENT*

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ABSTRACT

A change in New Zealand's climate, because of the increase in "greenhouse" gases in the atmosphere, may affect the productivity of *Pinus radiata* D. Don through increased wind damage, more severe infection by fungal pathogens, and areas becoming too dry or too wet for satisfactory growth. The current *P. radiata* improvement strategy is well suited to maintain genetic improvement in a changing environment. Future research should consider planting identical field trials at particular sites several years apart, and planting trials at and beyond the current extremes of climate. Research on alternative species should be encouraged.

Keywords: climate change; tree breeding; *Pinus radiata*.

INTRODUCTION

Global climate is predicted to change gradually but significantly over the next 50 years because of the increase in "greenhouse" gases, principally carbon dioxide, methane, nitrous oxide, tropospheric ozone, and chlorofluorocarbons, in the atmosphere. Two different scenarios ("most likely" and "warm") have been developed (Salinger & Hicks 1989) for the climate in New Zealand between the years 2030 and 2050 when greenhouse gases are predicted to be double the current level. These scenarios represent what could be plausible climate changes in New Zealand (Salinger & Hicks 1989).

Under the "most likely" scenario, temperatures are likely to rise in the North Island by between 1.2°C in the north and 1.6°C in the south. For Northland this would raise mean annual temperatures to between 15° and 17°C, and in Wellington the mean annual temperature would increase to around 14°C. In the South Island this scenario postulates temperature rises of about 1.3°C in the west and 1.8°C in the east, giving mean annual temperatures of between 11.5° and 13°C in Westland/Fiordland and between 12.5° and 14°C in the Canterbury Plains. The temperature increase should lead to fewer frosts. At the same

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time rainfall patterns are likely to be altered. North and west of the main North Island mountain ranges (Ruahine, Kaimanawa, Raukumara) rainfall would increase by 10–15%, the increase resulting from higher intensity rainfalls occurring on fewer days than at present. South and east of these ranges rainfall would decrease by about 5%, bringing annual rainfall to below 800 mm in the drier parts of Hawke's Bay and Wairarapa. In the South Island rainfall would increase by up to 15% west of the Main Divide. In the east, rainfall would tend to decrease by about 5% (10% in parts of eastern Southland and South Otago). Rainfall would be less than 600 mm on parts of the Canterbury Plains.

If climate change matched the "warm" scenario, temperatures would generally rise between 3° and 3.5°C, leading to even fewer frosts and bringing mean annual temperatures above 15°C in most of the North Island. Rainfall would remain about the same or increase over most of the country. Around Wellington, Wairarapa, and Manawatu in the North Island, along the West Coast, and in parts of Otago and Southland rainfall would decrease by about 5–10%.

Under both scenarios there would be a decrease in strong winds from westerly directions. However, this would be offset by an increase in strong winds (and tropical cyclones) from northerly directions extending over the top half of the North Island under the "most likely" scenario, and as far south as Nelson under the "warm" scenario. Sunshine hours per annum would tend to decrease by around 100 hours in the wetter areas, and increase by 50–100 hours in the drier areas.

Such changes in climate are likely to have a significant impact on *P. radiata* forestry in New Zealand. However, as the projected changes will occur gradually over the next 40–60 years and the average rotation age for *P. radiata* plantations is about 30 years, there is the opportunity to breed improved *P. radiata* which will be better adapted to the changed climate.

The objectives of this paper are to briefly describe the known environmental limitations to *P. radiata* growth, the current *P. radiata* improvement programme, and how the improvement programme might respond to climate change.

PINUS RADIATA: RESPONSE TO ENVIRONMENT

A survey of sample plots throughout New Zealand (Shula 1989) indicated that the maximum stem volume production (greater than 40 m³ mean annual volume increment) occurred in the North Island, generally from the Bay of Plenty southwards, on sites with volcanic or sandy loam soils. The mean annual temperature for the forests containing these sample plots varied between 9.8°C and 13.7°C (Table 1) (New Zealand Meteorological Service 1983) suggesting that the optimum mean annual temperature for *P. radiata* growth is in this range. This is confirmed by several other studies. For example, Hunter & Gibson (1984), in developing a model to predict site index (mean top height at 20 years) from environmental variables, concluded that, all other factors being equal, site index would be highest where the mean annual temperature was around 12°C. Booth & McMurtrie (1988) suggested that in Australia the optimum mean annual temperature for *P. radiata* growth may be between 12° and 14°C, while in Spain (Gandullo *et al.* 1974) *P. radiata* grows best when the mean annual temperature is between 10.3° and 13.9°C (Fig. 1). In contrast, Hollinger

(1990) suggested that the optimum mean annual temperature for *P. radiata* growth is at least 15°C. However, this conclusion is based on a linear regression estimated from a data set in which only three sample plots had a mean annual temperature above 13°C, and should be treated with caution.

Commercial forestry with *P. radiata* generally requires an annual rainfall greater than 600–750 mm (Lavery 1986). For those New Zealand forests in which mean annual volume increments above 40 m³ have been recorded (Shula 1989), mean annual rainfall varies between about 1100 and 2100 mm (Table 1) (New Zealand Meteorological Service 1983). In Spain (Gandullo *et al.* 1974) *P. radiata* grows best when the annual rainfall is between 1000 mm and 1940 mm (Fig. 1). Hence, it appears that an annual rainfall of between about 1000 mm and 2000 mm is optimum for growth. *Pinus radiata* grows well in areas with a winter peak in rainfall. It will not tolerate severe summer droughts.

TABLE 1—Mean annual temperature and annual rainfall for forests where mean annual volume increments over 40 m³ have been recorded

Forest	Mean annual temperature (°C)	Mean annual rainfall (mm)
Glenbervie	13.7	1934
Kaingaroa	10.7	1483
Tarawera	13.1	2046
Mangatu	13.4	1330
Wharerata	—	—
Te Wera	11.9	1837
Esk	11.9	1756
Gwavas	11.2	1257
Mohaka	12.8	1659
Karioi	9.8	1189

Source: New Zealand Meteorological Service (1983)

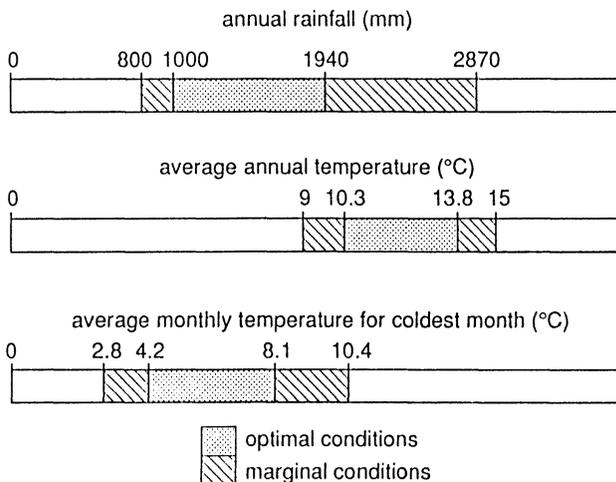


FIG. 1—Annual rainfall, average annual temperature and average monthly temperature for coldest month suitable for growth of *Pinus radiata* (adapted from Gandullo *et al.* 1974).

Although *P. radiata* may grow quickly in climates with a humid and moist warm season, these conditions may also cause increased attacks by fungal pathogens including *Dothistroma pini* Hulbary, *Cyclaneusma minus* (Butin) diCosmo *et al.*, and *Diplodia pinea* (Desm.) Kickx. Experiments with *Dothistroma pini* have indicated that infection by this pathogen is severe when daily mean temperature is between 16° and 18°C and the needle surface remains wet for at least 10 hours (Gadgil 1984). Severe infection occurs on specific sites and can lead to substantial losses in volume production (van der Pas 1981). The needle-cast disease associated with *C. minus* occurs over a wide range of temperatures (10°–25°C) and, therefore, a wide range of sites, with severity likely to be higher after mild autumns and winters (Gadgil 1985). Needle loss associated with *C. minus* reduces wood volume growth significantly (van der Pas *et al.* 1984). The development of leader dieback from infections of *Diplodia pinea* in green shoots also rises with increasingly humid conditions and increasing temperatures between 10° and 25°C (Chou 1982).

Pinus radiata is also susceptible to leader damage at extreme low temperatures, while its frost hardiness varies seasonally. In summer, *P. radiata* will not tolerate frosts below –6°C, while in winter it will tolerate frosts as low as –14°C (Menzies & Chavasse 1982).

Strong winds appear to have a detrimental effect on *P. radiata* growth. Studies in South Africa (van Laar 1967) have indicated that radial growth of *P. radiata* was measurably reduced when wind velocities exceeded 18 knots during the summer. Severe storms can cause considerable losses through windthrow and stem snapping. For example, in 1988, Cyclone Bola damaged more than 30 000 ha of *P. radiata* forests in New Zealand.

In addition to its effects on growth of *P. radiata*, climate change may have important effects on log and wood quality. Damage by wind and by fungal pathogens (such as *Diplodia pinea*) can increase malformation of harvested trees, thus reducing their merchantable value to sawmills. Increased temperatures are likely to induce increases in basic wood density of *P. radiata*, with associated positive effects on timber strength, pulp yield, and certain pulp qualities. Cown & McConchie (1983) found that wood density of *P. radiata* varied by between 40 and 70 kg/m³ from the south of the South Island to the north of the North Island and that these changes were positively correlated with mean annual temperature. There are indications that branch cluster frequency (an important factor in determining log quality) can vary with temperature, with multinodal trees being more frequent under warmer conditions, and “long internode” trees more frequent in cooler conditions (Carson & Inglis 1988). The influence of environment on final branch size (another important factor in determining log quality) is more complex. Final branch size is negatively correlated with mean annual branching frequency (Lavery 1986). However, branch growth is positively correlated with diameter growth (Lavery 1986), while regression models indicate that final branch size decreases with increasing site index.

Indications of the likely impact of increased carbon dioxide and other climatic changes have been obtained from controlled environment studies. Such studies have shown that the rate of net photosynthesis increases with increasing carbon dioxide concentration (Forest Research Institute 1987). Under optimum conditions of light, temperature, and humidity, increasing the carbon dioxide concentration from the current atmospheric level of 340 ppm to 640 ppm (the likely level during the latter part of the next century) increased the rate of net photosynthesis by 70%. This increase appears large enough to more than offset any loss in photosynthesis which might occur due to an increase in cloud cover arising from climate

change. Simulations using a model of radiation interception and photosynthesis (Grace, Jarvis & Norman 1987; Grace, Rook & Lane 1987) indicate that a reduction of approximately 100 hours of sunshine annually would reduce annual net photosynthesis by only about 2%. Such an increase in carbon dioxide concentration did not alter the proportional allocation of carbon (produced by photosynthesis) to stems, roots, and foliage in *P. radiata* seedlings (Hollinger 1987). However an increase in carbon dioxide concentration of this order significantly reduced the rate of transpiration, indicating that trees will require less water for the same amount of growth (Forest Research Institute 1987).

Nutritional status is, however, likely to influence the response of *P. radiata* to increased carbon dioxide concentrations in the atmosphere. Barlow & Conroy (1988) found that for phosphorus-deficient *P. radiata* seedlings the rate of net photosynthesis decreased without significantly altering the dry weight or water-use efficiency. For seedlings with adequate phosphorus, the rate of net photosynthesis, growth, and water-use efficiency all increased.

Although these results are generally indicative, we do not know whether the trends will hold in the long term (e.g., Kramer 1981), or whether studies on juvenile trees under artificial conditions will hold for mature trees in forest plantations.

From a New Zealand perspective, this information on the response of *P. radiata* to environmental conditions suggests that, if the conditions described in the climate change scenarios develop, there are several areas of concern.

- (1) An increase in tropical cyclones might lead to wind damage in the most important region for *P. radiata* forestry.
- (2) An increase in temperature and rainfall might lead to more severe infections by fungal pathogens.
- (3) Under the “most likely” scenario, the projected decrease in rainfall in eastern areas such as the Canterbury Plains might result in conditions too dry for the satisfactory growth of *P. radiata*.
- (4) An increase in temperatures in northern regions of New Zealand might create conditions too warm for satisfactory growth of *P. radiata*.

PINUS RADIATA IMPROVEMENT PROGRAMME

Tree improvement is one way by which we can hope to overcome the adverse effects of climate change. The New Zealand *P. radiata* improvement programme began at the Forest Research Institute in the 1950s, when “plus” trees were selected very intensively from plantations established in the 1920s and 1930s (Shelbourne *et al.* 1986). These trees were selected for their good growth rate, straight stems, and fine wide-angled branches. “First stage” seed orchards established using grafts from 15–25 of these “plus” trees have produced commercial quantities of seed since the early 1970s. These were “open-pollinated” seed orchards and, if well isolated from outside *P. radiata* pollen, they produced seed with improvement contributed by both the selected parents (Carson 1987). There have been large improvements in stem volume, straightness, and acceptability (stems suitable for final crop) of stands planted with such seed compared with unimproved seed (Fig. 2).

A further, less-intensive selection of about 600 “plus” trees, also from unimproved stands, was made in the late 1960s (Shelbourne *et al.* 1986). Seed was collected from the “plus” trees

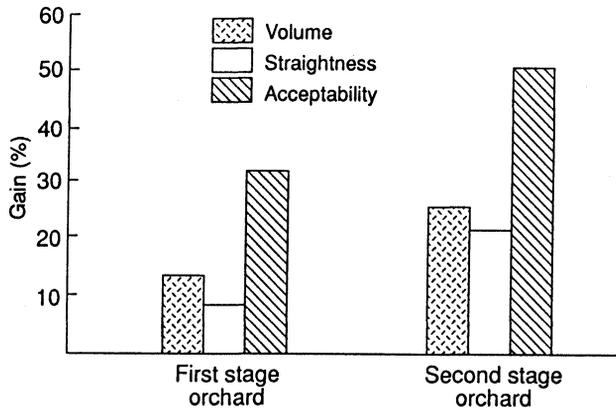


FIG. 2—Percentage gains in stem volume, straightness, and acceptability from seed from first- and second-stage seed orchards compared with unimproved seed (J. King, unpubl. data).

and used to plant a progeny trial for performance testing and ranking of the selections. Seed orchards were subsequently established using grafts and cuttings of only the better-performed parents. The combination of extensive phenotypic selection with progeny testing gave even greater increases in stem volume, straightness, and acceptability in seedlots produced from these “second-stage” orchards (Fig. 2).

Advanced-generation breeding of *P. radiata* is being undertaken through the selection of new “plus” trees from within the best families in the progeny tests of the first-generation “plus” trees. These selections will themselves be performance tested, and the better clones will be mated with one another to form a second-generation breeding population of higher genetic quality than the first.

The time taken to develop a new generation of improved *P. radiata* will be around 12–14 years (less than half the usual rotation age), and so several re-selections will be made during the next 50 years when climate is expected to change. To date, most of the emphasis has been on production of a *P. radiata* breed for general utility, with improved growth rate and stem form, and longer needle retention (related to *C. minus* infection). In addition, recent progress has been made in developing specialty breeds—for example, trees with long-internodes (Carson & Inglis 1988) and trees which are expected to have significantly less *Dothistroma* infection (Carson 1989; Carson *et al.* 1991).

A specialty breed of trees with increased resistance to *Dothistroma* needle blight has been developed for planting on the approximately 20% of *P. radiata* plantations which have conditions particularly conducive to *Dothistroma* infection. Heavy emphasis on resistance as a selection trait has led to a breed which will reduce the impact of the disease and thus increase growth on these sites. However, because this results in somewhat reduced genetic gains in growth rate on *Dothistroma*-free sites (Carson *et al.* 1991), *Dothistroma* resistance is not being heavily emphasised in the general utility breed. In contrast, resistance to needle loss related to *C. minus* is being incorporated into the general utility breed because of its significant effect on later growth rate, and its widespread occurrence. To date, resistance to

Diplodea pinea has not been incorporated into the general utility breed to any extent because severe infection has been very localised and intermittent.

Resistance to *Dothistroma* in *P. radiata* appears to be very amenable to population improvement using assumptions of quantitative inheritance (Carson & Carson 1989). This trait exhibits high additive genetic variance, little non-additive variance, and stable resistance over years and sites (Carson & Carson 1991). Stands of the best seedlot of the *Dothistroma*-resistant breed are expected to have an average infection of about 15% less than stands derived from other seedlots, as well as improved growth rate and stem form. Reduced disease levels will result in reduced growth loss from *Dothistroma* needle blight and something like a 56% reduction in the costs of aerial fungicide control, which in Kinleith Forest averaged NZ\$750,000 per annum over the last 6 years (Carson *et al.* 1991; Dick 1989). Second-generation crossing of *Dothistroma*-resistant parents is now under way, with a significant further reduction in *Dothistroma* levels expected from parents reselected within these crosses.

An important question facing any breeding programme is whether to breed trees for specific environmental conditions. An experiment to investigate genotype \times environment interaction in *P. radiata* was established in 1975, at 11 sites covering the major site types in New Zealand (Fig. 3). The sites represent a wide range of temperature and rainfall conditions present in New Zealand *P. radiata* plantations (Table 2). At each site there were six replicates of controlled-cross progeny representing a group of 25 parent “plus” trees.

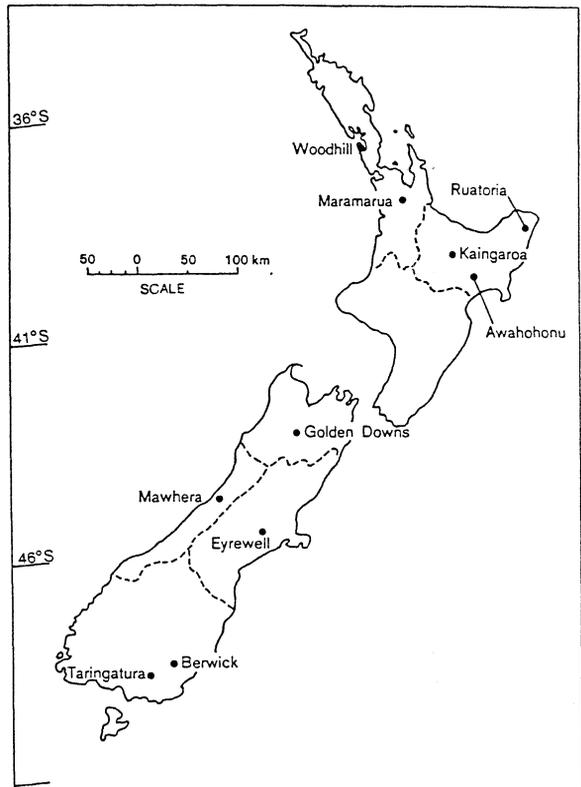


FIG. 3—Location of field trials for investigation of genotype \times environment interaction.

TABLE 2—Results of *Pinus radiata* genotype × environment interaction experiment at age 9 years

Forest	Mean diameter at breast height (cm)	Heritability of half-sib family effects	Phenotypic variance of half-sib family effects	Latitude (S)	Mean annual rainfall* (mm)	Mean annual temperature* (°C)
Woodhill	21.3	0.79	158	35° 00'	1328	14.6
Maramarua	16.9	0.31	42	37° 15'	1263	13.6
Ruatoria	20.6	0.46	67	37° 54'	1877	14.4
Kaingaroa, Site 1	25.7	0.82	109	38° 30'	1483	10.7
Kaingaroa, Site 2	23.6	0.64	77	38° 30'	1483	10.7
Awahohonu†	23.6	0.81	122	39° 10'	1756	11.9
Golden Downs	15.4	0.43	35	41° 43'	1307	10.5
Mawhera‡	19.3	0.50	65	42° 27'	1892	11.3
Eyrewell	12.4	0.25	30	43° 25'	849	11.0
Berwick	9.8	0.01	34	45° 58'	734	10.3
Taringatura§	16.7	0.56	47	45° 59'	839	10.1
All sites	18.7	0.74	34			

* New Zealand Meteorological Service (1983).

† Mean annual rainfall and temperature from Esk station.

‡ Mean annual rainfall and temperature from Totara Flat station.

§ Mean annual rainfall and temperature from Winton station.

Results of an assessment of diameter at breast height (1.4 m) at age 9 years indicate that heritabilities tended to be highest on sites with both the best average growth and the greatest variance for growth among trees (Table 2, Columns 1, 2, and 3). Although there was some statistical evidence for a genotype \times site interaction effect, a group of trees selected for good performance across all sites gave responses (“predicted genetic gains”) similar to groups of trees selected for their performance on specific sites—2.1 cm gain over an average diameter of 18.7 cm *v.* 2.2–2.4 cm gain, respectively (Carson 1991). Genetic gain predictions are probably not accurate enough to ensure the realisation of the difference between the predictions, and a regionalised programme focusing on performance on specific sites would require more resources to implement than a national programme.

For needle retention, a trait with moderately high heritability (also assessed at age 9), genotype \times site interaction was about the same as for diameter. Predicted genetic gains were not calculated for this trait, but would probably present a similar story to diameter, that is, regionalised seed production would probably not increase gains very much. Further, New Zealand plantation sites cannot easily be separated into those prone to premature needle loss and those which are not. In addition, needle retention may involve a complex set of variables, rather than simply being closely related to the size of the *C. minus* population, and the suitability of climatic conditions for spore production and dissemination (as with *Dothistroma* needle blight). Much more should be known about the biology and distribution of low needle retention before a regionalised selection programme is considered for this trait.

Therefore, we believe that under current climatic conditions one highly-selected set of *P. radiata* clones used as seed parents for the entire country would yield the highest returns from the breeding programme. These results also suggest that relative family performance does not vary much with different temperature, rainfall, and soil conditions, nor does growth rate vary in a predictable manner with changing environment.

IMPLICATIONS OF CLIMATE CHANGE FOR *PINUS RADIATA* IMPROVEMENT PROGRAMME

We consider that the current strategy for *P. radiata* improvement is appropriate, even in light of gradual but significant climate change over the next 50 years. One advantage of an improvement programme of the “recurrent selection” type is that it automatically considers and incorporates the effects of the most recent climate change. “Plus” trees are selected every 12–14 years from progeny tests, which have been planted and grown under current climatic conditions. The method of planting progeny trials allows the selection of families best adapted to the climate prevailing during the life of the progeny trial. The trees selected for use in the breeding programme are, therefore, those which are best adapted to any changed climatic conditions. Given that climatic conditions are suitable for *P. radiata* growth, the breeding programme will continue to produce performance-tested genotypes that are “well-buffered” for good growth over a wide range of climatic conditions.

Given the likelihood of increased levels of pests and pathogens, it may, however, be appropriate to place more emphasis on selection for disease resistance, and to consider development of further specialty breeds for resistance to diseases such as those caused by *Cyclaneusma minus* and *Diplodia pinea*. The *Dothistroma*-resistant breed will probably be required on a higher proportion of sites.

Another factor likely to have a significant impact on forest productivity is wind damage. Results from a progeny trial in Lake Taupo Forest that was damaged by Cyclone Bola in 1988 indicated that some families appeared to display wind tolerance (J. King, unpubl. data). Breeding for wind tolerance should be investigated, although this is a difficult trait to select for, since one cannot guarantee wind damage in progeny trials.

Further research on hybrids of the New Zealand landrace with native populations of *P. radiata* from Guadalupe and Cedros Island might be warranted, as these hybrids may be adapted to harsher environmental conditions than the New Zealand race.

FUTURE RESEARCH NEEDS

Questions about the long-term impact of climate change on plantation forestry may be best addressed by establishing identical field trials on particular sites at intervals of several years. Growth of similar genetic material and climatic variables could be monitored to determine their association. Such trials could usefully include a repetition of the genotype \times environment trial already described.

If climatic extremes are likely to increase as a result of climate change, field trials of promising families could be established in areas at, and beyond, the current extremes of climate. Such sites need not be restricted to New Zealand. *Pinus radiata* is also important in Chile and Australia—both countries possessing sites covering greater climatic extremes than in New Zealand. Field trials are much more reliable for identifying promising families than controlled-environment studies.

Continued research will be needed on alternative conifers to *P. radiata* for possible “contingency” use in regions where *P. radiata* could no longer be grown. Possible examples might include hybrids of *Pinus caribaea* Morelet (in warmer areas) and *Pinus pinaster* Aiton (in warm, drier areas).

Additional knowledge about the diseases which are likely to become more widespread and severe (especially *Dothistroma* needle blight and *Cyclaneusma* needle-cast) could enhance gains from breeding for increased resistance. Studies could include investigation of variation in virulence in the New Zealand *Dothistroma pini* population; the distribution of premature needle loss; the interrelationship of site-specific stress factors, *Cyclaneusma minus* infection, and premature needle loss; and further development of early selection methods.

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