Tree improvement programmes for forest health – can they keep pace with climate changes?

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Can tree improvement programmes develop "generic" resistance to offset potential new pest and disease problems that may arise more rapidly with climate change?

As forest geneticists consider physiological adaptations of forest tree populations under various climate change scenarios, they must also take into account likely impacts from new insect pest and disease introductions, as well as increased natural disturbances from native pests. What lessons can be learned from past investments in disease and pest resistance research and genetic improvement, particularly with the challenges of climate change scenarios? Can more generic and general resistance be developed to offset potential new pest and disease problems that will arise within a time frame of less than a decade?

The world's main commercial tree improvement programmes have focused primarily on productivity improvements in the first few generations of breeding, but they have sometimes included an insect pest and disease resistance component. Many pest and disease resistant individuals, and even specific resistance genes, have been found in forest tree species, and some are currently employed in breeding.

This article summarizes the results of a recent worldwide survey of research on insect and disease resistance which suggests that although some targeted resistance programmes have had substantial impacts on improving the health of planted forests, most of the gains have been for only a small number of major commercial species and have taken decades to develop. The article suggests that past approaches may not serve well under rapid climate change, and also identifies five future challenges that could undercut the potential for tree

As warming climate is thought to trigger outbreaks of Dothistroma needle cast disease (shown in lodgepole pine,* Pinus contorta*), resistance mechanisms that may reduce infection to several species of needle cast fungi would be worth pursuing

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Partial list of major breeding programmes in the world developing and planting insect pest and disease resistant forest trees

Tree species	Insect pest or disease problem	Type	Country
Pinus monticola	*Cronartium ribicola*	Fungus	United States
Pinus taeda	Fusiform rust disease (*Cronartium quercuum*)	Fungus	United States
Populus spp.	*Melampsora* spp.; *Venturia populina; Septoria populicola*	Disease, insects	United States
		Insects	China
		Disease, insects	Europe
Salix spp.	Leaf rust	Disease	Sweden
		Disease, insects	United States
Pinus radiata	Dothistroma needle blight (*Mycosphaerella pini*)	Fungus	New Zealand
Picea sitchensis	Green spruce aphid (*Elatobium abietinum*)	Insect	Denmark
Picea glauca and *P. sitchensis*	White pine weevil (*Pissodes strobi*)	Insect	Canada

improvement programmes to improve forest health in changing climates.

INFLUENCE OF CLIMATE CHANGE ON PEST AND DISEASE PROBLEMS

Climate change is expected to result in or require large-scale movement of species, and populations within species, into climatic zones where they may not currently exist. Bold new forest management strategies will be needed to offset adaptational lags of species and their populations to maintain productivity and forest health. Tree vigour and productivity will be the first line of defence against insect pests and diseases.

Furthermore, ranges of insect pests are expected to expand under several climate change modelling scenarios (e.g. nun moth, *Lymantria monacha*; gypsy moth, *Lymantria dispar*) (Vanhanen *et al.*, 2007). Diseases and insect pests continue to be introduced and to invade or threaten regions outside their natural distribution ranges (Lovett *et al.*, 2006). Warming climate is thought to be a major cause of epidemic outbreaks of native diseases and pests that are causing relatively new and catastrophic problems; recent examples include Dothistroma needle cast disease (Woods, Coates and Hamann, 2005) and mountain pine beetle (Aukema *et al.*, 2008) in western Canada.

RESULTS OF RESISTANCE BREEDING PROGRAMMES TO DATE

A survey of the literature to evaluate the effectiveness of tree breeding research for disease and pest resistance, carried out by FAO with assistance from the British Columbia Forest Service, Canada, classified activities according to four levels of breeding programme development:

- Status 1 – large breeding programmes that have resulted in operational planting of resistant material (seed-orchard seed or other propagule types);
- Status 2 – large research or breeding programmes that have not yet resulted in operational planting;
- Status 3 – large research or breeding programmes that have identified genetic variation in resistance in genetic/provenance trials;
- Status 4 – studies that have identified genetic variation in resistance in small research seedling or clonal trials.

Although the technical approaches that can be applied are somewhat predetermined by these levels, three technologies were also identified to categorize the initiatives further:

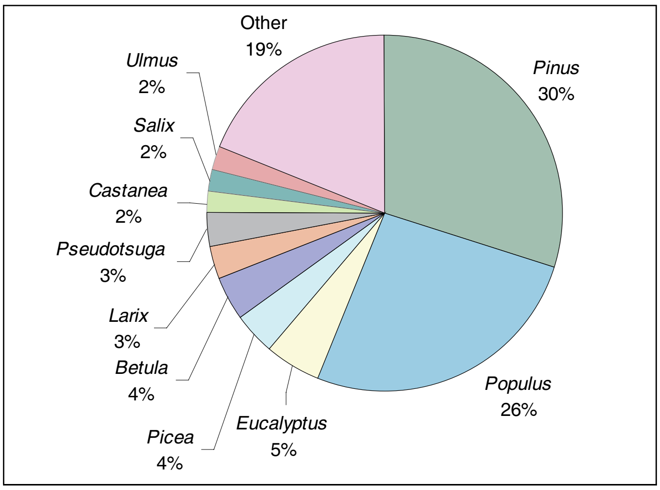
- traditional plant breeding methods;
- molecular biology approaches;
- genetic engineering.

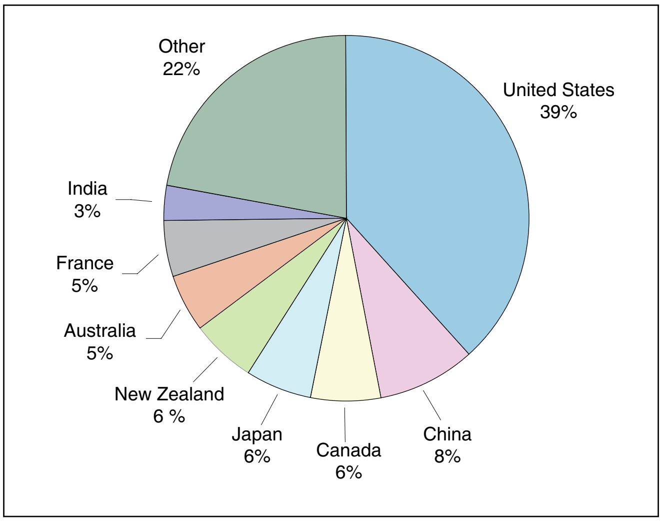
A total of 260 activities on breeding for pest and disease resistance in forest trees were recorded in the review (FAO, 2008). The list was not intended to capture all publications on resistance in a particular species, as some resistance programmes (e.g. that for fusiform resistance in *Pinus taeda*) have been reported in hundreds of scientific papers. The intention was rather to represent a sample of the literature in each programme area. The Table summarizes some of the programmes that have had the largest impact to date.

Survey summary

By forest tree species. Thirty-six tree genera were represented. Pines (*Pinus* spp.) and poplars (*Populus* spp.) were the two most commonly investigated genera, together representing more than half of the activities recorded (Figure 1).

1
Insect pest and disease resistance breeding programmes, by tree genus





2
Insect pest and disease resistance breeding programmes, by country

The most studied tree species included *Pinus radiata* (16 records), *P. taeda* (nine records), and *P. monticola* and *P. ponderosa* var. *ponderosa* (six records each). Other species with at least four activities were *Picea abies*, *Pinus contorta*, *Betula pendula*, *Cryptomeria japonica*, *Eucalyptus globulus*, *Hevea brasiliensis*, *Pinus lambertiana* and *Populus deltoides*.

By pest type and species. About 54 percent of reported activities investigated tree resistance to disease species, 36 percent targeted forest insect pests and 6 percent investigated both pest types. Resistance to mammals was the focus of only six activities (about 2 percent), and one activity dealt with nematode resistance.

The most commonly targeted insect pest species included *Chrysomela scripta* (five activities) and *Pissodes strobi* and *Thecodiplosis japonensis* (four activities each). The most commonly targeted disease species included *Cronartium ribicola* (18 activities) and *Cronartium quercuum* (seven activities). Four activities each addressed *Diplodia pinea*, *Heterobasidion annosum*, *Melampsora larici-populina* and *Ophiostoma ulmi*.

By country. The majority of research activities are published in developed countries, led by the United States with almost 39 percent of all activities (Figure 2), although some emerging developing countries such as China (about 8 percent), India (3 percent) and Brazil (1 percent) are active or have at least published and disseminated some results.

By approach. About 68 percent of the research focused on traditional plant breeding methods. Genetic engineering was the focus of almost 15 percent of the activities and molecular biology almost 13 percent. About 5 percent used a combination of the three approaches.

By status of breeding programme. About 63 percent of all research activities are Status 4, 22 percent are Status 3 and only 6 percent are Status 2. Just 9 percent of the recorded activities are Status 1, i.e. at the stage of planting resistant material operationally; furthermore many of these activities, although carried out by different organizations, represent work with the same tree species and pest or disease problem.

Impact of resistance work in planted forests

In general, the survey clearly shows that despite a large body of published research over more than 50 years, from hundreds of research initiatives or programmes around the world, relatively few programmes have developed resist-

*A relatively successful disease resistance programme targets white pine blister rust (*Cronartium ribicola*) in North America; a complex bark reaction kills tissue around the infection in a* Pinus strobus *tree with tolerance to the disease*

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*Isolation bags on western red cedar (*Thuja plicata*) for controlled pollination for deer browse resistance studies*

ant material for operational planting. Practical impacts from resistance breeding programmes have only been documented for four to five major commercial pest and disease problems.

For disease resistance, the two most successful programmes appear to be the fusiform rust resistance improvement in *Pinus taeda* and *Pinus elliottii* in the southern United States, and the white pine blister rust resistance programmes in the Inland Empire region of southern California and the Pacific Northwest of North America. *Pinus lambertiana* resistance to blister rust in California and southern Oregon, United States, is also notable. The most impressive documentation of success has been for fusiform resistance; average worth of plantations established with fusiform-resistant *P. taeda* improved 6 to 40 percent over plantations established with susceptible stock, while improvements for *P. elliottii* ranged from 40 to 90 percent (Brawner *et al.*, 1999).

Gains from the first-generation programmes of non-major gene resistant stock in *Pinus strobus* range from 3 to 70 percent survival (with one rare example of major gene resistance in *Pinus lambertiana* and *P. monticola* inferring 100 percent survival in the simplest situation [Kinloch *et al.*, 1999]). These figures may be underestimates as the survival of more recently planted material may be higher; nevertheless, the results clearly show that genetic gains are possible and important.

Several programmes (e.g. chestnut resistance to blight) seem to be on the verge of having novel materials ready for use; however, a long time will be required before their ecological or economic impacts can be evaluated. Dothistroma-resistant breeds in *Pinus radiata* have been developed, but the problem has largely been addressed through silvicultural practices (Mead, 2005).

In comparison with disease resistance, pest resistance programmes are less well developed and have resulted in less material that has reached large-scale reforestation programmes, although there is substantial work in the area (as shown in the Table). The survey revealed only two programmes using traditional plant breeding methods that could be classified as Status 1, one for spruce aphid (*Elatobium abietinum*) resistance (Harding, Rouland and Wellendorf, 2003) in Europe and the other for spruce terminal weevil (*Pissodes strobi*) resistance in British Columbia, Canada (King *et al.*, 1997). Work on transgenic material for resistance to stem-boring and leaf-eating insects is increasing; operational planting of this material is in its infancy but has been reported with poplars in China (Ewald, Hu and Yang, 2006). Work on *Eucalyptus* resistance to a number of leaf insects is increasing, but to the authors' knowledge the resistance has not been incorporated in materials being planted commercially.

Considerable time and resources have been invested to obtain resistant genotypes, gain experience in their use and achieve impacts in improving plantation health. Initiating an improvement programme for a tree species, even for a few simple traits, requires substantially more years than for a crop species. With a long process involving selection of germplasm for field testing, rearing of test stock, test establishment and meas-

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*Spruce terminal weevil (*Pissodes strobi*) larvae migrate down the leader to girdle and kill the top of the tree; a breeding programme for this pest in western Canada is one of the few insect resistance programmes that has reached the operational planting stage*

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A few surviving lodgepole pine trees resistant to mountain pine beetle in a young (age 20 years) family trial; high levels of attack in such long-term research field installations are typically an important first "genetic screening" for resistance to bark-chewing insects

urements at appropriate ages, selection of best material and establishment in seed or hedge orchards, it is not surprising that the successful programmes have taken one, two or even more decades to identify and develop silviculturally useful genetic resistance.

CHALLENGES FOR EFFECTIVE RESULTS IN CHANGING CLIMATES

Difficulty of finding specific mechanisms that explain plant or tree resistance

While many insect pest and disease resistance traits can be scored relatively easily by observing the presence or absence of the pest or disease on an individual tree, detailed phenotypic assessments of host reaction or pest behaviour (e.g. landing on and then leaving a tree) are required to develop a better understanding of what general mechanisms of resistance are at work.

Decades of research on herbivory in *Betula pubescens* (e.g. Haukioja, 2003) have uncovered a wide range of variations in birch that can impart resistance. For instance, there is a large spectrum of leaf compounds that change over the growing season; the level of resistance varies by herbivore species; and simple changes in nutrients, water content and leaf toughness were found to be as important as any of the more complex and detailed anatomical or chemical profiles in birch genotypes (Riipi *et al.*, 2005). To identify mechanisms of resistance that may impart some general resistances to classes of insect pests and diseases, and to incorporate this knowledge into programmes that can potentially deliver resistant germplasm, will be difficult but extremely valuable. Development of general resistance becomes more critical if it is not possible to predict what future insect pest species or pathogens will be encountered with climate change.

Transferability of research on wild trees to pedigreed trees in genetic improvement programmes

Studies carried out on trees in natural settings will not necessarily assist breeding programmes in developing more resistant germplasm. Much research on insect pest or disease interaction with host trees in the wild is important for modelling purposes (e.g. on spread rates and impacts in wild forests) and is of evolutionary interest, but it may not be possible to extrapolate the results to species or populations that have been artificially migrated under climate change adaptation strategies (Millar, Stephenson and Stephens, 2007). Work with pedigreed material from breeding programmes, if available and adequately challenged by various pests or diseases, may also be able to provide the basic information needed for stand or landscape impact models.

Decreasing resources for traditional genetic improvement of forest trees

In spite of the impressive progress to date in some programmes, it is likely that fewer resources will be available in the future for the study of specific host-pest interactions in classical tree improvement programmes. Globally, traditional training in quantitative genetics – a necessary skill set in tree breeding – has been waning (Eisen, 2008; Knight, 2003; Morris, Edmeades and Pehu, 2006). In addition, many of the largest and most successful tree breeding programmes are currently struggling because of major financial and structural changes in the forest industry (Byram, Miller and Raley, 2006). Available research resources will need to focus on testing for, developing and using resistances that may be able to help thwart both current and new, unknown challenges. Cross-resistance, i.e. resistance against many classes of pests or diseases (e.g. Andrew *et al.*, 2007), if it can be identified and tested adequately, may have the most utility in the future.

Lodgepole pine provenance test at age 30 years; field tests such as these have been important for studying the effects of climate change on adaptive genetic variation in growth potential and pest and disease resistance among forest tree populations

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Populus trichocarpa ***cuttings being lifted in the nursery for research plantings in field trials; poplars are widely used in genomics and transgenics, but long-term basic field studies are still needed to study natural levels of resistance and adaptation to climate change***

Adjusting investments in molecular biology and genomics research

The enormous sums invested in molecular biology in many countries, while being of great scientific interest, must be better aligned with applied programmes. The survey noted that approximately 13 percent of initiatives used molecular biology approaches. Genomics information is evolving at a rapid pace, and many products or tools will likely be of substantial interest to breeders. For instance, it may become possible to narrow down the key elements (e.g. families of genes) operative in resistance, such as a compound from resin terpenoid biosynthesis and production, alkaloid expressions, traumatic resin production, formation of resin ducts or physical barriers such as bark thickness or stone cells. However, the largest challenge will be in making the proper linkages between markers, gene expression measures and the phenotypic expressions of the trait in large pedigreed forest tree populations, and then determining how tree responses or traits affect pest or pathogen response.

Role of transgenic trees

Transgenic technology can address some specific pest problems temporarily, but it still must be considered only one tool within well-developed breeding programmes. Because trees are planted across landscapes, and now because of the added complexities that climate change will impose, adequate field testing over space and time will be needed to ensure that gene expression is stable within different genotypes. However, for short-rotation species such as poplar, it may be possible to manage transgenic trees using approaches similar to those currently being used in agricultural crops.

SUMMARY AND CONCLUSIONS

The results of the survey highlight three issues. First, since the “reaction time” for developing genetic options for insect pest and disease resistance has typically been in the order of decades, will this approach be useful in a world with rapidly changing climates? In the authors’ opinion, probably not. Therefore it may be necessary to develop strategies that may provide some “pre-emptive” or general resistances.

Second, since there may be little or no lead time to know which pests or diseases will pose threats in the future, are there some better “generic” forms or classes of resistance that could be developed in advance against various classes of insects or diseases? It would be highly desirable, if possible, to identify mechanisms of resistance that may be more affordable and allow for a shorter turnaround and development time than at present.

Third, will the resistance mechanisms currently being used be able to provide some protection from new or related pests and diseases?

Although a more general type of cross-resistance should not be expected to be a typical feature of most resistance mechanisms (Panda and Khush, 1995; Riipi *et al.*, 2005), it may now be important to seek to understand the degree of variation present in currently selected elite parent trees making up the seed production and breeding populations. A reduction in the number of genotypes that researchers should and can afford to work with needs to be tempered with the difficulty of accommodating more traits (Verryn, 2008), particularly if negative genetic correlations are present between traits of interest. Moreover, resistance does not always incur a physiological cost (e.g. King *et al.*, 1997), so mechanisms of resistance that are positively correlated with growth would also be desirable ones to pursue.

In summary, after five decades of research on insect pest and disease resistance in trees, resistance breeding has had significant local impacts; however, the successes are largely for a few of the main commercial programmes which have had substantial resources and structures in place to deliver the gain.

In the future, funding agencies and researchers may need to focus declining resources and research capacity on species for which silvicultural options to mitigate losses to insect pests and diseases are few. Research should also be focused on genotypes that are already in tree improvement programmes or that could form the basis of a programme.

Better alignment of forest genetics and forest health research programmes will be required if traditional tree improvement programmes are to capitalize on past investments in insect pest and disease resistance research and help mitigate the projected negative impacts of climate change on forest productivity and health. This is likely to become imperative with projections of increased pest and disease risks in the future. ◆

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