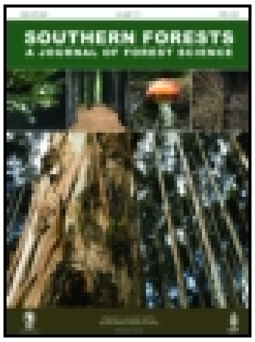


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# Alternative pine hybrids and species to *Pinus patula* and *P. radiata* in South Africa and Swaziland

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**Through the collaborative efforts of companies affiliated with the International Program for Tree Improvement and Conservation (Camcore), a number of pine hybrids have been produced over the last decade. Many of these have been planted in trials across southern Africa that broadly represent winter and summer rainfall areas, with the latter ranging from warm to cold temperate sites. The five-year survival and growth of the hybrids and other pines in 12 of these trials were compared with *Pinus radiata* in the winter rainfall, and *P. patula* in the summer rainfall, regions where these species have been planted extensively. Except for the highest altitude site, where freezing conditions are common, the survival of most hybrids and tropical pines was better than *P. patula* or *P. radiata*. This was, in part, attributed to their improved tolerance to the pitch canker fungus, *Fusarium circinatum*, which was present in the nursery at the time of planting. In the winter rainfall area, the *P. elliottii* × *P. caribaea* hybrid, *P. maximinoi* and, surprisingly, the *P. patula* hybrids performed well. In the summer rainfall regions, hybrids with tropical parents such as *P. caribaea*, *P. oocarpa* and *P. tecunumanii* were more productive in the subtropical/warm temperate zone and, with increasing elevation, those hybrids crossed with *P. patula* performed relatively better. The *P. patula* × *P. tecunumanii* hybrid, particularly when crossed with low-elevation *P. tecunumanii*, performed exceptionally across most sites.**

**Keywords:** productivity, survival, tolerance

## Introduction

Interspecific hybrids offer the opportunity to combine traits from both parent species and this can contribute to improved growth, disease and pest tolerance, and drought or cold resistance in specific environmental conditions. For this reason, and the potential of hybrid vigour, the development of pine hybrid programs is gaining impetus around the world. Assessing the performance of hybrids across diverse environmental conditions is an essential initial step towards determining where they will grow best.

Provenance trials introduced and established in the early 1970s by the Oxford Forestry Institute, and later by the International Program for Tree Improvement and Conservation (Camcore) in the tropics and subtropics, have improved our knowledge on the growth and wood properties of species such as *P. oocarpa*, *P. caribaea*, *P. patula* and *P. tecunumanii*, which are important in hybrid programmes in southern Africa (Mitchell et al. 2012; Malan 2015).The availability of these species presents an opportunity for them to be included in hybrid breeding programs for the purposes of improving growth and reducing the risks associated with climate change and pest and disease (Gapare and Musokonyi 2002; du Toit and Norris 2012; Malan 2015).

In South Africa, the first crosses between *P. elliottii* and *P. caribaea* var. *hondurensis* were established in trials in the late 1960s (Shelbourne 1992; Malan 2015). The primary objective was to combine the good growth characteristics of *P. caribaea* and the higher density of *P. elliottii*. Exceptional performance was observed (van der Sijde and Roelofsen 1986) and *P. elliottii* × *P. caribaea* became the first pine hybrid to achieve commercial status in South Africa. It was suited to sites with poor drainage, had better wind firmness and good stem form in addition to its vigorous growth. The *P. elliottii* × *P. caribaea* hybrid had an advantage in adaptability over both parents.

As a result of this, and many other examples of successful hybrid combinations, companies affiliated with Camcore embarked on a program to produce a number of different hybrids for testing across South America and Africa (Camcore 2007). The objective of this paper is to compare the performance of a number of pine hybrids with current commercial species tested across 12 sites in southern Africa.

## Materials and methods

### *Study material*

Many of the forestry companies that are members of the Camcore research program produced a number of putative pine hybrid crosses between 2003 and 2007. All the putative hybrid crosses were made from first-generation selections. These were verified by Camcore, North Carolina State University, USA where molecular markers were used to discriminate between pure and hybrid species (Camcore 2007). When the putative hybrid seeds were received from the members, some seeds were germinated. From the seedlings obtained, DNA was extracted and molecular markers (single nucleotide polymorphisms) were used for verification. Those seedlots where the molecular markers showed that more than 50% of the seedlings were true hybrids were distributed to regional coordinators (companies with well-established protocols for rooting cuttings). As the regional coordinator for South Africa, Komatiland Forests was responsible for propagating rooted cuttings from the hybrid seed and distributing these to other companies affiliated with Camcore in southern Africa (Table 1). The trials were raised at Tweefontein nursery near Sabie until they were transported to the receiving company 2–3 months before planting.

Trials established by four of the large forestry organisations in southern Africa, namely Komatiland Forests (KLF), Mondi, Sappi and Mountain to Ocean Forestry (MTO), between April 2008 and October 2009 were spread across the Mpumalanga, KwaZulu-Natal, Eastern Cape and Western Cape provinces of South Africa. One trial was planted in Swaziland (a land-locked country within the summer rainfall region of South Africa) (Figure 1). The climatic zones, altitude, mean annual temperature (MAT), mean annual precipitation (MAP) and planting date are summarised in Table 1 and trial locations are indicated by numbers 1 to 12 in Table 1 and Figure 1. The climatic zone classification in this report is according to the description by Louw and Smith (2012) for forest site classification.

Bulk seedlots representing second-generation *P. patula*, *P. maximinoi*, *P. tecunumanii* LE and HE, *P. pseudostrobus*, *P. chiapensis*, *P. elliottii*, *P. taeda* and *P. radiata* ($F_1$ and $F_2$) were used as controls. *Pinus radiata* was excluded from the trials established in the summer rainfall region and *P. patula* was excluded in the trials established in the winter rainfall region (Western Cape). The *P. radiata* seedling control was raised by MTO. The full names for abbreviated taxa used in the text are shown in Table 2.

### *Experimental design*

Depending on the availability of plant material, treatments were planted as 5 × 5 or 6 × 6 tree plots within a randomised complete block design, which was replicated between six and eight times (Table 1). All trees were planted at an espacement of 3 m × 3 m and two border rows were planted around the outer edge of each trial.

### *Data collection and analysis*

*Data collection*

The first survival assessment was carried out one month after planting and the dead plants replaced with cuttings/seedlings representing the same taxon. In the cases where there was an insufficient number of plants, *P. elliottii* or *P. taeda* seedlings were used as fillers and recorded as such. Growth assessments were carried out at age three and five years. In this paper we report on the survival (%), diameter at breast height (DBH; cm), height (m) and volume ($m^3$) of the treatments from the five-year assessment. Tree volume was estimated using the volume equation for juvenile trees (Ladrach and Mazuera 1978):

$$V = 0.00003 * H * \text{DBH}^2 \quad (1)$$

**Table 1:** Site characteristics and location for the 12 hybrid trials established across southern Africa. Site numbers refer to the numbers in Figure 1). MAT = mean annual temperature, MAP = mean annual precipitation, MTO = Mountain to Ocean Forestry, KLF = Komatiland Forests

| Site no. | 1 | 2 | 5 | 4 | 10 | 11 |
|---|---|---|---|---|---|---|
| Plant date | Oct 2008 | Oct 2008 | Apr 2008 | Sep 2008 | Oct 2009 | Jan 2008 |
| Location | Eastern Cape | Western Cape | Mpumalanga | KwaZulu-Natal | Mpumalanga | Mpumalanga |
| Plantation | Witelsbos | Kruisfontein | Wilgeboom | Woolstone (Mvoti) | Brooklands | Tweefontein |
| Latitude | 34°01′01.2″ S | 34°02′26.53″ S | 24°57′04.07″ S | 29°07′ S | 25°18′18.751″ S | 25°03′50.67″ S |
| Longitude | 23°54′44.9″ E | 23°10′29.11″ E | 30°56′25.98″ E | 30°31′ E | 30°45′22.148″ E | 30°48′51.25″ E |
| Altitude (m asl) | 196 | 236 | 970 | 1 137 | 1 160 | 1 255 |
| Replications | 6 | 6 | 8 | 6 | 6 | 8 |
| MAT (°C) | 24 | 16 | 19 | 17 | 18 | 17 |
| MAP (mm) | 942 | 945 | 1 180 | 930 | 1 050 | 1 180 |
| Climatic zone | Mediterranean | Mediterranean | Warm temperate-subtropical | Warm temperate | Warm temperate-subtropical | Warm temperate |
| Company | MTO | MTO | KLF | Mondi | KLF | KLF |
| Site no. | 3 | 7 | 12 | 6 | 9 | 8 |
| Plant date | Jan 2009 | Nov 2008 | Jan 2008 | Oct 2008 | Jan 2009 | Dec 2008 |
| Location | Hhohho | Mpumalanga | Mpumalanga | Mpumalanga | Mpumalanga | Mpumalanga |
| Plantation | Usutu | Spitkop | Spitskop | Spitskop | Jessievale | Belfast |
| Latitude | 26.503° S | 25°08′8.55″ S | 25°09′42.1′ S | 25°08′35.67″ S | 26°13′3.317″ S | 25°39′10.292″ S |
| Longitude | 31.022° E | 30°48′21.85″ E | 30°50′21.8′E | 30°52′14.96″ E | 30°34′25.1″ E | 30°01′15.148″ E |
| Altitude (m asl) | 1 294 | 1 300 | 1 470 | 1 610 | 1 725 | 1 890 |
| Replications | 6 | 6 | 8 | 6 | 6 | 6 |
| MAT (°C) | 17 | 17 | 16 | 15 | 14 | 13 |
| MAP (mm) | 1 150 | 1 180 | 1 300 | 1 300 | 900 | 900 |
| Climatic zone | Warm temperate | Warm temperate | Cool temperate | Cool temperate | Cold temperate | Cold temperate |
| Company | Sappi | KLF | KLF | KLF | KLF | KLF |

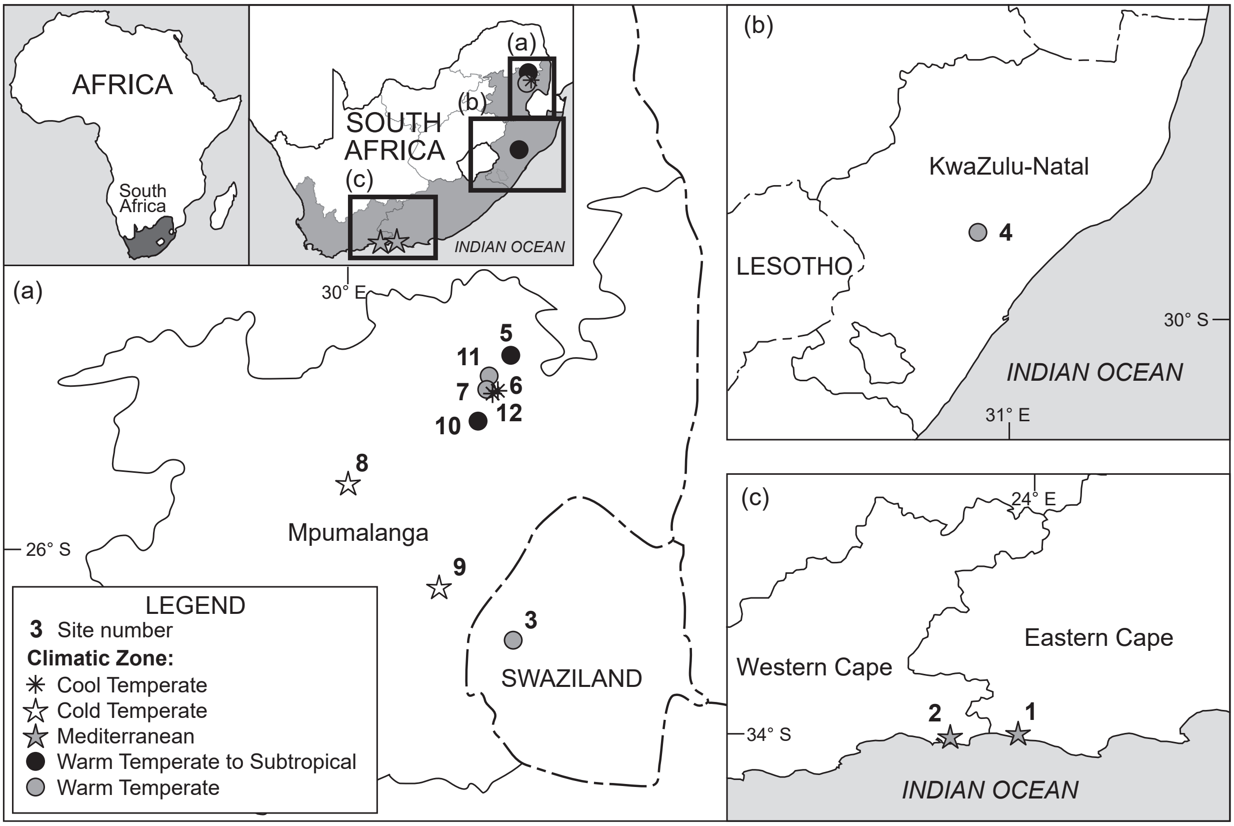


**Figure 1:** Location of the Camcore trials established in southern Africa between 2008 and 2009

where $V$ is the individual tree volume ($m^3$), DBH is the diameter at breast height at 1.3 m and $H$ is the tree height (m). Productivity was estimated using the individual tree volume of the surviving stems per plot across all replications per site.

*Data analysis*

The survival data were not analysed using statistical procedures. Rather the survival results are presented as an average per trial (Figure 2). Growth data were analysed using SAS 9.3 (Enterprise Guide 5.1, SAS Institute Inc., Cary, NC, USA, 2012). A general linear model was carried out using the PROC GLM procedure and the Student–Newman–Keuls (SNK) test was used to distinguish treatment differences at the 5% significance level. The PROC GLM procedure for individual sites was carried out to determine if there were significant differences between taxa (species/hybrid) for volume. All ANOVA results presented are type III sums of squares.

Model 2 was used to differentiate taxa differences at a particular site. In order to determine if taxa by site (altitude) interaction exists, model 3 was used. In each case the SNK ranking and standard error were used to present the results. Site productivity was determined by summing the total area ($m^2$) of all plots on which each treatment was planted, and the total volume of all surviving trees representing each treatment in these plots. The volume over the area of all plots was extrapolated to volume per hectare. All fillers used for blanking were excluded in the analysis.

**Table 2:** Taxa abbreviations used in text for all entries tested

| Taxon abbreviation | Taxon full description |
|---|---|
| Pchiap | *Pinus chiapensis* |
| Ppat | *Pinus patula* var. *patula* |
| Pell | *Pinus elliottii* |
| Ppseu | *Pinus pseudostrobus* |
| Ptae | *Pinus taeda* |
| Prad | *Pinus radiata* |
| Pmax | *Pinus maximinoi* |
| Ptec LE | *Pinus tecunumanii* (low-elevation source; LE) |
| Ptec HE | *Pinus tecunumanii* (high-elevation source; HE) |
| TecH × Car | *P. tecunumanii* HE × *P. caribaea* var. *hondurensis* |
| Car × TecL | *P. caribaea* var. *hondurensis* × *P. tecunumanii* LE) |
| Ell × Tae | *P. elliottii* × *P. taeda* |
| Pat × TecL | *P. patula* × *P. tecunumanii* LE |
| TecL × Car | *P. tecunumanii* LE × *P. caribaea* var. *hondurensis* |
| Pat × Ooc | *P. patula* × *P. oocarpa* |
| Pat × Pring | *P. patula* × *P. pringlei* |
| Pat × TecH | *P. patula* × *P. tecunumanii* HE |
| Ell × Car | *P. elliottii* × *P. caribaea* var. *hondurensis* |
| Pat × GregS | *P. patula* × *P. greggii* var. *australis* (southern variety) |
| Pat × Ell | *P. patula* × *P. elliottii* |
| Car × Ooc | *P. caribaea* var. *hondurensis* × *P. oocarpa* |
| TecH × Ooc | *P. tecunumanii* HE × *P. oocarpa* |
| Tae × Car | *P. taeda* × *P. caribaea* |
| Ell × GregS | *P. elliottii* × *P. greggii* var. *australis* (southern variety) |
| Ell × TecH | *P. elliottii* × *P. tecunumanii* HE |

The models used in the study for the analysis of the data are:

$$\bar{y}_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij} \quad (2)$$

where $\bar{y}_{ij}$ is the $j$th observed mean yield response of the $i$th taxon; $\mu$ is the overall mean yield of taxa at a possible environment; $\alpha_i$ represents the fixed effect of the $i$th replicate; $\beta_j$ represents the random effect of the $j$th taxon; and $\varepsilon_{ij}$ is the random error term.

$$\bar{y}_{ij} = \mu + \alpha_{ik} + \beta_j + \gamma_k + (\beta\gamma)_{jk}\ \varepsilon_{ijk} \quad (3)$$

where $\bar{y}_{ij}$ is the $j$th observed mean yield response of the $i$th taxon; $\mu$ is the overall mean yield of taxa at a possible environment; $\alpha_{ik}$ represents the fixed effect of the $i$th replicate in the $k$th site; $\beta_j$ represents the random effect of the $j$th taxon; $\gamma_k$ represents the fixed altitude effect of the $k$th site; $(\beta\gamma)_{jk}$ is the interaction random effect of the $j$th taxon in the $k$th site; and $\varepsilon_{ijk}$ is the random error term.

## Results

### *Survival*

The survival of *P. patula* in the summer rainfall region was in most instances poor. This was particularly true at the Tweefontein A84 (34%) and Spitskop B31b (36%) sites (Figure 2). In several cases, the dead and dying *P. patula* seedlings displayed symptoms that were typical of those associated with the pitch canker fungus, *Fusarium circinatum* (Mitchell et al. 2011). Samples were submitted to the Forestry and Agricultural Biotechnology Institute (FABI) at the University of Pretoria, where the fungus was positively identified. Mean site survival at Belfast, where night-time freezing temperatures are common during winter,

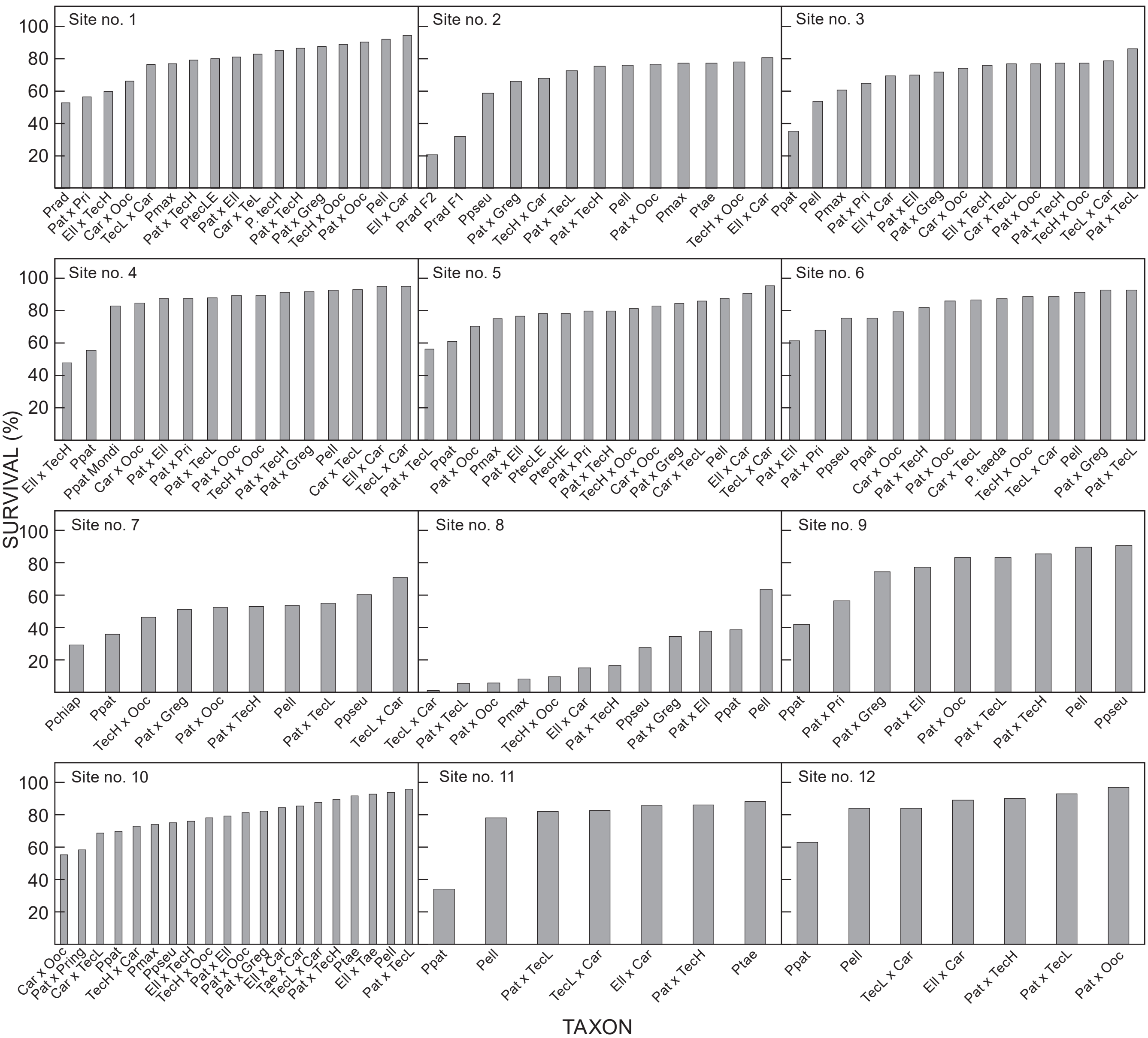


**Figure 2:** Survival at five years for all treatments at each of the 12 sites

was poor at 14.6% (Figure 2). It can be speculated that the poor survival of *P. patula* at Belfast and Jessievale was due to the presence of *F. circinatum* as seen in the other trials as it was planted with seedlings that originated from the same nursery.

Generally, the tropical hybrids crossed with *P. caribaea* as a parent showed better survival than *P. patula* and *P. radiata*. The only exception was when survival was impacted by frost (Figure 2). With increasing elevation, the relative survival of these hybrids decreased with very poor survival in the cold temperate sites. The survival for *P. elliottii* × *P. caribaea* and *P. tecunumanii* LE × *P. caribaea* was 15% and 1%, respectively, at Belfast, which was the coldest and highest altitude site (Figure 2).

The survival of *P. patula* hybrids was on average 23% better than *P. patula* (excluding Belfast) and at Belfast *P. patula* was 18% better than the *P. patula* hybrids. In the Mediterranean region, survival of *P. patula* hybrids was 45% better than that of *P. radiata*. The ranking of hybrids such as *P. patula* × *P. tecunumanii* LE and HE was generally good, but was outperformed by *P. tecunumanii* LE × *P. caribaea*, *P. taeda*, *P. elliottii* and *P. pseudostrobus* in most sites.

*Pinus elliottii* and *P. taeda* survived 20–40% better than *P. patula* and *P. radiata* across all sites (Figure 2). The species also survived better than most of the hybrids, with the exception of *P. elliottii* × *P. caribaea*. *Pinus elliottii* and *P. taeda* were the best surviving entries both at Belfast and Jessievale where frost was common. At lower altitudes and frost-free areas, *P. maximinoi* and *P. tecunumanii* LE and HE survival was generally above 70%. The survival of *P. pseudostrobus* was generally moderate on most sites ranging between 60% and 70%; it survived best at Jessievale (90%) and worst at Belfast (27%).

Similar to *P. patula* in the summer rainfall regions, the survival of *P. radiata* in the winter rainfall regions was very poor (below 30% at Kruisfontein and slightly over 50% at Witelsbos) (Figure 2). Although dying *P. radiata* seedlings were not assessed for the presence of *F. circinatum*, the high incidence of this pathogen in the area and susceptibility of *P. radiata* to *F. circinatum* leads us to speculate that this pathogen was responsible for the high mortality. *Pinus patula* × *P. tecunumanii* hybrids, *P. patula* × *P. oocarpa* and *P. patula* × *P. greggii* South survived significantly better (66–90%) and were comparable to *P. maximinoi* (77%) on both sites and *P. tecunumanii* LE (80%) and *P. tecunumanii* HE (85%) at Witelsbos.

Propagation material (seedlings and cuttings) were reported to have no impact on survival of *P. patula* (Mitchell et al. 2005). However, environmental conditions that are site specific and extreme conditions can play a major role in affecting survival. The study by Mitchell at al. (2005) concluded that correctly graded plant stock can improve the survival after planting. With best nursery practice, cuttings can have a well-developed root system and a larger root collar diameter compared with those of seedlings. These conclusions were based on *P. patula* and on pine hybrids there may be different outcomes but insufficient studies have been conducted. The personal observations are that hybrids develop at different rates, and some require more time to develop a sufficient rooting system. Some remain in the grass stage longer and are generally smaller during planting.

### *Growth*

Mean tree growth between the 12 sites, between taxa across sites, and the interaction between the two effects, differed significantly ($p < 0.0001$). Similarly, the mean growth performance of the trees representing each climatic zone viz. cold temperate, warm temperate, warm temperate to subtropical, and Mediterranean (Table 1) differed significantly and there was a significant change in the performance of the various taxa tested in each of the climatic zones ($p < 0.0001$).

On a yield per hectare basis, *P. patula* hybrids performed generally significantly better than *P. patula*, *P. elliottii* and *P. taeda* across most sites. The *P. patula* × *P. tecunumanii* hybrids and *P. patula* × *P. oocarpa* were particularly good on the warm sites (over 40 $m^3$ $ha^{-1}$) (Figure 3), but below 15 $m^3$ $ha^{-1}$ on colder sites such as Jessievale and Belfast.

The growth of *P. elliottii* × *P. caribaea* and *P. caribaea* × *P. tecunumanii* LE outperformed *P. elliottii* and *P. tecunumanii* LE (Figure 4) on the lower elevation sites. The productivity of these hybrids was generally better than *P. patula* hybrids on the lower sites. The productivity of *P. elliottii* × *P. caribaea* was better at Wilgeboom than at Brooklands and Witelsbos (Figure 3). However, on the warm to cold temperate zones the *P. patula* hybrids were generally better than hybrids such as *P. tecunumanii* LE × *P. caribaea* and *P. elliottii* × *P. caribaea* .

*Pinus radiata* had better growth than most entries at Witelsbos. On this site, it was not significantly different from *P. elliottii* × *P. caribaea* and *P. elliottii*. However, at Kruisfontein *P. radiata* performed poorer than *P. elliottii* × *P. caribaea* for both generations (Figure 4). The individual tree volume for *P. radiata* ($F_1$) was higher at Kruisfontein (0.03 $m^3$) than at Wiltelsbos (0.02 $m^3$) and a similar observation was made for volume per hectare, which was higher at Kruisfontein than at Witelsbos (Figure 3). The growth performance of *P. maximinoi* and *P. tecunumanii* LE was generally as good as or better than the commercial species viz. *P. radiata*, *P. patula* and *P. elliottii* on the sites that did not experience frost, with the exception of the lowest elevation Mediterranean site at Witelsbos.

*Pinus patula* × *P. tecunumanii* hybrids and *P. patula* × *P. oocarpa* showed significant potential on the warm to cool temperate regions (Figure 3). No differences in volume were found between *P. patula* and *P. patula* × *P. tecunumanii* LE at the cold temperate site of Belfast. However, survival of *P. patula* was 38% and only 5% for the hybrid.

Generally, *P. elliottii* × *P. caribaea* performed better at most sites across the climatic zones than *P. elliottii* and *P. patula*. In the Mediterranean zone, which is located in the Cape, *P. elliottii* × *P. caribaea* had a mean volume of 0.0318 $m^3$, which was better than that of *P. radiata* and *P. elliottii* in the same region.

## Discussion

### *Mediterranean region*

The average survival was higher at Witelsbos than Kruisfontein, and *P. radiata* had the poorest survival on both sites. The average survival for *P. radiata* ($F_1$ and $F_2$) was lower at Kruisfontein than at Witelsbos (Figure 2). The poor survival is likely to be associated with *F. circinatum* as it was an established pathogen in the nursery at the time. An outbreak of *F. circinatum* on young *P. radiata* between 5 and 9 years was reported in the Western Cape in 2005 (Coutinho et al. 2007). The trials reported on in this study were planted between 2008 and 2009; the *P. radiata* seedlings were supplied by the nursery in the same area where the outbreak was first reported.

*Pinus elliottii* × *P. caribaea* was the best surviving entry at both sites (94% and 81% at Witelsbos and Kruisfontein, respectively). Other combinations such as *P. elliottii*, *P. tecunumanii* (HE) × *P. oocarpa* and *P. patula* × *P. oocarpa* could be alternatives to improve survival as they performed better than *P. radiata* on both sites. This is likely due to their higher levels of tolerance to *F. circinatum* (Hodge and Dvorak 2000).

On volume productivity, *P. elliottii* × *P. caribaea* ranked better than most of the entries; at Witelsbos there was no observed differences between *P. elliottii* × *P. caribaea* and *P. radiata*, whereas at Kruisfontein *P. elliottii* × *P. caribaea* was highly significantly better than *P. radiata* (Figure 4). Generally, in the Mediterranean zone, *P. elliottii* × *P. caribaea* showed the best performance in terms of mean volume (Figure 3).

Alternatively, *P. tecunumanii* (LE and HE), *P. patula* × *P. tecunumanii* HE and *P. patula* × *P. oocarpa* showed promising results in terms of survival and mean volume at Kruisfontein. These species could be alternatively used in place of *P. radiata* to improve both survival and volume productivity. There were huge differences in volume productivity at the sites Kruisfontein and Witelsbos (Figure 3). This

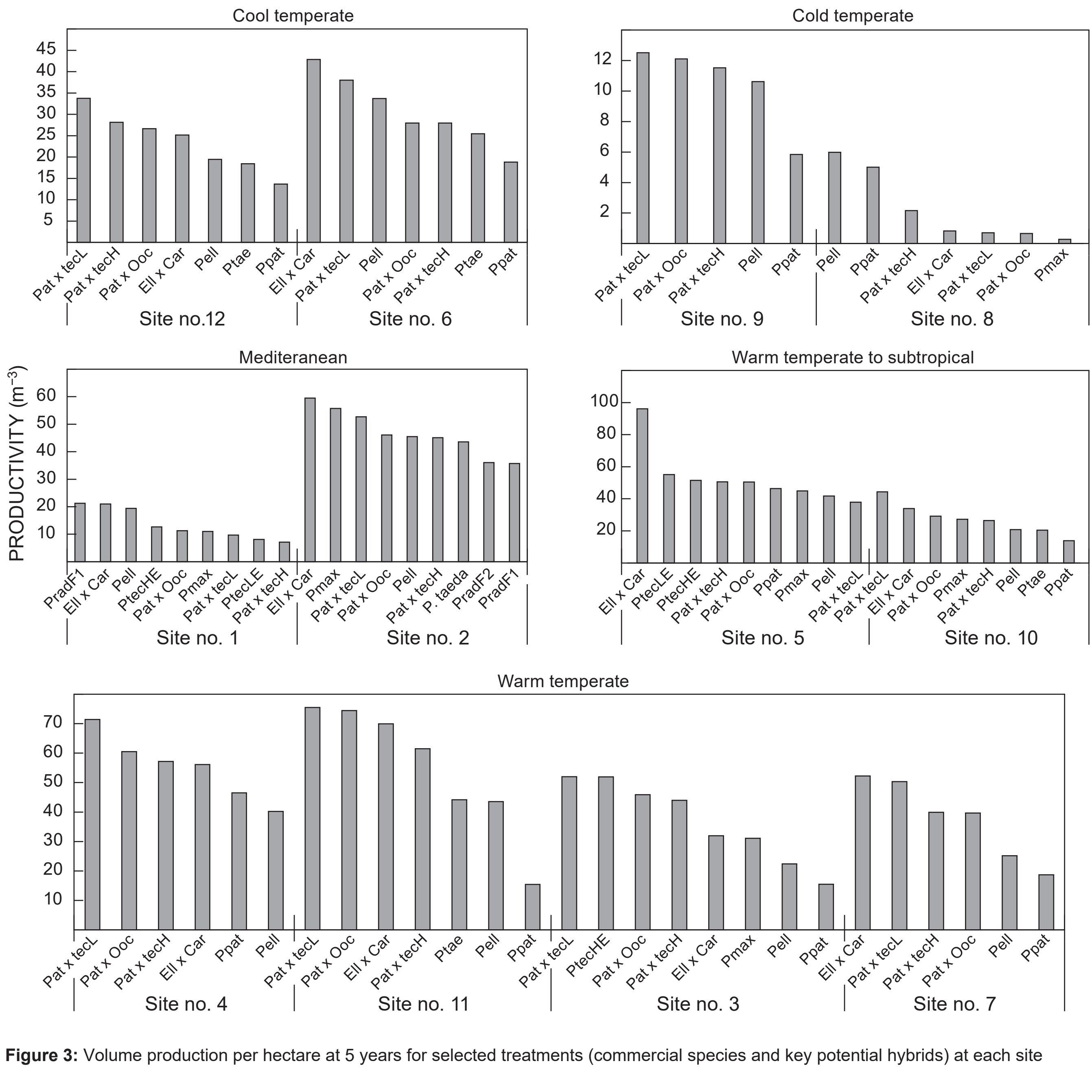


**Figure 3:** Volume production per hectare at 5 years for selected treatments (commercial species and key potential hybrids) at each site

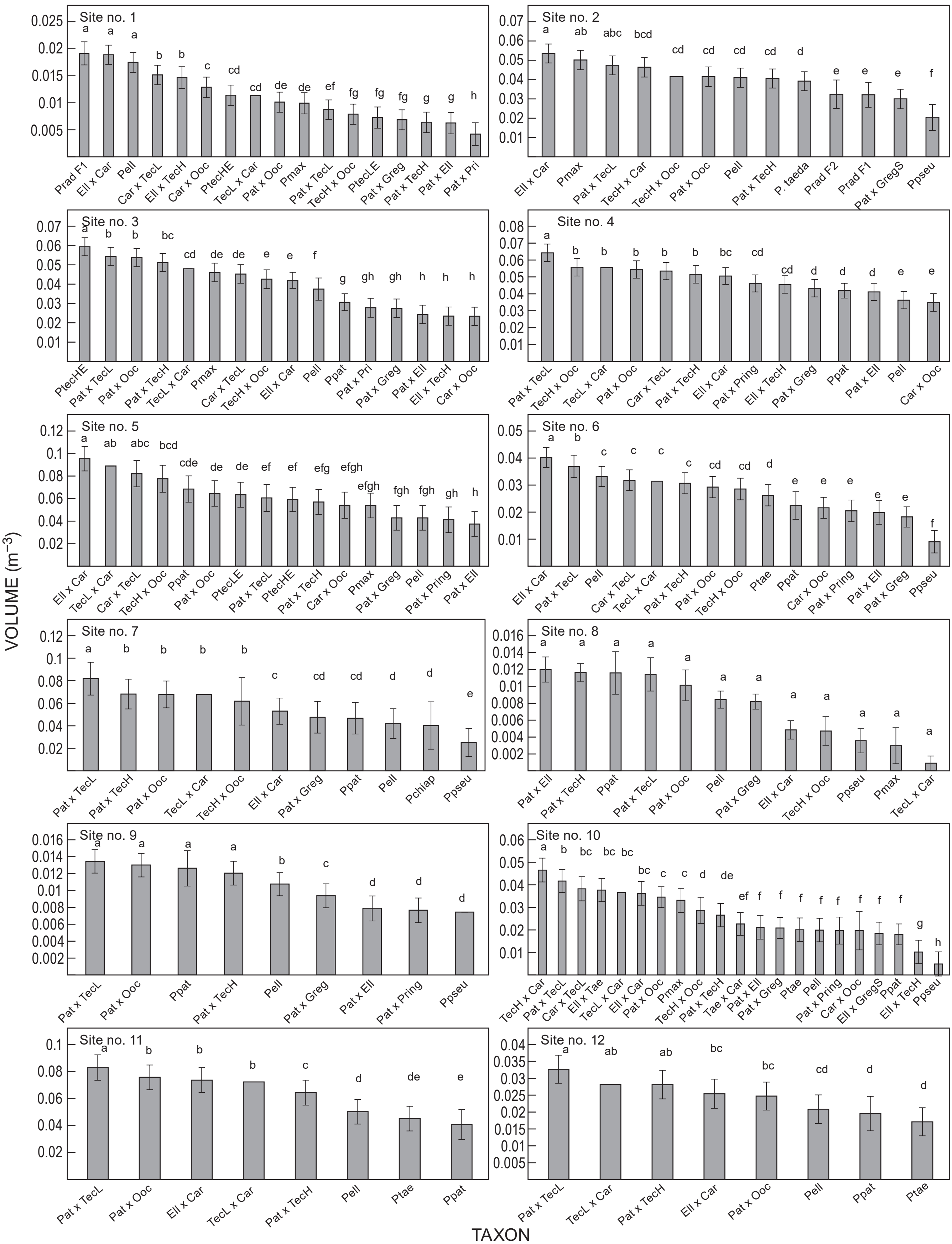


**Figure 4:** Individual tree volume at 5 years for all entries at each site. Error bars represent the SE. Different letters above bars indicate a significant difference at the 5% significance level

could reflect a direct impact of site index and differences in soil properties between the two sites.

***Warm temperature regions***

The warm temperate regions are located on the escarpment of Mpumalanga province. This area is mostly covered by fog and misty weather at most times. In this area the survival of most hybrids was better than *P. patula* at most sites. The poor survival of *P. patula* was confirmed to be due to the pitch canker fungus, *F. circinatum* (Hongwane et al. 2017).

In the warmer temperate region, the survival of the *P. patula* × *P. tecunumanii* hybrid was improved because of the *F. circinatum* tolerance of the *P. tecunumanii* parent (Mitchell et al. 2011). *Pinus tecunumanii* LE is reported to be more tolerant to *F. circinatum* than *P. tecunumanii* HE (Mitchell et al. 2011). Although the *P. patula* × *P. tecunumanii* HE hybrid may be able to tolerate mild frost, it will not survive as well as *P. patula* under heavy frost conditions (du Toit 2012). *Pinus patula* × *P. oocarpa* is also expected to show good survival due to its resistance to *F. circinatum* and drought (Dvorak et al. 2009) on sites that are free of frost. It may not be expected to survive better in harsher environments at higher altitudes as it is not frost tolerant.

In the absence of freezing temperatures, pine hybrids such as *P. elliottii* × *P. caribaea*, *P. patula* × *P. tecunumanii* hybrids and *P. patula* × *P. oocarpa* will survive significantly better than *P. patula* due to their increased levels of tolerance to the pitch canker pathogen, *F. circinatum*, and they are also better adapted to the environmental conditions where they were planted. Partly due to this reason they are becoming the preferred choice on warmer sites in the summer rainfall region.

In the warm temperate regions, care must be taken not to deploy hybrids in areas that experience localised frost. In addition, deploying them in areas prone to strong winds or hail should be avoided (Dvorak et al. 2000). Generally, under favourable conditions, hybrids such as *P. patula* × *P. tecunumanii* LE and *P. elliottii* × *P. caribaea* can perform better than *P. patula*, *P. elliottii*, *P. taeda* and *P. radiata*.

Hybrids such as *P. elliottii* × *P. caribaea* have the potential on the lower elevation sites to replace *P. radiata* and *P. patula* because of growth advantage (du Toit 2012; Malan 2015). *Pinus patula* × *P. tecunumanii* hybrids are potentially preferred to replace *P. patula* over a wide range of sites (Kanzler et al. 2014). Both of these hybrids have maintained a good stocking over *P. radiata* (in the Mediterranean region) and *P. patula* (in summer rainfall areas).

***Cool to cold temperate regions***

In the cold temperate regions, i.e. above 1 400 m above sea level (asl) in the Jessievale and Belfast areas, the survival of *P. patula* was less than 40%, which was similar to that at Tweefontein, Usuthu and Spitskop. *Pinus pseudostrobus*, *P. elliottii* and *P. patula* × *P. tecunumanii* (LE and HE) had the highest survival rates at Jessievale (above 80%) and at Belfast *P. elliottii* showed 63% survival. Belfast is a very harsh site, with night temperature falling below zero degrees Celsius for consecutive days. Figure 5 depicts

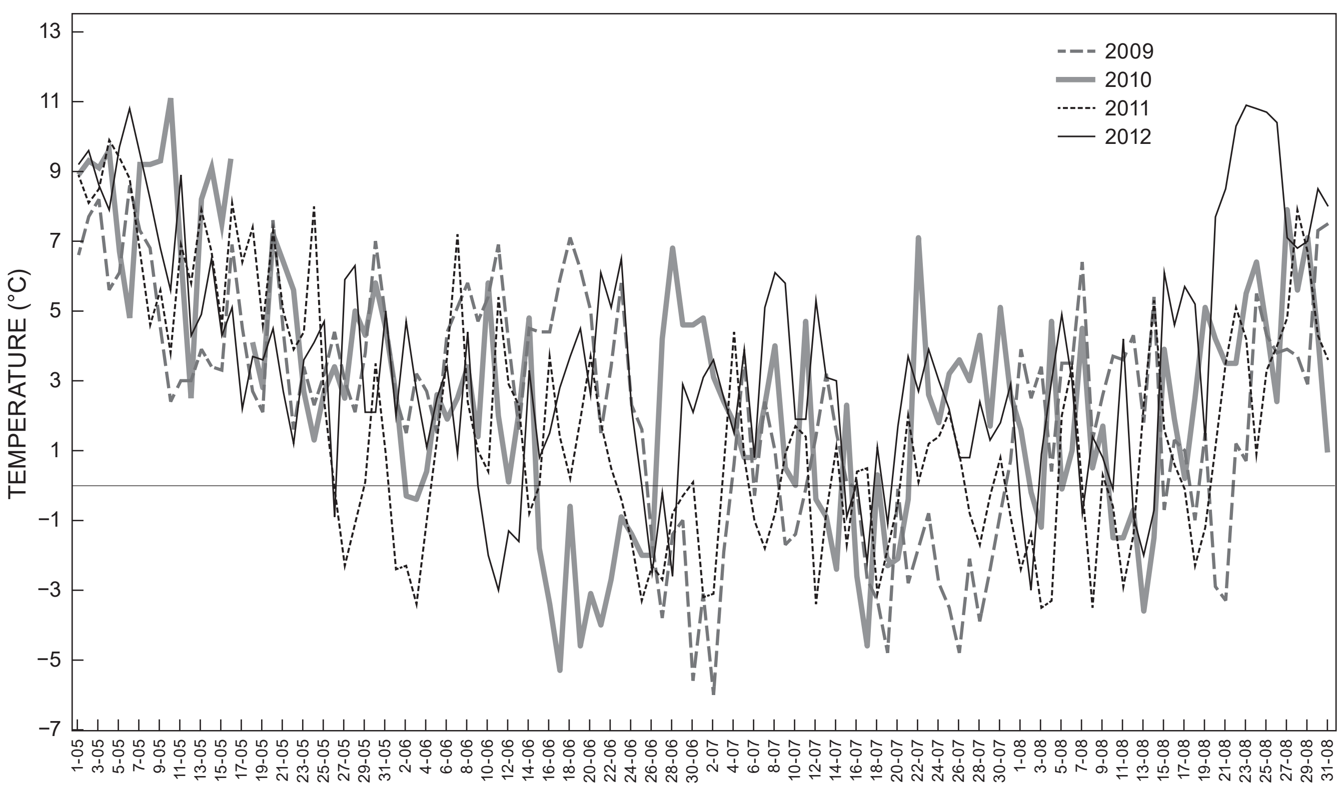


**Figure 5:** Minimum temperatures for Belfast between May and August in 2009 to 2012 (data provided by South African Weather Service 2017)

the actual winter minimum temperatures for the first four years (2009 to 2012) for Belfast, Mpumalanga province where the trial was planted (data provided by the South African Weather Service 2017). Freezing temperatures for consecutive days (Figure 5) could have a significant impact on the survival of less than six-month-old seedlings and cuttings, as temperatures started to drop below 5 °C in May 2009 and more than three days of freezing nights in its first winter.

On individual tree volume, there was no signaificant difference between *P. patula* × *P. tecunumanii* (LE and HE), *P. patula* × *P. oocarpa* and *P. patula* at Jessievale (Figures 2 and 4). At Belfast no significant differences were observed in tree volume, which was caused by the extremely poor survival and small sample size. There is an opportunity for *P. patula* × *P. tecunumanii* HE to replace *P. patula* in frost-free areas in the Highveld. However, *P. patula* remains the preferred species of choice in colder and harsher sites such as Belfast.

The *P. patula* × *P. tecunumanii* HE hybrid may show some tolerance to mild frost and may be expected to survive. However, *P. patula* would still survive better (du Toit 2012). *Pinus patula* × *P. oocarpa* is also expected to show good survival due to its resistance to *F. circinatum* and some drought tolerance (Dvorak et al. 2009). It may not be expected to survive better in harsher environments at higher altitudes as it is not frost tolerant, but it is drought tolerant (Kanzler et al. 2014). From 1 000 m asl and above, *P. patula* × *P. tecunumanii* hybrids are preferred for deployment to improve survival. However, as the conditions become too harsh, cold and dry, *P. patula* is the preferred specie. *Pinus patula* shows some tolerance to drought after it is well established in the field (Dvorak et al. 2000).

No conclusive observation was made on survival of *P. pseudostrobus* on the higher elevation sites and *P. patula* × *P. greggii* South also survived poorly on the same sites. Poynton (1979) reported similar results for *P. pseudostrobus* in these same areas. *Pinus pseudostrobus* was reported to perform better in the warmer temperate zone in the mist belt areas. However, it did not perform well for survival, growth and volume yield across all climatic zones in these series of trials. As a species, *P. greggii* has greater tolerance to drought and is better suited to harsher sites than *P. patula*. The northern population of *P. greggii* is, however, more cold and drought tolerant than the southern population and *P. patula* (Kanzler et al. 2014). In South Africa, heavy snow had little impact on both populations of *P. greggii* (Dvorak et al. 1996). The *P. patula* × *P. greggii* South hybrid may be expected to survive better than *P. patula* with respect to cold tolerance (Kanzler et al. 2014).

## Conclusion

The survival of most hybrids and tropical pines was better than *P. patula* or *P. radiata* except at the highest altitude sites. Tolerance to the pitch canker fungus, *Fusarium circinatum*, contributed to the survival of certain hybrids over *P. patula* and *P. radiata*. In the winter rainfall area, the *P. eliiottii* × *P. caribaea* hybrid, *P. maximinoi* and the *P. patula* hybrids performed well. In the summer rainfall regions, hybrids with tropical parents such as *P. caribaea*, *P. oocarpa* and *P. tecunumanii* were more productive in the subtropical/warm temperate zone, and with increasing elevation those hybrids derived from crosses with *P. patula* performed relatively better.

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