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Future outlook for *Pinus patula* in South Africa in the presence of the pitch canker fungus (*Fusarium circinatum*)

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Approximately 50% of the area planted to softwood trees in South Africa has been established with *Pinus patula*, making it the most important pine species in the country. More effort has gone into developing this species for improved growth, tree form and wood properties than with any other species. This substantial investment has been threatened in the last 10 years by the pitch canker fungus, *Fusarium circinatum*. The fungus infects and contaminates nursery plants and, once transferred to the field, causes severe mortality of young trees in the first year after establishment. Although nurserymen have some control of the disease, it is recognised that the best long-term solution to mitigate damage because of *F. circinatum* infection is to identify tolerant species, clones and hybrids for deployment in plantations in the future. Research has shown that alternative species such as *P. tecunumanii*, *P. maximinoi* and *P. elliottii* are suitable for warm sites. Pine hybrids, particularly between *P. patula* and the high-elevation sources of *P. tecunumanii*, appear to be a suitable replacement on subtemperate and temperate sites. Although these alternative species and hybrids are more sensitive to subfreezing temperatures than *P. patula*, their planting range can be increased by including cold tolerance as a selection criterion. Future breeding efforts will most certainly focus on improving the tolerance of pure *P. patula* to *F. circinatum,* which can be achieved by identifying specific family crosses and tolerant clones. The commercial deployment of disease-tolerant control-pollinated *P. patula* and hybrid families will most likely be established as rooted cuttings, which requires more advanced propagation technology. In the long term, new seed orchards comprised of *P. patula* clones tolerant to *F. circinatum* could be used to produce seed for seedling production.

Keywords: Camcore, *Fusarium circinatum*, *Pinus patula*, *Pinus patula* × *Pinus tecunumanii*, site–species matching

The history of *Pinus patula* in South Africa

Pinus patula was originally introduced into South Africa in 1907 (Kotze and Eckbo 1926, Burgers 1975, Wormald 1975, Dvorak 1997). Further introductions were made in 1911 and 1928 (Burgers 1975) but it is not known exactly where this seed was collected in Mexico. One report is that the third introduction came from Guajmalpa in the State of Mexico (Burgers 1975, Butterfield 1990). Other possible locations include the states of Hidalgo and Veracruz because the original roads in these areas often followed old Aztec trails that were in close proximity to natural stands of *P. patula* making for easily accessible seed collections (WS Dvorak pers. comm.). These early introductions formed the basis of the commercial deployment of the species in South Africa and the initial *P. patula* breeding programs (Adlard 1981) that started in the late 1950s (Coetzee 1985). The species performed exceptionally well in the summer rainfall region and had superior growth, stem form and wood properties (Poynton 1979). The selections made in the early plantings responded well to tree improvement efforts (Darrow and Coetzee 1983) and, by 1970, 223 600 ha had been planted to *P. patula* (Nyoka 2003).

Several introductions of *P. patula* seed were made at a later stage. In 1969/70 Coetzee and Fisk, of the South African Department of Forestry, made collections again in Hidalgo and northern Oaxaca and also in Puebla from five provenances and 40 trees (Darrow and Coetzee 1983). Many families from these collections outperformed the yield from commercial plantations at the time (Darrow and Coetzee 1983). A comprehensive seed collection was also carried out by Barrett (1972) from Argentina, who sent some seed to South Africa where a single trial was established. Several trials were also established in 1971 in Zimbabwe (then Rhodesia) from seed introduced in 1969 (Barnes and Mullin 1984). South Africa also received provenance material of *P. patula* from the Food and Agriculture Organization (FAO) in the 1980s. Although the majority of the selections in the South African orchards originate from the commercial plantings made in the 1920s (Coetzee 1985), selections from the provenance trials planted in South Africa and Zimbabwe have also been included in some breeding programs.

The largest collection of *P. patula* seed was made by Camcore at North Carolina State University (formally known as Central American and Mexican Coniferous Resources Cooperative, now known as the International Tree Breeding and Conservation Program) between the years 1986 and

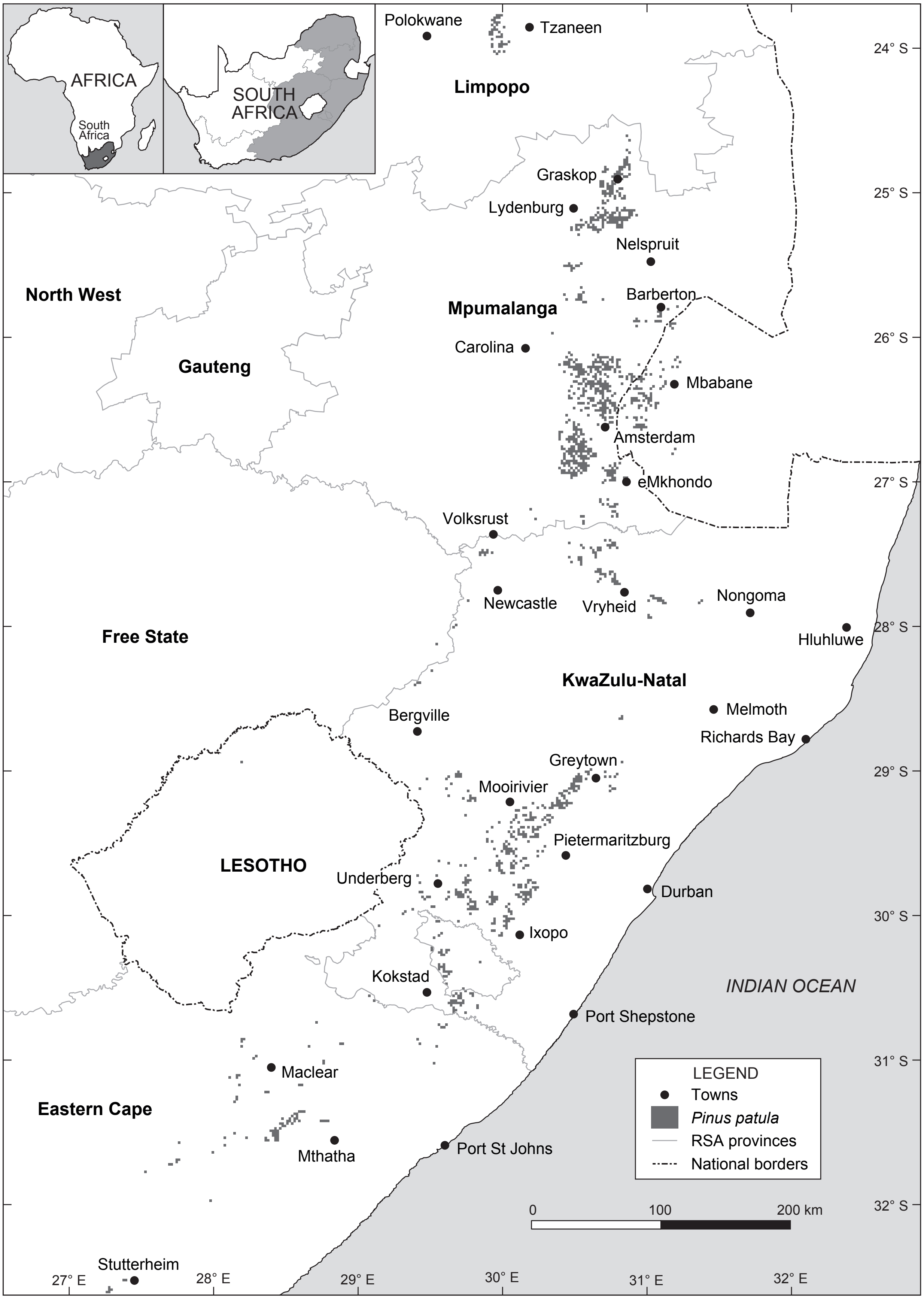

Figure 1: The optimal climatic distribution of *Pinus patula* within the current afforested regions along the eastern escarpment of South Africa

1994 where 22 populations/provenances and over 500 selected trees across Mexico were sampled (Dvorak et al. 1995, Dvorak 1997). The seeds from these trees were distributed to companies in Brazil, Colombia, Chile, South Africa and Zimbabwe where trials were established using the same field design (Dvorak 1997). Similar to the collection by Coetzee and Fisk (Darrow and Coetzee 1983) many of the selections outperformed commercial *P. patula* orchard material for volume which, by this stage, had undergone further improvement (Dvorak et al. 1995). To date, 289 F_1 selections, from 18 provenances, have been identified in the South African Camcore trials (Camcore unpublished data) and are available to members. These selections have not been commercially deployed and local breeding programs have only just begun testing their progeny. Considering that many of the selections outperformed advanced-generation orchard material, it can be expected that these selections would add much value to local breeding programs from the standpoint of productivity and genetic diversity.

Current status

Currently, 340 000 ha are planted to *P. patula* in South Africa, which is approximately 52% of the total area planted to pine (650 000 ha) (DAFF 2010). The tree performs exceptionally well in the afforested regions between Stutterheim in the Eastern Cape and Tzaneen in Limpopo where mean annual temperatures are less than or equal to 16.5 °C and rainfall is greater than 880 or 780 mm a^{-1} at its warmest and coolest planted limits, respectively (Figure 1, derived from gridded data supplied by Schulze et al. 2007). Although *P. patula* has proven to be an excellent species on these sites, it is particularly susceptible to a number of biotic and abiotic stress factors. Owing to its thin bark in the mid and upper sections of the main stem (Dvorak et al. 2000a) *P. patula* dies easily after fire damage (de Ronde and du Plessis 2002) and it is very susceptible to drought and high temperatures during the first year of establishment (Allan and Higgs 2000). Commercial stands of *P. patula* are also frequently affected by pathogens. In the early years of the commercialisation of the species, foresters learned that it was particularly susceptible to infection by the blue stain fungus *Diplodia pinea* (Swart et al. 1985), which could result in the loss of both young and mature stands after hail damage.

Today, the susceptibility of *P. patula* to *F. circinatum* is the most significant reason for poor survival after planting and the cause of death of young trees (Crous 2005). One company has measured a constant annual decline in survival of *P. patula* seedlings from approximately 88% in 2000 to approximately 64% in 2007 (Morris 2011) and it is estimated that 25% of all seedlings die in the first year in those nurseries where the disease has reached epidemic proportions (Crous 2005). It is clear that seedling mortality in the field results from contaminated or infected nursery plants (Mitchell et al. 2011) and, therefore, it is crucial that the pathogen is controlled in the nursery. It has also been noted that the correct planting of seedlings, which may be carrying *F. circinatum* spores, reduces the risk of infection and seedling mortality (Crous 2005), thus highlighting the importance of good silvicultural practice.

Opportunities to improve tolerance

Operational experience indicates that the most effective method to manage *F. circinatum* infections is to plant tolerant stock. This is best done by planting alternative pines, such as *P. elliottii* and *P. taeda,* that are more tolerant to infection (Hodge and Dvorak 2000, Mitchell et al. 2012a). Although the most popular alternative, *P. elliottii*, is known to be susceptible to *F. circinatum* as seedlings (Barnard and Blakeslee 1980), poor-ranking families are still significantly more tolerant than the general tolerance of *P. patula* in South Africa (Mitchell et al. 2012a). Given the good availability of *P. elliottii* and *P. taeda* seed, many forest companies have increased the planting of these two species in areas that were previously planted predominantly to *P. patula*. An analysis of the area planted by York Timbers for the past 6 years clearly shows this trend (Figure 2).

As an alternative to *P. patula* on the subtropical sites, *P. maximinoi* and *P. tecunumanii* have shown outstanding growth (Dvorak et al. 2000b, 2000c, Galpare et al. 2001), excellent wood properties (Malan 2006, 2010) and good tolerance to *F. circinatum* (Hodge and Dvorak 2000). The tolerance of families of *P. maximinoi* and *P. tecunumanii* from low-elevation (LE) provenances to *F. circinatum* is so high (Mitchell et al. 2012a) that they need not be screened to identify tolerant families for deployment. On the other hand, there is large variation between provenances (Hodge and Dvorak 2007) and families (Mitchell et al. 2012a) of the high-elevation (HE) source of *P. tecunumanii*. A number of *P. tecunumanii* (HE) provenances (Hodge and Dvorak 2007) and families (Mitchell et al. 2012a), as seedlings, are as susceptible as the general susceptibility of *P. patula*, which indicates the need to screen families of this source of *P. tecunumanii* to *F. circinatum*. Other subtropical species in the Oocarpa group (Price et al. 1998), such as *P. pringlei*,

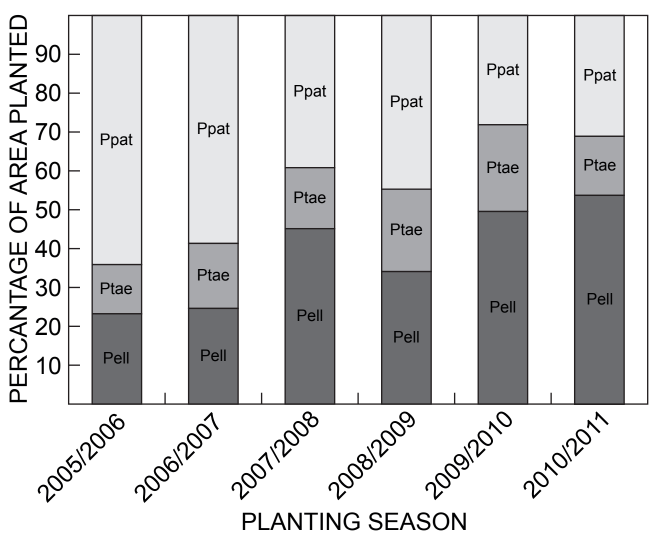

Figure 2: Proportions of *P. elliottii* (Pell), *P. taeda* (Ptae) and *P. patula* (Ppat) that were planted between July 2005 and June 2011 by York Timbers

P. jaliscana and *P. oocarpa*, are also tolerant to infection by *F. circinatum* in greenhouse trials (Hodge and Dvorak 2000). These species have not been field-tested as extensively as *P. tecunumanii* and *P. maximinoi*, but have shown potential for commercial deployment (Darrow and Coetzee 1983). The only species that can tolerate frost and has shown good tolerance to *F. circinatum* in greenhouse trials is *P. pseudostrobus* (Hodge and Dvorak 2000, Mitchell et al. 2012a). Generally, the species does not perform as well as *P. patula*, although some families show similar growth to *P. patula* in first-generation studies testing unimproved material (Camcore unpublished data). This indicates potential for further improvement and commercial deployment of the species.

Hybrids between *P. patula* and tolerant species such as *P. tecunumanii*, *P. oocarpa*, *P. elliottii* and *P. pringlei* (Hodge and Dvorak 2000) are significantly more tolerant to infection by *F. circinatum* than *P. patula* (Roux et al. 2007, Mitchell et al. 2012b). Greenhouse screening studies of these hybrids have shown that there is substantial tolerance in *P. patula* × *P. tecunumanii* (LE) families. In addition, despite significant variation among hybrid families of *P. patula* × *P. tecunumanii* (HE), this hybrid is more tolerant than *P. patula* (Mitchell et al. 2012b). The most susceptible *P. patula* × *P. tecunumanii* (HE) families are similar to the mean tolerance of *P. patula*. Trial results also indicate that the variation in susceptibility of *P. patula* × *P. tecunumanii* (HE) families is mostly because of the specific combination of the two parents (Mitchell et al. 2012b). An added benefit of the *P. patula* × *P. tecunumanii* hybrid is the improvement in frost tolerance over *P. tecunumanii* (Grandos 2012) because of the frost tolerance of *P.patula* (Dvorak et al. 2000a). This has been recorded for other hybrids (Duncan et al. 1996) and consequently it is predicted that hybrids will be more tolerant of climate change (Warburton and Schulze 2006). Young plantings indicate that the *P. patula* × *P. tecunumanii* (HE) hybrid performs well on sites that receive a minimum mean annual rainfall of 800 mm and a mean annual temperature of between 15.0 and 17.0 °C (Figure 3).

Significant variation in the tolerance to *F. circinatum* exists within *P. patula*. Provenances such as El Cielo, Yextla and Conrado Castillo are three of the most tolerant provenances in greenhouse trials (Hodge and Dvorak 2007). Inclusion of material from these provenances in seed orchards should improve the tolerance of commercial plantings. It is also possible to identify tolerant *P. patula* clones within those currently deployed as both trees and seedlings (RGM unpublished data). Tolerance, however, is limited to 5% (RGM unpublished data), which indicates that large numbers of clones need to be tested to identify a sufficient number for the initiation of a new seed orchard comprised of tolerant clones. The tolerance of *P. patula* can also be improved by identifying specific full-sib families, as opposed to identifying open-pollinated families, that produce more tolerant progeny (Mitchell et al. 2012c). Such crosses can be repeated annually. The combined results of these studies indicate that screening large numbers of *P. patula* families and clones for tolerance to *F. circinatum*, in greenhouse and field trials, can identify those with improved tolerance that can be used to establish new seed orchards. This is the most promising long-term strategy for minimising the impact of *F. circinatum* when planting *P. patula*.

Screening for tolerance to *F. circinatum* will become an increasingly important consideration when making future selections in *P. patula*. Advanced generations of *P. patula* have been developed for improved growth but the deployment of this material is severely restricted because of the presence of *F. circinatum*. It is, therefore, likely that breeders will begin focusing on identifying subpopulations of clones tolerant to *F. circinatum*. Given the good growth of *P. patula* × *P. tecunumanii* and *P. patula* × *P. oocarpa*, breeders are already extensively testing specific full-sib family crosses of these hybrids. This will likely extend to selecting those that are also more tolerant of frost.

Large-scale production of improved material

Until tolerant clones and hybrids are developed, good nursery hygiene is critical to ensure the successful deployment of *P. patula*. This is best addressed by ensuring that *F. circinatum* is controlled at each step in the plant production process. This includes ensuring that the growing medium, trays, sowing shed, wooden nursery beds, soil beneath the nursery beds, and any equipment used in the plant production process are free of the pathogen. It is highly recommended that the grow-out area is sterilised between each cycle before the next crop is placed on the beds. This can effectively be done by applying a strong solution of chlorine to the area and follow-up applications of chlorine can be applied to the soil beneath the seedlings during the growing period. It is also important to ensure that all plants adjacent to the newly established seedlings are free of the disease. Only when such rigorous steps are taken can one expect to see an improvement in the control of *F. circinatum*.

Given the limited availability of seed, tolerant *P. patula* clones, families and hybrids will most likely be deployed as rooted cuttings. Historically, nurseries have focused on producing large numbers of seedlings that are relatively easy to produce. The production of cuttings is more complicated. For example, newly placed shoots need to receive regular misting and have elevated root zone temperatures to improve rooting success (Mitchell 2002). In addition, the volume of the pot that hedges are grown in, and nutritional status of the parental hedged plant, is important in determining the quantity and quality of shoots harvested. Hedges have limited lifespans that differ between species and hybrids. *Pinus patula*, for example, can be kept as seedlings in a hedged state for a maximum of 2.5 years before hedges must be replaced (Mitchell et al. 2004, Mitchell and Jones 2006). The implication of this is that controlled-pollinated families that are tolerant to *F. circinatum* need to be annually reproduced in order to continually supply the nursery with juvenile hedge material. Less is known about the maturation period for the *P. patula* hybrids and the large-scale commercial deployment of these must be accompanied by research on this topic. When compared to seedling production, the technology to improve the rooting success and high

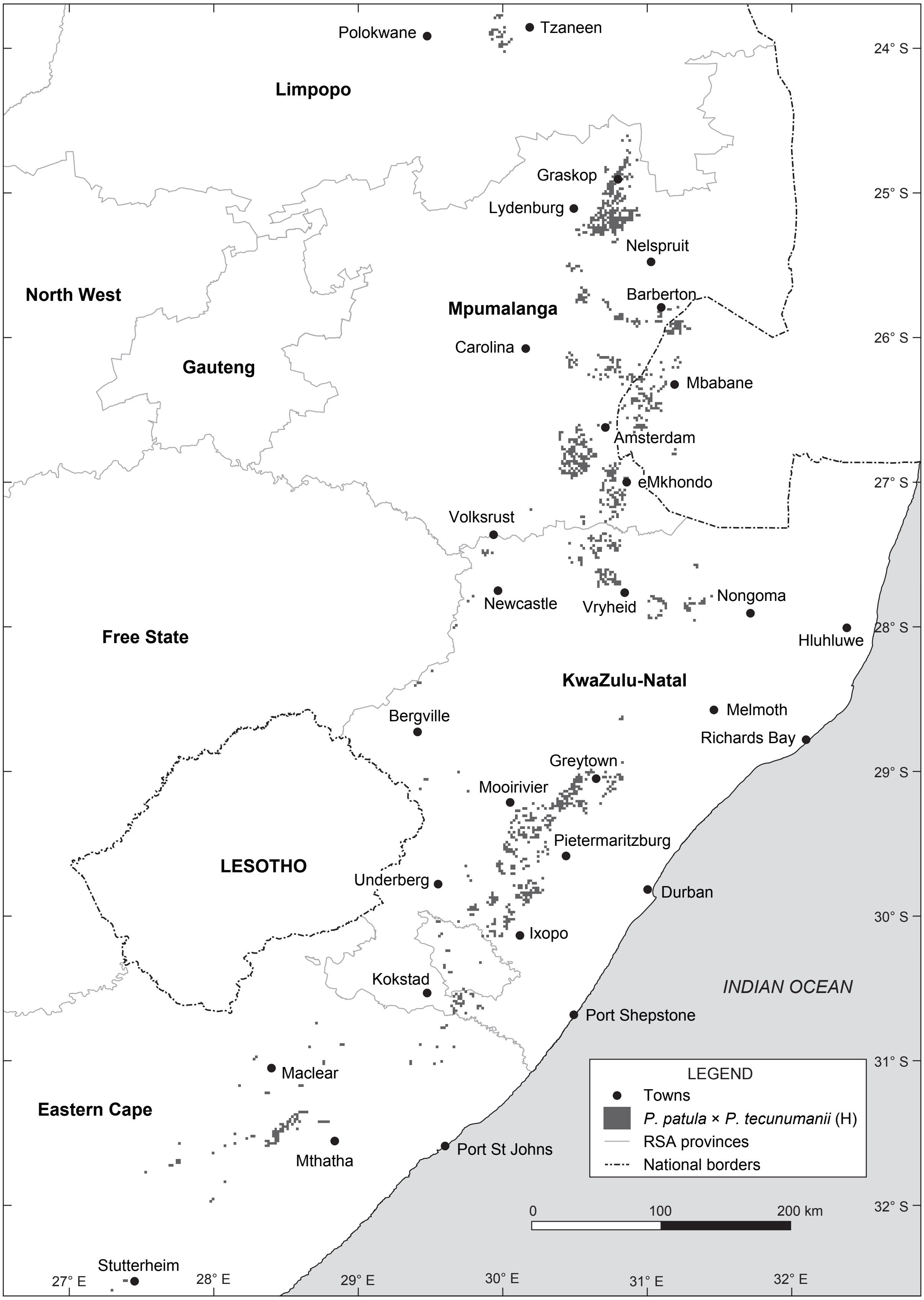

Figure 3: Predicted distribution for those afforested areas that will be climatically well suited to the *P. patula* × *P. tecunumanii* (HE) hybrid (15–17 °C mean annual temperature based on early trial results). These cover a large portion of land also suitable to *P. patula*

Table 1: Three-month survival[1] of *P. maximinoi* and *P. tecunumanii*, compared with that of *P. patula* and other pines, in Camcore progeny trials established during early 2008

Details	Plantation							
	Spitskop, B13	Tweefontein, A84		Brooklands, G2		Wilgeboom, C2		
Location	25°9′42.1″ S 30°50′21.82″ E	25°03′50.7″ S 30°48′51.24″ E		25°18′32.96″ S 30°45′27.29″ E		24°57′4.07″ S 30°56′25.98″ E		
Altitude (m)	1 470	1 260		1 160		980		
Mean annual temperature (°C)	16	17		18		19		
Mean annual precipitation (mm)	>1 300	>1 300		850–1 050		1 050–1 300		
Climatic zone	Temperate	Subtemperate		Warm-temperate		Subtropical		
Trial number	16X08A	15X08A	16X08B	15X08C	16X08C	15X08B	16X08D	
Month and year planted	Jan 2008	Jan 2008	Jan 2008	Mar 2008	Mar 2008	Feb 2008	Feb 2008	
Species	Survival in each trial (%)							Mean survival
P. maximinoi	100.0	93.3	91.7	95.5	97.2	94.2	100.0	96.0
P. patula	83.3	72.2	69.4	86.1	86.1	91.7	75.0	80.5
P. taeda	100.0	–	94.4	–	100.0	–	94.4	97.2
P. elliottii	91.7	91.7	86.1	100.0	94.4	100.0	97.2	94.4
P. tecunumanii (low elevation)	94.6	97.2	92.2	94.4	98.8	94.4	94.7	95.2
P. tecunumanii (high elevation)	96.7	97.2	92.5	97.2	98.6	94.4	93.6	95.7

[1]Trials were blanked one month after planting

throughput of cuttings is changing rapidly and nurserymen will be required to keep abreast of these changes.

Operational deployment

With the addition of alternatives, particularly hybrids between *P. patula* and species tolerant of *F. circinatum*, significant changes to future site–species recommendations will need to be made. These alternatives and hybrids will outperform *P. patula* on many sites and will each occupy a specific niche where *P. patula* has historically been planted. In most cases, species and provenances that are more tolerant to *F. circinatum* (Hodge and Dvorak 2007) are more susceptible to frost (Mitchell et al. 2012d). Therefore, if not exposed to frost, especially in the first year after planting, species such as *P. tecunumanii* and *P. maximinoi* will survive better than *P. patula* because of their good tolerance to *F. circinatum*. This tendency has been observed in a number of Camcore trials (Table 1).

The *P. patula* × *P. tecunumanii* (LE) and *P. patula* × *P. oocarpa* hybrids have become a popular alternative to planting *P. patula* on the warmer sites of South Africa where they also survive better than *P. patula* (Table 2). Undoubtedly, the *P. patula* × *P. tecunumanii* (HE) hybrid is proving to be the most suitable alternative to *P. patula* on a wide range of sites, which include those that are temperate (RGM unpublished data). Not only does the *P. patula* × *P.tecunumanii* hybrid grow well (Nel et al. 2006) and is more tolerant to *F. circinatum* (Roux 2007, Mitchell et al. 2012b), it also has solid wood properties similar to those of *P. patula* (Malan 2010).

Although the susceptibility of *P. patula* to *F. circinatum* has caused the loss of many millions of rands because of the poor survival of seedlings (Mitchell et al. 2011), this has expedited the testing and development of pine hybrids and alternative species (Dvorak 2012). As has been seen with *Eucalyptus* hybrids, not only are these in many cases more tolerant to diseases (Bayley and Blakeway 2002), they are also showing improved growth and wood properties (Malan 1993). It is quite possible, therefore, that the added future benefits of pine hybrids and alternative species far outweigh the losses that *F. circinatum* has caused the South African forest industry.

Table 2: Three-month survival[1] of hybrids between *P. patula* and *P. oocarpa* or *P. tecunumanii* compared with *P. patula* and *P. elliottii* on two sites free of frost

Trial	98-10-H01A3	98-10-H01A1
Plantation	Spitskop, B31b	Wilgeboom C2b
Location	25°08′8.55″ S 30°48′21.85″ E	24°57′4.07″ S 30°56′25.98″ E
Altitude (m)	1 300	970
Climate zone	Warm temperate	Subtropical
Plant date	Nov 2008	Feb 2008
P. elliottii	62%	98%
P. patula	55%	64%
P. patula × *P. oocarpa*	73%	97%
P. patula × *P. tecunumanii* (high elevation)	81%	98%
P. patula × *P. tecunumanii* (low elevation)	76%	98%

[1]Trials were blanked one month after planting

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