ABSTRACT

NILSSON, NILS BERTIL OSCAR. Growth and Modulus of Elasticity of Selected Pine Species and Hybrids Three Years After Planting in South Africa. (Under the direction of Dr. Gary R. Hodge, Dr. Lewis J. Frampton, Dr. William S. Dvorak and Dr. Johan Bergh).

Growth data and modulus of elasticity (MOE) of 11 different pine species and hybrids were examined at six sites in three different regions in South Africa. Tests were measured approximately three years after planting. Growth traits and three different MOE variables were assessed in order to see if there were pine species more suitable than the current commercial species. Average survival across sites was 61.8 % and varied from 26.4 % to 87.8 %. Most sites exhibited significant species differences for growth traits. There were significant interaction effects for species within the regions for growth traits. There were significant species differences for all three MOE variables at all of the four sites that were included in the analysis of wood properties. When combining the four sites that were used for the wood property analyses, there were significant species differences for the three different MOE variables. Across all four sites where wood properties were analyzed the MOE variable ranged from 3.03 to 6.40 GPa. Based on the results from this study, despite the high mortality rates that were experienced on many sites, there are alternative pine species that are showing comparable growth rates to the current commercial species. For approximating MOE, it is concluded that assuming a constant green density does not affect the species ranking but if the aim is to find the “true” MOE, sampling in the field is needed.

Growth and Modulus of Elasticity of Selected Pine Species and Hybrids Three Years After Planting in South Africa

by
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DEDICATION

To my grandparents, Folke and Karin Nilsson, Bertil and Signe Petersson for always being there.

BIOGRAPHY

Oscar Nilsson was born in Loshult, Sweden, the 30th of September 1986. He graduated from secondary school in Sollentuna in 2002 and from high school in Ängelholm in 2005. He continued his studies in 2008 at the Swedish University of Agricultural Sciences (SLU) in Umeå, where he graduated in 2011 with a Bachelor's degree in forest science. He subsequently enrolled in the Euroforester Masters Program at the Swedish University of Agricultural Sciences in Alnarp. After completing the Euroforester Master Program, he continued his studies as a student in the Atlantis program in the EU-US Transatlantic Masters degree in Forest Resources at North Carolina State University, in 2012.

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CHAPTER 1 INTRODUCTION AND LITERATURE REVIEW

1.1 General

The forest industry makes an important contribution to the South African economy, producing 1.2 % of GDP (SAY 2012). Approximately 1.3 million hectares of forest plantations exist in the country, which represents 1.04 % of the total land area. Softwood species are used on roughly half of the plantation area. Softwood plantations are managed mainly for sawlogs but also for pulpwood to some extent. The major use of the sawn timber is as building products however, some sawn timber is used for furnishing and electric poles. Eighty-three percent of forest plantations in South Africa are privately owned (FES 2012). Further expansion of plantation land is limited by agriculture and dry climates, so it will be important to increase wood production per ha through gains in tree breeding and intensive silviculture practices. Additional improvements are possible from better species-site matching and use of alternate species and hybrids.

An important component in modern commercial plantation forestry is genetic tree improvement in order to improve traits such as growth, quality, disease resistance, etc. (du Toit and Norris 2011, Dvorak 2012). Genetic tree improvement can increase volume growth, decrease rotation lengths and may lead to more valuable end products. Hence, genetic tree improvement is of crucial value since it increases the profitability of plantation forestry.

A big challenge in management of forest plantations in South Africa is the high diversity of different site types. Topography and climatic conditions varies within a big spectrum, which makes site-specific species-matching crucial to optimize growth and profitability (du Toit 2012). Testing different species on a multitude of different sites will contribute to the knowledge of which species are most suited to different sites and could identify "new" species that are not yet planted commercially by the South African forest industry on a large scale (Hodge and Dvorak 2012).

du Toit (2012) recently made quite extensive site-specific pine species recommendations in South Africa focusing on the most established pine species. However, the current study includes second generation pine species on a multitude of sites in South Africa which is unique and important since this planting stock includes genetically improved material.

Over the last 30 years, the South African forest industry has worked actively with tree improvement in cooperation with Camcore (International Tree Breeding and Conservation Program), testing and evaluating large genetic bases of material from Mesoamerican pine species. The aim was, and still is, to improve existing breeding programs and to find "new" suitable pine species for plantation forestry (Hodge and Dvorak 2012). The primary pine species for use in plantation forestry in South Africa are *Pinus patula* Schiede ex Schlecht. & Cham. var. *patula*, *Pinus elliottii* Engelm., the *P. elliottii* Engelm. x *P. caribaea* Morlet var. *hondurensis* (Sénéclauze) W.H. Barrett & Golfari hybrid and *P. radiata* var. *radiata* D. Don. Lesser amounts of *Pinus greggii* Engelm. ex Parl. var. *greggii* (*Pinus greggii* North) and

Pinus greggii Engelm. ex Parl. var. *australis* (*Pinus greggii* South), *Pinus maximinoi* H.E. Moore and *Pinus tecunumanii* Eguiluz & J.P. Perry (Dvorak et al. 2009, Hodge and Dvorak 2012) have been planted. These species are interesting for the forest industry in South Africa because of their adaptability to different sites and a multitude of environmental niches (Hodge and Dvorak 2012).

There are indications that other Mesoamerican pine species have better growth than *P. patula* to different degrees on different site types in South Africa (Dvorak and Shaw 1992, Dvorak and Donahue 1992, Dvorak and Ross 1994, Dvorak et al. 1996, Hodge and Dvorak 2012). Hodge and Dvorak (2012) concluded that both genetically unimproved *P. tecunumanii* and *P. maximinoi* showed considerably better growth than the genetically improved *P. patula* across a range of sites with low frost incidence. In the same study, unimproved *P. greggii* var. *australis* showed good potential as an alternative species, with slightly lower growth than *P. patula*. It should be taken into consideration that the alternative species are unimproved, compared to the improved comparison species *P. patula*. An increased growth gain of approximately 5-25% can be expected for the first generation of improved pines (Gleed 1982, Eldridge 1982, van Wyk and van der Sijde 1983, Cleland 1985, Talbert et al. 1985, Shelbourne et al. 1989, Rehfeldt et al. 1991, McKeand and Svensson 1997, Carson et al. 1999, Mugunga 2003). Verryn and Snedden (2012) illustrated an overall plantation production increase of 90% in South Africa, most probable from tree improvement and silviculture when comparing growth in 2005 to a baseline of 1980. Noticeable is that the plantation area only increased by 10% during the same years.

1.2 Objectives

The objectives of this thesis are to:

i. Assess if there are pine species with better growth than the commercially used species.

ii. Determine if alternate species have better Modulus of Elasticity (MOE) than the commercially used species.

The first objective is addressed by using growth data collected from Camcore species-site trials in South Africa. The second objective is addressed by sampling individual trees in the same trials to determine some wood properties.

1.3 *Pinus elliottii*

Pinus elliottii is an important commercial timber species in its native range, which is in the lower coastal plain of southeastern USA, ranging from South Carolina to Florida. The natural habitat of *P. elliottii* is in the proximity of streams, swamps and bays where soil moisture is high. However, current fire suppression in this region has given the species an opportunity to spread into dryer sites, replacing other species (Barnett 2002). Annual precipitation in its native environment ranges from 1150-1500 mm with the majority of rain falling during the eight to nine month-long growing season. Furthermore the species is adapted to a dry season of one to four months. The species occurs at low altitudes, most often from sea-level to 150 m on a variety of soils. However, *P. elliottii* grows best on deep well-drained soils that are capable of holding abundant amounts of water provided from rain, during the growing season. The mean annual temperature is in the range 15 to 24^{o}C (Barnett 2002).

The species has been introduced to a number of other countries, South Africa among them, due to the fast juvenile growth and highly valuable wood products (Barnett 2002, Mullin et al. 2011). In South Africa, *P. elliottii* is the second most planted pine species, behind *P. patula*, occupying slightly more than 27 % of the softwood plantation area (FES 2012). Laboratory results have shown that *P. elliottii* exhibits moderate frost tolerance, similar to *P. tecunumanii* HE (Hodge et al. 2012), even though field results would probably show a higher cold resistance than *P. tecunumanii* HE. The species has shown relatively high susceptibility to the pitch canker fungus in the southern US, even though it is less susceptible than *P. patula* (Hodge and Dvorak 2000). However, in South Africa *P. elliottii* is considered to be less susceptible. Variation in pitch canker tolerance in southern US is extensive and heritability is high which means high potential for genetic improvement towards increased pitch canker tolerance for *P. elliottii* (Mitchell et al. 2012). The drawback with *P. elliottii* compared to *P. patula*, is its slower growth, which might not compensate for its higher resistance (Mitchell et al. 2012).

1.4 *Pinus greggii*

Pinus greggii is a Mesoamerican pine that is represented by two varieties, *Pinus greggii* var. *greggii* (*Pinus greggii* North) and *Pinus greggii* var. *australis* (*Pinus greggii* South). In their native range in Mexico, the two varieties are distinctly separated geographically by 360 km in a northern and southern spatial distribution (Dvorak et al. 2000d). Seeds of *P. greggii* with unknown origin were introduced to South Africa in the late 1960s by Mondi (Kietzka et al. 1996).

P. greggii var. *greggii* is adapted to dry sites in northern Mexico where annual precipitation ranges from 600 to 750 mm (Dvorak et al. 2000d). However, in some years annual precipitation does not exceed 500 mm (Dvorak et al. 2000d). Since var. *greggii* is adapted to dry sites, it grows poorly on soils that are poorly drained and seasonally wet. The variety *greggii* is found at altitudes ranging from approximately 2300 to 2800 m (Dvorak et al. 2000d). Furthermore, var. *greggii* exhibits better cold hardiness than most other Mexican closed-cone pines (Hodge et al. 2012). A typical var. *greggii* site can have a mean annual temperature of 13^{o}C with maximum monthly deviations of 5^{o}C (Dvorak et al. 2000d). Hodge and Dvorak (2012) concluded in the most extensive growth potential study so far, that unimproved var. *greggii* had 63.8 % less volume than improved *P. patula* in South Africa after 8 years. Var. *greggii* is only a viable alternative to *P. patula* at high elevations in cold and/or dry sites on harsh sites but its growth rate is relatively low. Var. *greggii* could for example be used at high elevation sites (>1700 m) in the Drakensberg mountains in the north-eastern Cape region that are too cold or too dry for *P. patula* (Hodge and Dvorak 2012).

P. greggii var. *australis* is found on sites with higher annual precipitation than var. *greggii*. The mean annual precipitation at sites where this variety is found is 1365 mm (Dvorak et al. 2000d). Var. *australis* is found on deeper well-drained soils than var. *greggii* and at lower elevations (ranging from 1200 to 2300 m) (Dvorak et al. 2000d). Var. *australis* possesses approximately the same level of cold hardiness as *P. patula* (Dvorak et al. 2000d, Hodge et al. 2012). A typical var. *australis* site can have an annual mean temperature of approximately

$20^{o}C$ with maximum monthly deviations of $4^{o}C$ (Dvorak et al. 2000d). Var. *australis*' niche in South Africa is at altitudes ranging from 900 to 1500 m (Dvorak et al. 2000d) in regions that experience warm summers and cold winters, and distinct or uniform precipitation patterns (Hodge and Dvorak 2012). It has better drought tolerance than *P. patula* (Dvorak et al. 2000d). It is an alternative to *P. elliottii*, which is the currently used as a species for these harsher sites (Hodge and Dvorak 2012). Hodge and Dvorak (2012) concluded that unimproved var. *australis* had 17.5 % less volume growth than improved *P. patula* in South Africa after 8 years. Var. *australis* is within the range where selection can make it a realistic feasible alternative. Therefore, var. *australis* has far more potential as a commercial plantation species than does var. *greggii* in South Africa. However, a negative trait for var. *australis* is its naturally poorer stem and branch form than *P. patula*. Nevertheless, stem form can be improved in a breeding program.

Both varieties of *P. greggii* are highly susceptible to pitch canker. The fungus has been found primarily in the nursery but also on young trees in different regions of South Africa (Hodge and Dvorak 2000, Mitchell et al. 2011). Therefore, it is not a suitable species in geographic zones with a high incidence of pitch canker (Mitchell et al. 2012).

1.5 *Pinus maximinoi*

Pinus maximinoi is the second most common pine species after *P. oocarpa* in Mesoamerica. The species has approximately the same natural distribution as *P. oocarpa* but its distribution does not range as far north (Dvorak et al. 2000a). The species occurs in disjunct populations at altitudes from 700 to 2400 m (Dvorak and Donahue 1992). However, individual trees can be found at higher and lower altitudes. Average monthly temperatures vary from 14 to 27^{o}C throughout the year (Dvorak et al. 2000a).

In its native environment *P. maximinoi* occurs in areas within the spectrum of 900 to 2200 mm annual rainfall and experiences a six month dry period. In high elevation subtropical cloud forests *P. maximinoi* is found growing together with *P. tecunumanii* but often as a smaller component in a mixture (Dvorak et al. 2000a).

The species is found on deep well-drained soils but there is no single soil type that defines the natural range of *P. maximinoi*. However, there are two categories of forest types where the species occur. These are moist subtropical forests and semi-dry pine and pine-oak forests (Dvorak et al. 2000a).

Observations in natural stands suggest that *P. maximinoi* possesses the same limited level of cold hardiness as *P. tecunumanii* when used as an exotic, since the species sometimes grows sympatrically. However, there are contradicting results between laboratory and field results. Laboratory results from Hodge et al. (2012) suggest *P. maximinoi* is slightly more frost tolerant than *P. tecunumanii*. However, in field trials in Uruguay, *P. maximinoi* has shown higher mortality due to frost than *P. tecunumanii*. *P. maximinoi* also possesses good tolerance against pitch canker (Hodge and Dvorak 2000, Mitchell et al. 2012).

In South Africa, *P. maximinoi* is of interest because of its extremely good growth. In a recent thorough study by Hodge and Dvorak (2012), unimproved *P. maximinoi* had 42.2 % better volume growth compared to improved *P. patula*. In the same study, it was concluded *P. maximinoi* should be developed into a major commercial pine species because of its good growth and its high potential on a multitude of sites. The species could be used in the same areas that *P. tecunumanii* currently is used, which is the warmer part of Mpumalanga (Hodge and Dvorak 2012).

However, there are several complications connected to the species. The most important are that it does not produce large quantities of seed (just like *P. tecunumanii*), it exhibits a high level of graft incompatibility (Dvorak et al 2000a), it often produces large branches, it produces foxtails and it is not frost tolerant (Hodge and Dvorak 2012). However all problems can be addressed in one way or another. Vegetative propagation programs can be developed in order to produce enough commercial seedlings. The large branches need to be addressed through breeding. Foxtailing occurs at high frequency in the tropics when the species is planted at altitudes too low. Planting the species on proper sites and further selection against foxtails may solve the problem (Hodge and Dvorak 2012). At higher latitudes in South Africa, the percentage of foxtails falls off drastically. Regarding cold tolerance, the species should be used in areas that do not experience frost events. The species' niche as an exotic plantation species in South Africa overlaps somewhat with *P. tecunumanii*. However, *P. maximinoi* will perform better than the latter on deeper and more fertile soils, as well as at high elevations without frost events (Hodge and Dvorak 2012).

Despite the good growth compared to most other exotic pine species in South Africa, the forest industry has shown skepticism towards using the species. The major reasons have been poor seed supply, uncertainty regarding *P. maximinoi's* wood quality and use of the end product (Hodge and Dvorak 2012).

1.6 ***Pinus patula***

Pinus patula is the most widely planted pine species in South African plantations as previously described. This species grows on approximately 330.000 ha of land which corresponds to slightly more than half of the total softwood plantation area in the country. *P. patula*'s main planting zone is in the northern and southern regions of Mpumalanga province, the Eastern Cape and KwaZulu-Natal (FES 2012). In its native environment in Mexico, *P. patula* is commonly found on well-drained soils at altitudes ranging from 1490 to 3100 m with annual precipitation ranging from 1000 to 2500 mm. Average temperatures ranges from 10 to 18 °C and can fall well below freezing during wintertime (Dvorak et al. 2000c).

The species was introduced into South Africa in 1907 (Perry 1991). In South Africa, *P. patula* grows best in the mist belt regions on deep, well-drained soils at elevations above 1000 m (Kanzler et al. 2012). *P. patula* is recommended in areas with mean annual temperatures between 12 and 18°C (du Toit 2012). *P. patula* has quite good cold tolerance and can withstand frosts as well as dry periods for several months. However, the growth is much better in warm and humid conditions (Perry 1991). The cold tolerance of *P. patula* is comparable to *P. greggii* var. *australis*, which can be explained by the sympatric occurrence of the two species in their natural environment. However *P. patula* is considered to be less drought tolerant than the latter and develops best on moderately temperate and misty sites, while *P. greggii* survives better on colder sites where there is a risk of seasonal droughts (Hodge et al. 2012).

A major threat to a sustainable use of *P. patula* in South Africa is the recent severe outbreak of the pitch canker fungus (*Fusarium circinatum* Nirenberg & O´Donnell). *P. patula* is highly susceptible to the pitch canker fungus in the nursery and has been heavily affected. The most significant effect of pitch canker on *P. patula* is on seedlings that die shortly after plantation establishment. The pitch canker fungus outbreak that has occurred during the last decade has led to a decrease in the use of *P. patula*. It has also led to a growing interest in alternative pine species, hybridization, as well as breeding and selection for increased resistance (Mitchell et al. 2011).

The historic breeding base of *P. patula* in South Africa, prior to infusion of more genetic material from the Camcore program, originated from three small seed collections from unknown locations in Mexico in the early 1900s. This has led to concerns about levels of genetic diversity in the original *P. patula* genetic base. Despite a rather limited *P. patula* collection base, substantial gains have been made through tree improvement programs in South Africa. Further seed imports were made in 1949 with the aim to capture more genetic diversity. However, first indications were that these later imports would not make any big difference in enhancing growth and wood quality traits of *P. patula* (Wormald 1975).

1.7 *Pinus pseudostrobus*

Pinus pseudostrobus Lindl. has a natural distribution scattered across southern Mexico and Guatemala. It grows at altitudes ranging from 1600 to 3200 m mainly on mountain slopes. Mean annual precipitation varies throughout the native range from approximately 800 to 1500 mm. Frost is a common feature in the higher altitudes during wintertime (Perry 1991). The mean annual temperature where *P. pseudostrobus* occurs range from 13 to 18^{o}C and the species usually grows on volcanic soils. *P. pseudostrobus* has the capacity to tolerate growing on shallow soils. Furthermore, *P. pseudostrobus* is comparable to *P. patula* in many aspects but has exhibited slower growth rates than in South Africa and now is seldom planted on the Highveld (van Wyk 2002).

A recent laboratory study of Hodge et al. (2012) showed that *P. pseudostrobus* possessed excellent frost resistant compared to some other Mesoamerican and North American pines in tropical experiment conditions, and recommended further field testing on harsh, cold sites in South Africa. *P. pseudostrobus* shows the best resistance to the pitch canker fungus among the cold hardy Mesoamerican pines (Hodge and Dvorak 2000). Mitchell et al. (2011) describes the species as a possible alternative to *P. patula* on colder sites in the future, due to its good tolerance against the pitch canker fungus.

1.8 *Pinus radiata*

Pinus radiata var. *radiata* D. Don, sometimes referred to as Monterey pine (in this document, referred to as *P. radiata*), is of much importance for plantation forestry worldwide. It originates from three discrete populations in the California mainland and on the Cedros and Guadalupe Islands west of the Baja California peninsula in Mexico (Rogers 2002, Burdon 2002). The current area of the native *P. radiata* is small and threatened by invasive exotic species, for example the population on Guadalupe Island has only about 200 trees remaining. (Rogers 2002).

In its native range, the mainland *P. radiata* generally experiences 400 to 800 mm of annual precipitation, while the island populations only gets around 150 mm. The rainfall comes in the winter while during the summer it does not rain at all on average (Rogers 2002). The climate can be described as a variant of a dry to mesic Mediterranean climate where sea fog contributes a crucial amount of water during the rainless summer, especially for the island populations. *P. radiata* grows from sea level to an altitude of 420 m on a maximum distance of 8 km from the coast on the mainland and up to 1200 m on the Guadalupe Island. The species grows on a multitude of different soil types (Burdon 2002, Rogers 2002). However, moderately fertile deep sandy loams are ideal (Burdon 2000). Mean annual temperature in its native habitat ranges from approximately 12 to 14^{o}C (Axelrod 1988).

P. radiata experiences rare occasional frost events in its native range (Burdon 2000, Rogers 2002), thus it has at least some cold tolerance. In a laboratory experiment the species frost tolerance was comparable to that of *P. greggii* var. *australis*, (Hodge et al. 2012). *P. radiata* is extremely susceptible to the pitch canker fungus and outbreaks in the southern and southeastern Cape have been recorded (Hodge and Dvorak 2000, Mitchell et al. 2011).

Despite its small natural distribution in California and on the two islands, *P. radiata* has been planted on more than 4 million hectares in 2002, of which the large majority is located in the Southern Hemisphere (Burdon 2000, Burdon 2002, Rogers 2002). It is used on approximately 9 % on the softwood plantation area in South Africa and is confined to the Cape regions (FES 2012). Due to its small range of natural distribution, *P. radiata* will perform well in a narrow range of environments that experience Mediterranean climates. The species requires fertile soils in order to make use of its high growth potential and grows best on deep well-drained soils (Burdon 2002).

1.9 *Pinus taeda*

The natural distribution of *Pinus taeda* L. is somewhat similar to *P. elliottii*'s but covers a larger area in the southeastern USA, where it is the most important timber tree species. In its native range, the species experiences a relative evenly distributed precipitation pattern throughout the year, although mild summer droughts and heavy rainfall events are quite common. Typical in its native environment are hot summers and cool winters. The elevation range of *P. taeda* is between 0 to 900 m and mean annual precipitation is between 900 to 2200 mm (Schultz 1997a). The species originally evolved near swamps but has good adaptability to a wide variety of sites. Its natural distribution in the southern USA has greatly increased since the colonization period. It grows on a multitude of different soil types, textures and moisture levels (Schultz 1997a). In its native range, mean annual temperatures range from 15 to 21^{o}C (Schultz 1997a).

As an exotic, *P. taeda* is used in many countries around the world including South Africa. It was introduced into the country in the 1890s, earlier than *P. patula*, and plantations were established by 1908 (Schultz 1997b). However, the plantings failed, due to lack of mycorrhizal fungi (Schultz 1997b). In the late 1960s improved seeds became available which led to a wave of large scale plantings (Schutz and Wingfield 1979). This subsided when abnormal wood formation was observed for a small proportion of the species (Herman 1988, Peterson 2002).

P. taeda experiences frost events to a different extent across its native range in the eastern USA, and is considered very cold tolerant relative to most of the Mexican pine species (Hodge et al. 2012). It is considered to have good tolerance to the pitch canker fungus (Hodge and Dvorak 2000).

In South Africa, *P. taeda* is recommended for cool areas that experience their dry period in wintertime. The deep soils in the Eastern Cape are pointed out as a particularly suitable area for the species (Grey and Taylor 1983). Its geographic range in South Africa is from latitude 24^{o} S to 34^{o} S (Schultz 1997b). *P. taeda* is recommended for elevations below 1800 m in South Africa, as well as in regions with mean annual precipitation greater than 950 mm (Schönau and Schulze 1984). *P. taeda* plantations have recently become more common because of the species' better resistance against pitch canker. However, the species' quite narrow spectrum of suitable sites in South Africa may stand in the way for more extensive establishments (Mullin et al. 2011, Mitchell et al. 2012).

1.10 *Pinus tecunumanii*

Named after the Mayan Indian chief "Tecún Umán", *Pinus tecunumanii* consists of two subpopulations that occur naturally, ranging from the highlands of southern Mexico to central Nicaragua (Dvorak et al. 2000b). Populations of *P. tecunumanii* are small and often fragmented. Depending on origin, the provenances are classified based on their altitude above sea-level. Populations that are found above 1500 m altitude are called high elevation (HE), and those below 1500 m altitude are referred to as low elevation (LE) subpopulations (Dvorak et al. 2000b). Morphologic and molecular data seem to support the division of HE and LE populations (Dvorak et al. 2009).

Annual precipitation in sites where *P. tecunumanii* occurs is between 1000 to 2500 mm. Most HE populations occupy mountainous cloud forest environments, which contributes additional moisture from frequent fogs. In the native environment, HE populations on the San Cristobal de las Casa plateau in Chiapas, Mexico experience short frost events during the winter months (Dvorak et al. 2000b). Trials in South Africa have also shown that HE populations exhibits better cold hardiness than LE populations (Mitchell et al. 2013), and this has also been observed in artificial freezing studies (Hodge et al. 2012). HE populations are usually found on fertile and well-drained sandy or clay loams. In contrast, LE populations often grow on shallower and sometimes poorer soils (Dvorak et al. 2000b). Trees from both subpopulations naturally hybridize easily with *P. patula* when planted as exotics especially where the latter is dominant in the landscape (Hodge and Dvorak 2012).

The two subpopulations also differ substantially in resistance against pitch canker. HE populations are moderately susceptible as seedlings while LE populations exhibit much more resistance (Hodge and Dvorak 2000, Hodge and Dvorak 2007, Mitchell et al. 2012).

P. tecunumanii should be established on deep soils in areas without too strong of seasonal winds. Annual precipitation should be between 900 to 2400 mm with a dry season of maximum five months annually. In northern Mozambique, *P. tecunumanii* withstands dry seasons of eight months duration without problems, most likely because the clayey soils hold moisture well into the dry season (Dvorak, pers. comm.). Many of the LE populations have very good drought resistance after the establishment phase (Dvorak et al. 2000b).

A problem for *P. tecunumanii* as an exotic species is stem breakage, which most often occurs in the upper part of the crown at heavily branched whorls (Dvorak et al. 1993, Malan 1994). Dvorak et al. (1993) concluded that stem breakage varied from 5 % to 12 % at the age of 6.5 years in South Africa. Therefore, it is an important factor to take into consideration, and something that can limit productivity gains. However, it is believed that the problem can be addressed by good silvicultural practices and by selection in provenance and progeny tests where susceptibility for stem breakage is taken under consideration (Hodge and Dvorak 2012). Worth noting, is that the stem breakage problem appears to be minor in the *P. patula* x *P. tecunumanii* hybrid crosses.

1.11 Hybrids

Hybrids among pine species have been used since the early to mid-1900s (Dungey 2001). The theory behind the use of hybrids is that the offspring will combine their parents' positive traits, creating a better offspring than the pure parent species. In South Africa this could be, for example, combining good growth with high frost tolerance and/or high resistance against the pitch canker fungus. SAFRI (South African Forestry Research Institute) began testing different pine hybrids in 1968 (Kietzka 2002).

It is often more costly to use hybrids compared to pure species because of the complexities of producing and testing them. However, hybrids offer a new spectrum of genetic variation, which is and can be very important for the forest industry (Dungey 2001).

1.12 *Pinus elliottii* x *caribaea* var. *hondurensis*

Much of the knowledge of the *P. elliottii* x *caribaea* hybrid comes from Queensland, Australia, where in 2010 it was planted on almost 70.000 ha. There is also experience of the hybrid from Argentina where it has shown superior performance compared to the pure species in field trials. Hence, the interest has increased which has led about 21.000 ha of plantations of the *P. elliottii* x *caribaea* hybrid there. (Cappa et al. 2013).The *Pinus elliottii* x *caribaea* hybrid is planted commercially in Argentina, Australia and South Africa. The species exhibited good volume growth potential in the initial testing in South Africa in 1968, which led to more extensive testing (Kietzka 2002). For example, van der Sijde and Slabbert (1980) showed that the hybrid outperformed pure *P. elliottii* with a volume growth three times as high at 4.5 years age. A follow up study conducted by van der Sijde and Roelofsen (1986) showed that the hybrid still had a much higher volume growth than the pure *P. elliottii*. Similar results have also been shown in research trials in Zimbabwe (Gwaze 1999). The hybrid appears to get the high growth rate from *P. caribaea* and stem straightness, wind firmness, high wood density and adaptability to wet sites from *Pinus elliottii* (Dieters and Brawner 2007).

1.13 Acoustic velocity assessments to measure wood stiffness in standing trees

Fast growing forest plantations are the future of the forest industry. A big challenge in tree improvement programs is to develop fast, precise and cost effective assessment methods in order to make selection for wood quality traits (Wang et al. 2007). Strength and stiffness properties of the wood are of importance since these relate to the solid wood quality. These wood properties determine the value and utility of wood products for structural application (Eckard et al. 2010). It is proved that acoustic measurements in standing trees can predict many wood properties (Wang et al. 2007).

The main focus of softwood plantations in South Africa is the production of sawlogs for building products (FES 2012), thus accurate prediction of mechanical timber properties of standing trees would be useful to tree breeders in the selection of superior genetic material (Lindström et al. 2002, Ivkovic et al. 2009, Matheson et al. 2008, Wessels et al. 2011).

There are different ways to assess solid wood traits in standing trees including destructive and non-destructive sampling methods. Usually wood properties are measured with destructive methods, which are both expensive and time consuming. Samples must first be collected in the field and later analyzed in the laboratory. Acoustic time-of-flight tools such as the TreeSonic (Fakopp Enterprise, Agfalva, Hungary) have recently been developed. These tools are non-destructive approaches to measure important wood traits and are less time consuming than destructive sampling and therefore, less expensive. Time-of-flight tools relate the velocity of an acoustic stress wave in the stem to dynamic modulus of elasticity (furthermore denoted as MOE) (Eckard et al. 2010). MOE is a measure of wood stiffness, a critical market trait for sawtimber.

The principle of the TreeSonic is simple: two sensors are inserted into the main stem, one meter apart, and the time of flight between the transmit probe and the receiver probe is recorded for a single pulse of a sound wave. By knowing the time and assuming the green density of the species, MOE can be calculated with the following equation:

$$MOE = \rho V^2 * 10^{-9} \tag{1}$$

Where ρ is the green density of the material (kg/m^3), V is the longitudinal wave velocity of a sound wave (m/s) and MOE is the modulus of elasticity (GPa).

Figure 1. TreeSonic time-of-flight tool.

A big advantage with acoustic time-of-flight tools is that they provide a non-destructive measure of wood stiffness. The holes in the individual tree are almost unidentifiable after a measurement, and therefore, the growth and development of the tree should not be affected. It is a good way to screen young trees in field trials when taking wood samples destructively would not be feasible (Eckard et al. 2010). Ivkovic et al. (2009) concludes that for large scale evaluation of stiffness, acoustic measurement might be more appropriate than components measurements such as density. Furthermore Ivkovic et al. (2009) recommends the use of acoustic tools in combination with increment core density in order to predict stiffness.

1.14 Dynamic Modulus Of Elasticity (MOE)

Wood stiffness is measured as MOE, in Gigapascals (GPa). Higher MOE means that the product performance and value of the lumber increases, which is of crucial importance (Lindström et al. 2002). MOE as a measure of wood stiffness is one of the most important mechanical properties for structural end uses. Hence, MOE is a crucial characteristic for structural material since it has direct impact on structural timber grade outturn and profit (Matheson et al, 2008, Ivkovic et al. 2009). Furthermore the selection for high MOE in breeding programs is fast and inexpensive (Matheson et al. 2008). MOE expresses the ratio between a force per unit area and the relative elongation that acts to deform the object elastically (non-permanent). As given by equation 1, MOE is dependent on green density. The green density is most often assumed to be constant between and within trees, which allows the selected trees to be ranked by the velocity measurements alone (Mochan et. al 2009).

For example, the green density of *P. radiata* trees is normally assumed to be a constant somewhere in the range of 1000-1100 kg/m^3 (Wielinga et. al 2009) when MOE is calculated. Grabianowski et al. (2004) assumed a density of 1050 kg/m^3, while Lasserre et al. (2004), Ivkovic et al. (2009) and Matheson et al. (2008) assumed 1000 kg/m^3 for the species when determining the MOE.

When calculating the MOE for *P. radiata* Wielinga et al. (2009) concludes that the acoustic velocity is the most important value for determining the MOE. The assumption of a constant green density did, to a large extent, not affect the accuracy of the estimated MOE, meaning that the MOE is close to directly related to the velocity.

Mora et al. (2009) supports assessments with acoustic tools such as the TreeSonic if the objective is for ranking purposes and not for finding the “true” MOE. Hence, the bias is consistent from tree to tree and without interaction effect. Mora et al. (2009) finds the green density for *P. taeda* in trials in southeastern USA to range between 966 to 1018 kg/m^3. Furthermore Mora et al. (2009) concludes that the impact of an assumed green density as a constant is something that needs to be evaluated further. *P. taeda* is assumed to have a similar green density as *P. radiata*. In an assessment of stiffness variation Lindström et al. (2004) assumed the green density to be 1000 kg/m^3.

1.15 Hypothesis

Based on the reviewed literature there seems to be high potential for other pine species to outperform the rate of growth of *P. patula* in South Africa. The most promising species is *P.maximinoi* that has shown incredible growth rates in unimproved material and the *P. patula* x *tecunumanii* hybrid. It is anticipated that the improved material should show even greater potential, especially on fertile, deep and well-drained sites, and on high elevations that do not experience frost events. After *P. maximinoi*, both subpopulations of *P. tecunumanii* are considered to have potential in outperforming *P. patula*. The sites with highest potential for *P. tecunumanii* are very similar to those of *P.maximinoi*.

The assumption that green density is similar within species is hypothesized not to be true all the time, because different sources claim different green density values. Furthermore it is also anticipated that the green density differs among species, and that this will affect the MOE rankings when comparing different species.

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CHAPTER 2 GROWTH AND MODULUS OF ELASTICITY OF SELECTED PINE SPECIES AND HYBRIDS THREE YEARS AFTER PLANTING IN SOUTH AFRICA

(In the format appropriate for submission to Southern Forests)

GROWTH AND MODULUS OF ELASTICITY OF SELECTED PINE SPECIES AND HYBRIDS THREE YEARS AFTER PLANTING IN SOUTH AFRICA

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ABSTRACT

Growth data and modulus of elasticity (MOE) of 11 different pine species and hybrids were examined at six sites in three different regions in South Africa. Tests were measured approximately three years after planting. Growth traits and three different MOE variables were assessed in order to see if there were pine species more suitable than the current commercial species. Average survival across sites was 61.8 % and varied from 26.4 % to 87.8 %. Most sites exhibited significant species differences for growth traits. There were significant interaction effects for species within the regions for growth traits. There were significant species differences for all three MOE variables at all of the four sites that were included in the analysis of wood properties. When combining the four sites that were used for the wood property analyses, there were significant species differences for the three different

MOE variables. Across all four sites where wood properties were analyzed the MOE variable ranged from 3.03 to 6.40 GPa. Based on the results from this study, despite the high mortality rates that were experienced on many sites, there are alternative pine species that are showing comparable growth rates to the current commercial species. For approximating MOE, it is concluded that assuming a constant green density does not affect the species ranking but if the aim is to find the “true” MOE, sampling in the field is needed.

KEYWORDS

Plantations, MOE, green density

INTRODUCTION

The forest industry makes an important contribution to the South African economy, contributing 1.2 % of GDP (SAY 2012). Currently there are almost 1.3 million ha of plantations in the country (SAY 2012). Further expansion of plantation land is limited by agriculture and dry climates. Therefore, it will be important to increase wood production per ha through gains in tree breeding and intensive silviculture practices. Additional improvements are possible from better species-site matching and use of alternate species and hybrids.

A big challenge in management of forest plantations in South Africa is the high diversity of different site types. Topography and climatic conditions vary within a big spectrum, which makes site-specific species-matching crucial to optimize growth and profitability (du Toit 2012). Testing different species on a multitude of sites will contribute to our knowledge of species' performance across a number of locations and help us choose well-adpated species that could be commercially grown by the South African forest industry (Hodge and Dvorak 2012).

Over the last 30 years Camcore (International Tree Breeding and Conservation Program) at North Carolina State University has been working together with private South African forest companies on the evaluation of a wide range of species with the aim to improve existing breeding programs and to find "new" suitable pine species for plantation forestry (Hodge and Dvorak 2012, Dvorak 2012). As part of the testing effort, a well defined *ex situ* gene conservation program has also been implemented.

Some pine species and hybrids with commercial or potential use in South Africa include *Pinus elliottii* Engelm., the *P. elliottii* Engelm. x *P. caribaea* Morlet var. *hondurensis* (Sénéclauze) W.H. Barrett & Golfari hybrid, *Pinus greggii* Engelm. *ex* Parl. var. *australis* (*Pinus greggii* South), *Pinus greggii* Engelm. *ex* Parl. var. *greggii* (*Pinus greggii* North), *Pinus maximinoi* H.E. Moore, *Pinus patula* Schiede *ex* Schlecht. & Cham. var. *patula*, *Pinus pseudostrobus* Lindl., *P. radiata* var. *radiata* D. Don., *Pinus taeda* L. and *Pinus tecunumanii* Eguiluz & J.P. Perry. These pine species are adapted to the different environmental niches that make up the plantation forest areas in the eastern part of the country. Two major limitations to growth of pine species in the country include disease problems from the pitch canker fungus (*Fusarium circinatum Nirenberg & O'Donnel*) and susceptibility to drought and cold.

Species Overview

Pinus elliottii is an important commercial timber species in its native range, which is in the lower coastal plain of southeastern USA, ranging from South Carolina to Florida. The natural habitat of *P. elliottii* is in the proximity of streams, swamps and bays where soil moisture is high. Annual precipitation in its native environment ranges from 1150-1500 mm. The species occurs at low altitudes, most often from sea-level to 150 m on a variety of soils. However, *P. elliottii* grows best on deep well-drained soils that are capable of holding abundant amounts of water provided from rain, during the growing season. The mean annual temperature is in the range 15 to 24^{o}C (Barnett 2002). In South Africa, *P. elliottii* is the second most planted pine species after *P. patula*, occupying slightly more than 27 % of the softwood plantation area (FES 2012). The drawback with *P. elliottii* compared to *P. patula*, is its slower growth, which might not be compensated by its higher resistance to pitch canker. (Mitchell et al. 2012).

Pinus greggii is a Mesoamerican pine that is represented by two varieties, *Pinus greggii* var. *greggii* (*Pinus greggii* North) and *Pinus greggii* var. *australis* (*Pinus greggii* South). In their native range in Mexico, the two varieties are distinctly separated geographically by 360 km in a northern and southern spatial distribution (Dvorak et al. 2000d). A typical var. *greggii* site can have a mean annual temperature of 13^{o}C with maximum monthly deviations of 5^{o}C (Dvorak et al. 2000d). In its native environment annual precipitation ranges from 600 to 750 mm (Dvorak et al. 2000d). Var. *greggii* is only a viable alternative to *P. patula* at high elevations on harsh cold and/or dry sites, but its growth rate is relatively low. Var. *greggii* could for example be used at high elevation sites (>1700 m) in the Drakensberg mountains in the north-eastern Cape region that are too cold or too dry for *P. patula* (Hodge and Dvorak 2012). A typical var. *australis* site can have an annual mean temperature of approximately 20^{o}C with maximum monthly deviations of 4^{o}C (Dvorak et al. 2000d). The mean annual precipitation in its native environment is 1365 mm (Dvorak et al. 2000d). Var. *australis*' niche in South Africa is at altitudes ranging from 900 to 1500 m (Dvorak et al. 2000d) in regions that experience warm summers and cold winters, and distinct or uniform precipitation patterns (Hodge and Dvorak 2012).

Pinus maximinoi is the second most common pine species after *P. oocarpa* in Mesoamerica. The species has approximately the same natural distribution as *P. oocarpa* but its distribution does not range as far north (Dvorak et al. 2000a). The species occurs in disjunct populations at altitudes from 700 to 2400 m (Dvorak and Donahue 1992). However, individual trees can be found at higher and lower altitudes. Average monthly temperatures vary from 14 to 27^{o}C throughout the year (Dvorak et al. 2000a). In its native environment *P. maximinoi* occurs in areas within the spectrum of 900 to 2200 mm annual rainfall and experiences a six month dry period (Dvorak et al. 2000a). The species is found on deep well-drained soils but there is no single soil type that defines the natural range of *P. maximinoi*. However, there are two categories of forest types where the species occur. These are moist subtropical forests and semi-dry pine and pine-oak forests (Dvorak et al. 2000a). In South Africa *P. maximinoi* is of interest because of its extremely good growth. The species could be used in the same areas that *P. tecunumanii* currently is used, which are lower elevation and warmer sites in Mpumalanga (Hodge and Dvorak 2012).

Pinus patula is the most widely planted pine species in South African plantations. This species grows on approximately 330.000 ha of land which corresponds to slightly more than half of the total softwood plantation area in the country (FES 2012). In its native environment in Mexico, *P. patula* is commonly found on well drained soils at altitudes ranging from 1490 to 3100 m with annual precipitation ranging from 1000 to 2500 mm. Average temperatures ranges from 10 to 18 °C and temperatures can fall well below freezing wintertime (Dvorak et al. 2000c). In South Africa, *P. patula* grows best in the mist belt regions on deep, well-drained soils at elevations above 1000 m (Kanzler et al. 2012). *P. patula* is recommended in areas with mean annual temperatures between 12 and 18°C (du Toit 2012).

Pinus pseudostrobus is a species with a natural distribution scattered in southern Mexico and Guatemala. It grows at altitudes ranging from 1600 to 3200 m mainly on mountain slopes. Mean annual precipitation varies throughout the native range from approximately 800 to 1500 mm. (Perry 1991). The mean annual temperature where it occurs ranges from 13 to 18^{o}C and the species usually grows on volcanic soils. *P. pseudostrobus* has the capacity to tolerate growing on shallow soils. Furthermore, *P. pseudostrobus* is comparable to *P. patula* in many aspects but has exhibited slower growth rates than in South Africa and now is seldom planted on the Highveld (van Wyk 2002). *P. pseudostrobus* shows the best resistance to the pitch canker fungus among the cold hardy Mesoamerican pines (Hodge and Dvorak 2000). Mitchell et al. (2011) describes the species as a possible alternative to *P. patula* on colder sites in the future, due to its better tolerance against the pitch canker fungus.

Pinus radiata var. *radiata* D. Don, sometimes referred to as Monterey pine (in this article, referred to as *P. radiata*), is of much importance for plantation forestry worldwide, and it originates from three discrete populations in the California mainland and on Cedros and Guadalupe Islands west of the Baja California peninsula in Mexico (Rogers 2002, Burdon 2002). In its native range, the mainland *P. radiata* generally experiences 400 to 800 mm of annual precipitation, while the island populations only gets around 150 mm (Rogers 2002). The climate can be described as a variant of a dry to mesic Mediterranean climate where sea fog contributes with a crucial amount of water during the rainless summer, especially for the island populations. *P. radiata* grows from sea-level to an altitude of 420 m on a maximum distance of 8 km from the coast on the mainland and up to 1200 m on the Guadalupe Island. The species grows on a multitude of different soil types (Burdon 2002, Rogers 2002). However, moderately fertile deep sandy loams are ideal (Burdon 2000). Mean annual temperature in its native habitat ranges from approximately 12 to 14^{o}C (Axelrod 1988). It covers approximately 9 % of the softwood plantation area in South Africa and is confined to the Cape regions (FES 2012). Due to its small natural distribution *P. radiata* is confined to a narrow range of environments that experience Mediterranean (winter rainfall) climate. The species requires fertile soils to make use of its high growth potential and grows best on deep well-drained soils (Burdon 2002).

The natural distribution of *Pinus taeda* is somewhat similar to that of *P. elliottii*, but covers a larger area in the southeastern USA. The elevation range of *P. taeda* is between 0 to 900 m and mean annual precipitation is between 900 to 2200 mm (Schultz 1997a). The species originally evolved near swamps but has good adaptability to a wide variety of sites. In its native range, mean annual temperatures range from 15 to 21^{o}C (Schultz 1997a). It was introduced into South Africa in the 1890s, earlier than *P. patula*, and plantations were established by 1908 (Schultz 1997b). However, the plantings failed, due to lack of mycorrhizal fungi (Schultz 1997b). In South Africa, *P. taeda* is recommended for cool areas that experience a dry period in wintertime. The deep soils in the Eastern Cape are particularly suitable area for the species (Grey and Taylor 1983). Its geographic range in South Africa is from latitude 24^{o} to 34^{o} S (Schultz 1997b). *P. taeda* is recommended for elevations below 1800 m in South Africa, as well as in regions with mean annual precipitation greater than 950 mm (Schönau and Schulze 1984). The species' quite narrow spectrum of suitable sites in South Africa may stand in the way of more extensive establishments (Mullin et al. 2011, Mitchell et al. 2012).

Pinus tecunumanii, named after the Mayan Indian chief "Tecún Umán", has a broad range from the highlands of southern Mexico to central Nicaragua. Populations of *P. tecunumanii* are small and often fragmented. Depending on origin, the provenances are classified based on their altitude above sea-level. Populations that are found above 1500 m altitude are called high elevation (HE), and those below 1500 m altitude are referred to as low elevation (LE) subpopulations (Dvorak et al. 2000b). Most HE populations occupy mountainous cloud forest environments, which contributes additional moisture from frequent fogs. (Dvorak et al. 2000b). HE populations are usually found on fertile and well-drained sandy or clay loams. In contrast, LE populations are often growing on shallower and sometimes poorer soils (Dvorak et al. 2000b). *P. tecunumanii* should be established on deep soils in areas without strong seasonal winds. Annual precipitation should be between 900 to 2400 mm with a dry season of maximum five months annually (Dvorak et al. 2000b).

The *P. elliottii* x *P. caribaea* hybrid has shown good volume growth (van der Sijde and Slabbert 1980, van der Sijde and Roelofsen 1986, Gwaze 1999, Kietzka 2002). The hybrid superiority appears to be derived from a combination of desirable traits from the two pure species. The hybrid seems to get the high growth rate from *P. caribaea* and stem straightness, wind firmness, high wood density and adaptability to wet sites from *P. elliottii* (Dieters and Brawner 2007). Much of the knowledge of the *P. elliottii* x *caribaea* hybrid comes from Queensland, Australia, where in 2010 it was planted on almost 70.000 ha. There is also experience of the hybrid from Argentina where it has shown superior performance compared to the pure species in field trials (Cappa et al. 2013). The *P. elliottii* x *caribaea* hybrid is quite well known in South Africa and planted commercially.

Modulus of elasticity

An important attribute of timber is its wood stiffness measured as modulus of elasticity (MOE) since it determines the value and utility of wood products for structural application (Eckard et al. 2010). Hence, MOE is a crucial characteristic for structural material since it has direct impact on structural timber grade outturn and profit (Matheson et al, 2008, Ivkovic et al. 2009). Usually wood properties are measured with destructive methods, which are both expensive and time consuming. Samples must first be collected in the field and later analyzed in the laboratory. Acoustic time-of-flight tools such as the TreeSonic (Fakopp Enterprise, Agfalva, Hungary) have recently been developed. These tools are non-destructive approaches to measure important wood traits and are less time consuming than destructive sampling and therefore, less expensive. Time-of-flight tools relate the velocity of an acoustic stress wave in the stem to MOE (Eckard et al. 2010).

The main focus of softwood plantations in South Africa is the production of sawlogs for building products (FES 2012), so accurate prediction of mechanical timber properties of standing trees would be useful to tree breeders in the selection of superior genetic material (Lindström et al. 2002, Ivkovic et al. 2009, Matheson et al. 2008, Wessels et al. 2011).

When approximating the MOE, a constant green density value is often assumed for MOE comparisons within species. For example, the green density of living *P. radiata* is normally assumed to be a constant somewhere in the range of 1000-1100 kg/m^3 when MOE is to be calculated (Wielinga et. al 2009). Grabianowski et al. (2004) assumed the density of 1050 kg/m^3, while Lasserre et al. (2004), Ivkovic et al. (2009) and Matheson et al. (2008) assumed 1000 kg/m^3 for the species when determining the MOE. Mora et al. (2009) found the green density for *P. taeda* in trials in southeastern USA to range between 966 to 1018 kg/m^3.

The objectives of this paper are to:

i. Assess if there are pine species with better growth than the commercially used species.
ii. Determine if alternate species have better Modulus of Elasticity (MOE) than the commercially used species.

MATERIALS AND METHODS

This study was carried out to evaluate the growth and wood quality of some properties for 24 different species, provenances and hybrids. The study was based on six species trials located in eastern and southern South Africa with plant material provided by Camcore members in the region, established from December 2009 to June 2010 (see table 1 and 2, figure 1). The trial design was the same at all six locations, a randomised complete block design with four replications, where every replication originally was planted with 36 (6 x 6) trees and where species were randomised within the replication, making it 144 trees per species at every site. Measurements of diameter at breast height (DBH, 1.3 m) and total tree height were taken at approximately three years of age. A volume index for juvenile trees was calculated (see equation 1).

$$\text{Volume} = 0.00003\ (DBH^2 * height) \quad (1)$$

INSERT TABLE 1 and TABLE 2 and FIGURE 1

TreeSonic

The TreeSonic microsecond timer (Fakopp Enterprise, Agfalva, Hungary) was used on four of the six sites in order to assess MOE. At these four sites, species with a survival of 50 % or more and a mean DBH larger than 4 cm were sampled. For the TreeSonic measurements, eight of the 16 interior trees in every replication were sampled; if necessary, outer trees were sampled to get the correct sample size. Trees with largest DBH were chosen. The probes of the TreeSonic were driven into the stem 1.5 and 0.5 m from the ground at approximately 45^o from the main axis of the stem. The stress wave was induced by hitting the start probe with a steel hammer. The transit time for the stress wave (μs/cm) between the start and the stop probe were recorded from the microsecond tool. Three replications of the hammer striking the start probe were done at the same place on the tree for every measured tree and the average of the three recordings was used as the final transit time. The recordings were converted from μs/cm to m/s by dividing 100000 into the recorded value from the TreeSonic.

INSERT FIGURE 2

In order to assess green densities, 4 out of the 8 trees in every replication that were measured with the TreeSonic were drilled bark-to-bark at breast height with a hand held 5 mm Haglöfs increment corer and cores were collected. The term ´green density´ refers to the wood density of a standing living tree. The green density consists of a wood cell component and a water component (basic density and water). Immediately after extraction, wood cores were packed in plastic wrapping, and marked with a pen on a piece of masking tape that was put on the plastic wrapping to maintain identity and put into a cooler box. At the end of the day the samples were measured and weighed to the nearest 0.01 gram with an electronic scale in order to measure green weight. The samples were then oven dried at 50 ^{o}C for 48 hours and weighed again to the nearest 0.01 grams with an electronic scale to measure dry weight. Densities were calculated by dividing the weight (green or oven dry) by the green sample volume.

$$\mathrm{d(g)\ or\ d(od)} = \frac{\mathrm{w(g)\ or\ w(od)}}{\mathrm{v(g)}} \qquad (2)$$

Where d(g) or d(od) is the green or oven dry density (kg/m^3), w(g) or w(od) is the green or oven dry weight (kg) and v(g) is the green volume calsulated as the length of the increment core x πr^2, with r = 2.5 mm, the radius of the increment corer. MOE was calculated as:

$$\mathrm{MOE} = \rho V^2 * 10^{-9} \qquad (3)$$

Where ρ is the green density of the material (kg/m^3), V is the longitudinal wave velocity (m/s) and MOE is the modulus of elasticity (GPa).

The green density for every tree that was drilled of a specific species or provenance was calculated and used in the calculations to get the average MOE for that specific species or provenance (see equation. 2) at a particular site. Two other MOE variables were created (MOE2 and MOE3). The MOE2 variable was calculated with mean green densities for a particular species or provenance across all sites. MOE3 was calculated with assuming a mean green density of 1000 kg/m^3 for all species or source of species.

Moisture content is defined as the percentage weight of the water in the wood in relation to the oven dried weight (Koch 1972).

$$\text{Moisture content} = \frac{\mathrm{w\ (w)}}{w\ (d)} * 100 \qquad (4)$$

Where w (w) is the weight of the water assessed as the green weight minus the dry weight and w (d) is the weight of the dry material. Moisture content was calculated for all trees which were sampled with the increment core.

Pearson correlations were calculated for the different MOE variables across all sites.

Soil sampling

Soil sampling was done to better describe and characterize each test site. A soil auger was used to drill two holes per site to a depth of 1 m, if possible. Depth, color and texture of the A & B horizons were determined in the field. For color assessment, the Munsell® soil chart was used. Soil was collected from two soil auger holes at each site and combined to represent each horizon. The samples for each horizon in each test were labeled, placed in a plastic and sent to the Institute for Commercial Forestry Research (ICFR), Pietermaritzburg, South Africa. Samples were then analyzed to quantify physical and chemical soil properties (see table. 3).

Linear Models

The replication x species interaction and comparisons among species and replications were analyzed using a mixed-effect model procedure to account for different variances. The following mixed-model was used:

$$y_{ijk} = \mu + F_i + Rj + FR_{ij} + E_{ijk} \qquad (5)$$

where,

y_{ijk}	is the *k*th observation of the *j*th replication for the *j*th species
F_i	is the fixed effect of the *i*th species, (i=1,…,24)
R_j	is the random *j*th replication effect (i=1,…,4), ~NID (0, σ^2_R)
E_{ijk}	is the error term ~NID (0, σ^2_E)

The site x species interactions and comparisons of traits among sites and species were calculated using a mixed-effect model procedure to account for different variances. The following mixed-model was used:

$$y_{ijkl} = \mu + S_i + R(S)_{j(i)} + F_k + SF_{ik} + FB(S)_{ijk} + E_{ijkl} \qquad (6)$$

where,

y_{ijkl}	is the *l*th observation of the *j*th block within the *i*th site for the *k*th species
μ	is the overall mean
S_i	is the random *i*th site effect (i=1,…,6), ~NID $(0, \sigma^2_S)$
$R(S)_{j(i)}$	is the random *j*th replication effect within the *i*th site (j=1,…,4), ~NID $(0, \sigma^2_R)$
F_k	is the fixed effect of the *k*th species, (k=1,…,24)
SF_{ik}	is the random *k*th species by *i*th site interaction effect ~NID $(0, \sigma^2_{SF})$
$FB(S)_{ijk}$	is the random *k*th species by *j*th block effect for the *i*th site, ~NID $(0, \sigma^2_{BF})$
E_{ijkl}	is the error term NID $(0, \sigma^2_E)$, ~NID $(0, \sigma^2_E)$

Differences among species means were evaluated using Tukey-Kramer test for each of the characteristics.

RESULTS

Soil analyses

The A & B horizons ranged from sand to clay loams. Soil pH in the A horizon was very acidic with pH (KCL) values ranging from 3.4-4.3. Most of the sites were at least moderately well-drained except for Ncalu and Weza which were moderatley poorly drained. Wildebeest, Glen Cullen and Ruigteveli had soil organic matter < 1.5% in the A horizon, while the other three sites had at least three times that amount (see table 3).

INSERT TABLE 3

Survival and Growth

Mean survival for species at each site is presented in table 4. All of the tests had some species with greater than 75% survival, with the exception of 99-55-03E1, PG Bison, Wildebeest. Average survival across all species and all sites was 61.8%, and test mean survival varied from 26.4 % (at 99-55-03E1, PG Bison, Wildebeest, Eastern Cape) to 87.8% (at 99-18-03C, Mondi, Ncalu, KwaZulu-Natal). Across sites, species survival ranged from 0% to 97%. Only species with survival of 50 % or more were analyzed for growth traits. These relatively large differences in survival should be taken into consideration when interpreting the growth and wood property analyses.

INSERT TABLE 4

There were significant species differences for height, DBH and volume at four of the six sites. The other two sites, Wildebeest and Glen Cullen in Eastern Cape, both had low average survival, and although there were significant differences among species for height, differences for DBH and volume growth were not significant (see table. 5).

INSERT TABLE 5.

Single-site analyses

<u>Ncalu, KZN (KwaZulu-Natal)</u>

At test 99-18-03C, Ncalu, KZN, altitude is 1130 m, mean annual rainfall is 809 mm, and mean annual temperature is 16 ^{o}C. Site quality is defined as the relative productivity of a site for tree species, and at Ncalu, site quality was good with a fertile, moderately poor-drained, silt soil. The common commercial pine species in this region is *P. patula*. Species survival averaged 87.8 % and ranged from 77 % (*P. tecunumanii* LE) to 96 % (*P. patula*). Growth was also good at this site. The *P. patula x tecunumanii* LE KLF hybrid was significantly superior to all other species for height and volume growth; its mean height was 6.23 m. This can be compared to the normal commercial species *P. patula*, which averaged at 5.53 m. *P. greggii* var. *greggii* and *P. pseudostrobus* are ranked in the bottom for all growth traits, mean height was of 3.56 m for the first and 4.19 m for the latter (see table. 6).

Weza, KZN

At test 99-49-03D, Weza, KZN, altitude is 1100 m, mean annual rainfall 996 mm and average annual temperature is 14.4 ^{o}C, which is lower than the other site in this region. Site quality is inferior to the Ncalu test in the same region, the soil is a moderately poor drained, clay loam. The common commercial pine species in the Weza region are *P. patula* and *P. elliottii*. Species survival averaged survival was 66.7 % and ranged from 38 % (*P. tecunumanii* HE) to 93 % (*P. elliottii x caribaea* SAPPIX) with 11 species with a survival of 50 % or more. Growth was intermediate and inferior to the other site in the KZN region for most species. The *P. elliottii x caribaea* SAPPIX hybrid and the pure *P. elliottii* showed best growth for all growth parameters, mean heights were 3.67 m for the former and 3.42 m for the latter. A comparison with the common checklot of the commercial species *P. patula* was not possible since the species was not included in the analysis due to its low survival of 38%. However, two other *P. patula* sources were included in this trial, and these two sources (PatKLFG and PatKLFE) had survival above 50% and were analyzed for growth traits. Many of species at Ncalu outgrew these two *P. patula* sources, including the *P. elliottii x caribaea* SAPPIX and the *P. elliottii*. The major reason for the poor survival at this site seems to be that there was an unusual dry period following the planting date. There was 30 mm of precipitation within the first week after the trial was established in mid-February, but March was very dry with only 14 mm of precipitation. During the seven month period from March to September 2010 precipitation was only 128 mm, which is lower than usual. For example in 2011 and 2012 the precipitation during this time period was more than double

(SAWS 2013). *P. greggii* var. *greggii* and *P. pseudostrobus* performed the worst for all growth traits, the former had an average height of 2.04 m and the latter 1.83 m (see table. 7).

<u>Wildebeest, EC (Eastern Cape)</u>

At test 99-55-03-E1, Wildebeest, EC, altitude is 1421 m, mean annual rainfall is 989 mm and mean annual temperature is 14 ^{o}C. Site quality is intermediate with intermediate fertile moderately well drained Hutton soil with a sandy loam texture. The commercial pine species in the region is *P. patula*, but both sources in this trial had survival too low for inclusion in the growth analysis. Species survival was very poor perhaps because the planting was done in mid-February on a rather harsh site, located on an exposed hillside with relative low levels of organic content and nutrients. Precipitation during the first seven and a half months after trial establishment was only about 250 mm, with three months of less than 10 mm, which has probably affected the survival negatively (SAWS 2013). Furthermore the closest weather station (in Elliot, 50 km away) at approximately the same altitude shows that temperatures in June, July and August often went below freezing. For example in 2010, the temperature was below 0 ^{o}C during 32 days with -6.6 ^{o}C as the coldest. This relatively cold climate could have contributed to the low survival. Average survival was 26.4 % and ranged from 0 % (*P. maximinoi*, *P. pseudostrobus* and *P. tecunumanii* LE) to 63 % (*P. greggii* var. *australis*). Only three species had a survival over 50 % and are included in the analysis. Growth was also poor in this trial. Average heights ranged from 1.86 m for *P. elliottii* to 2.25 m for *P. taeda* (see table. 8).

Glen Cullen, EC

At test 99-55-03-E2, Glen Cullen, EC, altitude, mean annual rainfall and mean annual temperature is very similar to the other site in this region. Site quality is intermediate with characteristics very similar to that of test 99-55-03-E1, Wildebeest, EC. Since the two sites in EC are located close to each other, the commercial pine species are the same. Species survival was low, because of planting in mid-February, and relatively low levels of organic content and nutrients. The same weather station as for the Wildebeest site has been used for rainfall data and hence, the low rainfall during the establishment phase of the trial has probably affected the survival negatively. Just as for the Wildebeest site, the relatively cold climate (SAWS 2013) has probably had a negative impact on survival for many species and survival at the two sites in the EC region are somewhat similar. Average survival was 51.3 % and ranged from 1 % (*P. tecunumanii* LE) to 93 % (*P. greggii* var. *australis*), with 5 species surviving at 50 % or more. Growth was intermediate and *P. greggii* var. *australis* performed best for all growth variables but not significantly better than the two *P. patula* sources. Average height of *P. greggii* var. *australis* was 3.39 m, compared to 3.38 m and 3.36 m for the two *P. patula* sources. *P. greggii* var. *greggii* had the lowest growth rates for diameter and volume growth (see table. 9).

Ruigtevlei, WC (Western Cape)

At test 99-55-03-E3, Ruigtevlei, WC, altitude is 110 m, mean annual rainfall is 698 mm and the mean annual temperature is 16.7 ^{o}C. Site quality is poor with relatively infertile, well-drained sandy soil that is low in organic content. The common commercial species in the region is *P. radiata*, which also had best growth. Species survival was good. Average survival was 82.1 % and ranged from 53 % (*P. radiata* MTOC) to 97 % (*P. greggii* var. *australis*). Growth was intermediate, and three different *P. radiata* sources (Rad, Rad MTOC and Rad MTOS) performed best in all growth aspects. Height growth averaged 2.88 m, 3.09 m and 3.26 m for the three different sources of *P. radiata*, while *P. pseudostrobus* and *P. greggii* var. *greggii* performed the worst with 1.55 m for the former and 1.51 m for the latter (see table. 10).

Brackenhill, WC

At test 99-55-03-E4, Brackenhill, altitude is 299 m, mean annual rainfall 945 mm and mean annual temperature 16.7 ^{o}C. Site quality is good with intermediate fertility, and moderately-well drained sandy loam soil. This site has higher levels for many of the nutrients and more organic content in the soil, compared to the other test site in the WC region. The commercial species is *P. radiata*, just like the other test in the same region. Species survival was poor. Average survival was 45.5 % and ranged from 17 % (*P. greggii* var. *greggii*) to 89 % (*P. elliottii* x *caribaea* MTO). This site was planted in late-June, which was unsuitable timing since it had not rained at all the previous ten days and rained less than 10 mm the following 15 days after planting. Other than that, the rainfall pattern was quite normal for the rest of 2010 (SAWS 2013). At this site, the normal commercial species would be *P. radiata*, but in this test, all three *P. radiata* sources (Rad, Rad MTOC and Rad MTOS) had survival below 50 %, and were not included in the growth analysis of variance. The common commercial control (Rad) had best survival among the three *P. radiata* sources (45%), and had average height of 3.12 m, very similar to *P. elliottii*, which was ranked second best for all growth traits. Interestingly the *P. elliottii x caribaea* MTO hybrid performed best in all growth aspects at this site, average height was 3.5 m, while the *P. elliottii x caribaea* SAPPI hybrid performed worst in height growth (2.41 m) and diameter growth and second worst in volume growth. Similar to the *P. radiata* sources, the *P. greggii* var. *australis* was not included in the growth analyses because of its low survival (47%). However, the species showed promising growth results and would have been ranked in the top among species at this site for growth traits, with for example an average height growth of 3.31 m, even better than *P.elliotti* (3.11 m) and *P.radiata* (3.12 m) (see table. 11).

INSERT TABLE 6 to 11

Multiple-site analyses for each region

There are highly significant site x species interaction effects in two of the three regions (KwaZulu-Natal and Western Cape) for all growth traits (see table. 12). In the Eastern Cape region survival was low, resulting in there being only one degree of freedom for the site x species interaction, which makes it difficult to confirm significant differences. There was a significant site x species interaction for all growth traits in the KwaZulu-Natal region, furthermore there were five common species at the two tests in this region. At the 99-18-03C Ncalu trial, *P. maximinoi* is performing significantly better than *P. elliottii*, the former had a height growth of 5.56 m compared to 4.44 m for the latter. At the 99-49-03D Weza trial, the relationship between these two species was different. *P. elliottii* had significantly better growth in all aspects compared to *P. maximinoi*; the former had an average height growth of 3.42 m and the latter 2.98 m. At these two sites *P. pseudostrobus* and *P. greggii* var. *greggii* were ranked last while as above mentioned, the *P. elliottii* and the *P. maximinoi* showed very different results for the growth traits.

There was also a significant site x species interaction for all growth traits in the Western Cape region where there were five common species, but none were any of the *P. radiata* sources due to their < 50% survival at Brackenhill. At the 99-55-03-E3 Ruigtevlei trial, *P. elliottii x caribaea* SAPPI is performing significantly better than *P. elliottii x caribaea* MTO, height growth averaged 2.81 m for the former and 2.43 for the latter. At the 99-55-03-E4 Brackenhill trial the relationship was different. *P. elliottii x caribaea* MTO had a mean height growth of 3.50 m which was significantly better than *P. elliottii x caribaea* SAPPI that averaged 2.41 m. Species truly behaved differently within these two latter regions. Hence, the mean of a species in any region was not used for multiple site analysis for comparison between the regions.

INSERT TABLE 12

Wood properties results

There were significant species differences for all three MOE variables at all of the four sites that were included in the analysis of wood properties. Moisture content, green density and dry density exhibited significant species differences on three of the four sites. When there were five or more DF, significant differences were shown among all analyzed variables (see table. 13).

INSERT TABLE 13

At test 99-18-03C, Ncalu, KZN, wood property analysis was possible for all 13 species. Average green densities ranged from 935.3 (*P. taeda*) to 1059.8 kg/m^3 (*P. maximinoi*). Average dry densities ranged from 338 (*P. elliottii*) to 395.5 kg/m^3 (*P. tecunumanii* LE). The MOE variable had a large dispersion. Values ranged from 3.34 (*P. elliottii x caribaea* SAPPIN) to 6.40 GPa (*P. patula x tecunumanii* LE KLF). Furthermore, *P. maximinoi* also showed a high average MOE value (6.28 GPa) (see table. 14 and 15).

At test 99-49-03D, Weza, KZN, average wood property analysis was only possible for five of the 15 species because of the poor growth and intermediate survival. Average green density ranged from 925.9 (*P. taeda*) to 965.9 kg/m^3 (*P. patula x tecunumanii* LE YORK), while dry densities ranged from 353.6 (*P. elliottii*) to 396.3 kg/m^3 (*P. patula x tecunumanii* LE YORK). The MOE variable ranged from 3.14 (*P. elliottii*) to 5.08 GPa (*P. patula* KLFE) (see table. 16 and 17).

At test 99-55-03-E2, Glen Cullen, EC, wood property analysis was possible for four of the nine species. Green densities ranged from 895.9 (*P. patula*) to 999.5 kg/m^3 (*P. greggii* var. *greggii*), while dry densities ranged from 354.3 (*P. patula*) to 384.6 kg/m^3 (*P. greggii* var.

greggii). Notable is that species ranking is the same for both green and dry density. At this trial the MOE variable ranged from 2.21 (*P. elliottii*) to 4.37 GPa (*P. patula*) and *P. elliottii* had significantly lower MOE than all other species (see table. 18 and 19).

At test 99-55-03-E4, Brackenhill, WC, wood property analysis was possible for six of the 13 species. Average green densities ranged from 928.4 (*P. taeda*) to 988.1 kg/m^3 (*P. radiata*). Notable is that all analyzed species except *P.taeda* had very similar green densities. Dry densities ranged from 344.6 (*P. radiata*) to 386.5 kg/m^3 (*P. greggii* var. *australis*). *P. radiata* was ranked highest among species for green density and lowest for dry density. The average MOE variable varied from 2.88 (*P. radiata*) to 4.54 GPa (*P. tecunumanii* HE). *P. elliottii* also had a low average MOE value of 3.01 GPa (see table. 20 and 21).

INSERT TABLE 14 to 21

When combining the four sites that were used for the wood analyses, there were significant species differences for green density and the three different MOE variables. The three different ways of approximating MOE gives the same high significant differences for species. Moisture content was significantly different for species at a lower probability level (p-value < 0.10). Surprisingly, dry density did not show a significant difference for species. Perhaps contributing to this lack of significance is the fact that *P. radiata* had significantly higher dry density than that of *P. elliottii* at the 99-18-03C Ncalu KZN site while, at the 99-55-03E4 Brackenhill WC site, this relation is the opposite. Significant site x species interactions were found for dry density, moisture content, and all MOE variables, and it seems that these interactions are obscuring any species differences for dry density and moisture content. However, for the MOE variables, species differences are still strongly significant (see table. 22).

INSERT TABLE 22

Across all four sites where wood properties were analyzed green density varied from 926.7 (*P. patula*) to 1059.8 kg/m^3 (*P. maximinoi*). Dry densities ranged from 353.0 (*P. radiata*) to 396.3 kg/m^3 (*P. patula x tecunumanii* LE YORK). Notable is that *P. radiata*, unlike the other species with quite similar green density and dry density rankings, is ranked among the top for the green density, while it is ranked lowest for the dry density, a pattern that is not shown by other species (see table. 23).

Across all four sites where wood properties were analyzed the MOE variable ranged from 3.03 (*P. elliottii*) to 6.40 GPa (*P. patula x tecunumanii* LE KLF). *P. maximinoi* and *P. tecunumanii* LE were two other species that distinguished themselves with high MOE values around 6. The three *P. elliottii x caribaea* hybrids did show low MOE, with values around 3.3 GPa. Worth noting is that the different MOE variables give roughly the same results and similar ranking across sites (see table. 24).

INSERT TABLE 23 and TABLE 24

DISCUSSION

This study shows that some species had better growth than the normal commercial species on some sites. The growth results confirm to some extent the results of Hodge and Dvorak (2012) that there is a potential gain for ‘new’ species. *P. patula* is the normal commercial species in two regions; the species seem to be outperformed by more species at lower altitudes, such as in the Western Cape, which is confirmed with the literature (Dvorak et al. 2000c).

There have been indications that *P. maximinoi* could be developed into a major commercial species in South Africa (Hodge and Dvorak 2012). In this study the species did not show the best growth at any site. However, it should be borne in mind that there were no really suitable sites for *P. maximinoi* in this study, since the species in South Africa is recommended for the warmer areas of Mpumalanga (Hodge and Dvorak 2012).
The big differences in survival across the sites are an important factor having implications for this study. The reason behind the low survival is considered to be different at each location. Date of planting varied both within and between the regions for the different trials which had an effect on the survival. At some sites, trial establishment was performed in dry periods. Some trials were located in cold areas where frost was a common feature. Texture, drainage and % organic matter varied greatly among the sites, affecting tree growth and development. Differences were also experienced for the ,wood traits of green density, dry density and MOE variables across the different sites.

Survival and species rankings of growth varied within the three regions. In the KwaZulu-Natal region, the two sites are different which probably affects both the growth and survival. The test 99-18-03C, Ncalu, KZN, is performing just like expected, days below 0 ^{o}C are very rare (SAWS 2013). Both survival and growth were good. There are some reasons for the good performance at this site. In the 99-49-03D field trial at Weza in the same region, survival was worse and species growth performances were heavily inferior. Days when the temperature reaches below 0 ^{o}C are not uncommon during June to August in this region (SAWS 2013). The two sites are almost located at identical altitudes but soil conditions vary which probably is one of the biggest reasons for the differences in growth. The soil at the 99-18-03C site at Ncalu is of a silt type, more fertile and with considerably less clay content than that of 99-49-03D at Weza. Mesoamerican pines and hybrids between those perform best at the 99-18-03C site at Ncalu. At the 99-49-03D Weza site, *P. elliottii* x *caribaea*, and North American species such as *P. elliottii* and *P. taeda* perform best. These species are considered to be able to perform better on sites with high soil moisture, while the Mesoamerican pines are considered to perform worse (Barnett 2002, Schultz 1997a). Another important factor for the differences in growth and survival is that the 99-49-03D Weza site is located on an exposed hillside while the 99-18-03C site at Ncalu is more protected from the winds since it is located in a flatter area with surrounding plantations. Furthermore, the planting dates may have affected the survival results to some extent. The 99-18-03C Ncalu site was planted in December which is close to optimal while the 99-49-03D Weza site was planted in mid-February.

At the Western Cape, there was a big difference in survival between the two sites. The survival at 99-55-03-E4 Brackenhill was only 45.5% on average for all species, while it was 82.1% at the 99-55-03-E3 Ruigtevlei site. Growth also differed between the two sites, with better average growth at the 99-55-03-E4 site despite its inferior survival rates. Planting date and weather at the planting probably affected the differences in survival within this region. For example, the 99-55-03-E4 Brackenhill site was planted in late June when the region was experiencing a dry period. In comparison, the 99-55-03-E3 Ruigtevlei site was planted in late March, which is a more appropriate time for planting in the region. This fact has a large impact on the differences in survival on the two sites. Furthermore, the few species with a survival of 50% or more at the 99-55-03-E4 Brackenhill site performed quite well. Notable at both sites is that North American species have performed best, despite the good drainage at both sites, which is favorable for the Mesoamerican species. The 99-55-03-E3 Ruigtevlei site is sandier than the 99-55-03-E4 Brackenhill site. This in combination with higher levels of organic content and nutrients at the 99-55-03-E4 Brackenhill site is probably the reason for the better growth here. The commonly used species in this region is *P. radiata*, which is also performing best at the 99-55-03-E3 Ruigtevlei site. However, the survival of that species at the 99-55-03-E4 Brackenhill site was lower than 50 % which was the criterion for being excluded from the analysis.

At the Eastern Cape sites the survival was very low, 26.4 % for the 99-55-03-E1 Wildebeest site and 51.3 % for the 99-55-03-E2 Glen Cullen site. Both sites were planted in mid-

February which can be considered to be too late in the planting season in the region. Both sites are also located in exposed areas for wind since the 99-55-03-E1 Wildebeest site is located on a hillside and 99-55-03-E2 Glen Cullen is located in a small isolated plantation area. These facts in combination with relatively cold climate with many days below freezing, soils with low organic content and low nutrient levels are the most probable reasons for the bad survival and low growth rates. It is hard to find a reason for the better performance at the 99-55-03-E2 Glen Cullen site in this case.

This study has found that there are significant differences for green density among species. Average green density across all four sites included in the wood property analysis ranged from 926.7 for *P. patula* to 1059.8 kg/m^{3}for *P. maximinoi*. The assumption of a constant green density for all species may not accurately reflect their MOE. For example, in this study under an assumption of constant green density of 1000 kg/m^3, *P. patula* was estimated to have an MOE3 of 5.28 GPa. In comparison, using the observed green density for P. patula (926.7 kg/m^3), the MOE2 was estimated to be 4.93 GPa. If MOE2 is considered more accurate, then MOE3 is an overestimate of 7.1%. The opposite effect was observed for *P.maximinoi*, which had a very high green density of 1059.8 kg/m^3. For this species, MOE3 was calculated as 6.00 GPa, while MOE2 (using the observed green density of 1059.8 kg/m^3) was calculated as 6.36 GPa. In this case, MOE3 underestimates wood stiffness by 5.7% compared to MOE2. With either approach, (assuming constant green density of 1000 kg/m^3 or using the observed green density), *P. maximinoi* has higher MOE than *P. patula*, but MOE3 underestimates the differences between the two species. This aspect should be taken into consideration when comparing MOE for different species using the method of a constant green density. MOE for species with high actual green density will be underestimated and species with low green density will be overestimated. However, in general, the species rankings in these two examples are the same with both methods. When using the overall mean green density for a species across all sites (MOE2) to calculate MOE, results only differ a little compared to the MOE variable. If the purpose of a study is to find species ranking and not true MOE, a constant green density can be used since rankings using specific green density for the species on the specific site do not improve the results to a large extent.

Correlations between the MOE and MOE2 variables, and the MOE and MOE3 variables are 0.98, while the correlation between MOE2 and MOE3 is 0.99. This shows that the method using a constant green density of 1000 kg/m^3 (as in MOE3) when calculating the MOE is an adequate approach.

The study confirms the results of Wielinga et. al (2009) to some extent, where the green density impact on *P. radiata* clones for MOE was assessed, even though in this study comparisons were among species. Hence, assuming a constant green density for all species is probably a more time and cost efficient way to approximate MOE for ranking, compared to a time consuming sampling procedure to achieve ‘correct’ green density. This agrees with the results of Mora et. al (2009) who examined this relation for *P. taeda*. However, in order to get the true MOE, a constant green density might be misleading.

Highest MOE values were found at the 99-18-03C Ncalu site. The MOE of *P. patula x tecunumanii* LE, *P. tecunumanii* LE were expected to be higher than for the MOE of *P. elliottii* and *P. radiata*, which is confirmed by the results from this study. These two first species together with *P. maximinoi* are ranked highest among the species in this study. The three species MOE values ranges from 5.50 (*P. tecunumanii* LE, MOE2 variable) to 6.40 GPa (*P. patula x tecunumanii* LE KLF, MOE variable). The *P. elliottii* and the different *P. elliottii x caribaea* hybrids were ranked lowest for all MOE variables, which is an indicator that the species juvenile wood might not be suitable for some end products. However, the trial is in an early stage and it might not be appropriate to draw any conclusions of timber properties at the end of the rotation based on the material from this study.

It is hard to find implications for growth and survival based on these results. The most important factors seem to be soil nutrition, soil texture, soil depth, drainage, altitude, exposure, temperature patterns, rainfall and date planted. The relative importance of these aspects is hard to separate. Due to differences among the three regions it is difficult to give a single recommendation for all regions. Growth patterns are also different among the species, some species are sprinters while others are slow starters that grows more quickly after some years. It is also hard to make species recommendations based on these results due to the high mortality experienced at many sites. However in general these aspects should be followed: Planting date needs to be adapted to the regions' different conditions. Exposure wise, sites should be located in a suitable place and fertile sites are preferred over less fertile sites.

It is also hard to make species recommendations in the different regions based on growth, survival and MOE from the results of this study. In the KZN region *P. patula* is performing well, it has good survival, good growth and a high MOE. Since the two sites in this region are quite different it is hard to make a general recommendation. For sites like the 99-18-03C site at Ncalu, *P. maximinoi* and the common commercial species in this region *P. patula* are doing well in these three aspects. However, the *P. patula x tecunumanii* LE KLF hybrid is doing best. At the 99-49-03D site at Weza, the control *P. patula* KLFE is doing best when combining the survival, growth and MOE. Notable at this site, is that the common source *P. patula* has almost double the mortality rate as the control *P. patula* KLFE.

In the Eastern Cape region the results from this study supports that *P. greggii* var. *australis* shows the best potential. The species has over 50 % survival at both sites in the region, furthermore it is ranked high for growth parameters as well as for MOE. In the Western Cape region the two sites differ, which makes it hard for a general species recommendation. At sites similar to 99-55-03-E3 at Ruigtevlei, three different sources of *P. radiata* are performing best for growth parameters, two of those are controls and exhibit lower survival than the other. Sampling for MOE was not taken at this site but overall *P. radiata* is ranked in the bottom for MOE among all species in this study. At sites more similar to the 99-55-03-E4 Brackenhill site *P. elliottii x caribaea* MTO and pure *P. elliottii* performed well and had relatively high survival, even though their MOE values are relatively low. These two species might be recommended instead of the commonly used *P. radiata*, mostly due to higher survival rates.

CONCLUSIONS

Based on the results from this study, despite the high mortality rates that was experienced on many sites, there are alternative pine species that are showing comparable growth rates to the current commercial species. Considering other traits such as wood properties or disease resistance, these species seems to have a role in the South African commercial forestry portfolio of suitable species in the future. For example at elevations in the KZN region at sites similar to that of Ncalu, *P. patula* x *tecunumanii* LE and *P. maximinoi* are performing well; these species could be incorporated in breeding programs and their early good performances should not be neglected. In the WC region at sites similar to Ruigtvlei or Brackenhill where *P. radiata* is used in a large extent, viable options to add to breeding programs might be *P. elliottii x caribaea* and *P. elliottii*, even though their MOE values are low.

When approximating MOE, little variation was found when using a constant green density or when using a species specific green density. Hence, the assumption of a constant green density does not affect the species ranking of the predicted MOE, as much as the specific MOE value. However, MOE for species with high actual green density will be underestimated when using a constant green density and vice versa. Focus should be on improving the acoustic tools and not in determining the correct green density if the aim is rapid information for ranking purposes. As stated by Mora et. al (2009), the assumption and impact of a constant green density needs to be further evaluated. Further studies should be done to see if and how the MOE changes over time at the sites included for wood property analysis in this study. An appropriate way would be to assess the same trees when the height and diameter is measured at 5 and 8 years that is standard in Camcore trials, which allow investigation of the age-age correlation.

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Table 1. The major species tested in the South African species-site trials. Species tested on most sites are listed in the top of the table, while species only tested on one or two sites are listed under controls. Code used in the article is listed under code.

Species or hybrid	Description	Code	Source
P. elliottii	F1 selections Duku seed orchard	Ell	KLF
P. greggii var. *australis*	1st generation Mondi seed orchard – M9649	GregS	Mondi
P. greggii var. *greggii*	1st generation Mondi seed orchard – M9649	GregN	Mondi
P. maximinoi	F1 Camcore provenance selection	Max	KLF
P. patula	2nd generation Mondi seed orchard – M9648	Pat	Mondi
P. pseudostrobus	F1 selections Jessievale seed orchard	Pseu	KLF
P. radiata	2nd generation CS MTO/106/02/09/2007	Rad	MTO
P. taeda	1st generation Mondi seed orchard – PT66480	Tae	Sappi
P. tecunumanii HE	2nd generation seed F1 Camcore selection	TecH	KLF
P. tecunumanii LE	1st generation collection from Sappi clone bank	TecL	Sappi
Controls			
P. elliottii x caribaea MTO	Commercial cuttings	ECC MTO	MTO
P. elliottii x caribaea SAPPI	Commercial cuttings	ECC SAPPI	Sappi
P. elliottii x caribaea SAPPIN	Cuttings collected from Sappi Ngodwana	ECC SAPPIN	Sappi
P. elliottii x caribaea SAPPIX	PECH mix. Mix of production families	ECC SAPPIX	Sappi
P. maximinoi OXF	Commercial lot Zimbabwe seed from Ezigro or Baziya	MaxOXF	Mondi
P. patula KLFE	2nd generation KLF seed orchard – 104.0412 Enzeleni	Pat KLFE	KLF
P. patula KLFGF	2nd generation KLF seed orchard – 104.0412 Glen Fahy	Pat KLFGF	KLF
P. patula PGB	Commercial seedling PG Bison nursery	Pat PGB	PG Bison
P. patula x oocarpa KLF	du Plessis collected cuttings from Tweefontain	PatxOoc KLF	KLF
P. patula x tecunumanii LE KLF	du Plessis collected cuttings from Tweefontain	PatxTecL KLF	KLF
P. patula x tecunumanii LE YORK	Mix of commercial production families Sabie nursery	PatxTecL Y	York
P. radiata MTOC	Commercial cuttings	Rad MTOC	MTO
P. radiata MTOS	Commercial second generation seedlings	Rad MTOS	MTO
P. taeda MONDIB	Mondi seed orchard – M9547 Baziya nursery	Tae MONDIB	Mondi

Table 2. Site information for the six tests in the South African species-site trials.

TestID	99-18-03C	99-49-03D	99-55-03E1	99-55-03E2	99-55-03E3	99-55-03E4
Site	Ncalu	Weza	Wildebeest	Glen Cullen	Ruigtevlei	Brackenhill
Company	Mondi	Merensky	PG Bison	PG Bison	PG Bison	PG Bison
Region	KwaZulu-Natal	KwaZulu-Natal	Eastern Cape	Eastern Cape	Western Cape	Western Cape
Date planted	3-Dec-09	18-Feb-10	18-Feb-10	16-Feb-10	25-Mar-10	25-Jun-10
Spacing (m)	3 x 2.5	3 x 3	3 x 3	3 x 3	2.7 x 2.7	2.7 x 2.7
Latitude	30°11.920´ S	30°33.800´ S	31°12´11 S	31°06´33 S	34°00´58 S	34°01´19 S
Longitude	30°04.800´ E	29°44.330´ E	28°05´30 E	28°10´16 E	22°52´48 E	23°08´15 E
Altitude (m)	1130	1100	1421	1406	110	299
Mean annual rainfall (mm)	809	996	989	989	698	945
Mean annual temperature (°C)	16	14.4	14	14	16.7	16.7
Previous crop	*Eucalyptus spp.*	*Pinus spp.*	*P. patula*	*P. patula*	*P. radiata*	*P. radiata*

Table 3. Soil information for the six sites in the South African species-site trials. Two soil samples were taken on each site, to a one meter depth (if possible), and analyzed at Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

TestID	**99-18-03C**	**99-49-03D**	**99-55-03E1**	**99-55-03E2**	**99-55-03E3**	**99-55-03E4**
Site	Ncalu	Weza	Wildebeest	Glen Cullen	Ruigtevlei	Brackenhill
Company	Mondi	Merensky	PG Bison	PG Bison	PG Bison	PG Bison
Region	KZN	KZN	EC	EC	WC	WC
Soil type			Hutton	Hutton		
Drainage	Moderately poor drained	Moderately poor drained	Moderately well drained	Moderately well drained	Well drained	Moderately well drained
Horizon	**A**	**A1**	**A**	**A**	**A**	**A**
Texture	Silt	Clay loam	Sandy loam	Sand	Sand	Silt loam
Depth (cm)	0-70	0-20	0-30	0-30	0-50	0-5
Munsell	7.5 YR 4/2	7.5 YR 4/2	5 YR 3/3	5 YR 4/4	5 YR 3/1	10 R 3/1
Sand %	15	15	64	77	84	48
Silt %	59	32	21	15	13	43
Clay %	25	53	15	8	3	9
pH KCL	4.43	4.16	4.10	4.22	3.72	3.42
pH H_2O	5.22	4.76	5.12	4.87	5.01	4.66
Organic content %	6.77	4.8	1.27	0.66	0.98	9.63
N (LECO) %	0.25	0.19	0.07	0.03	0.03	0.55
P (Bray 2) ppm	16	15	15	16	15	36
K meq/100g	0.02	0.02	0.01	0.01	0.01	0.02
Mg	0.11	0.01	0.04	0.03	0.06	0.16
Horizon	**B**	**A2**	**B**	**B**	**B**	**B**
Texture	Clay loam	Clay loam	Sandy loam	Sandy loam	Sand	Sandy loam
Depth (cm)	70-	20-60	40-	30-	50-	5-70
Munsell	5 YR 4/6	7.5 YR 4/4	5 YR 4/6	5 YR 4/8	5 YR 4/4	5 YR 4/4
Sand %	16	10	62	67	83	64
Silt %	38	27	24	22	13	24
Clay %	46	63	14	11	4	12
pH KCL	4.67	4.31	4.31	4.19	4.53	3.78
pH H_2O	5.81	4.51	5.27	5.18	5.73	4.72
Organic content %	2.14	2.62	0.3	0.27	0.49	2.67
N (LECO) %	0.13	0.12	0.01	0.02	0.01	0.13
P (Bray 2) ppm	18	17	17	22	23	29
K meq/100g	0.02	0.02	0.02	0.02	0.02	0.02
Mg	0.06	0.01	0.04	0.05	0.07	0.03

Table 3. Continued

Horizon		**B**				
Texture		Sandy clay				
Depth (cm)		60-				
Munsell		7.5 R 4/6				
Sand %		48				
Silt %		2				
Clay %		51				
pH KCL		4.32				
pH H_2O		5.20				
Organic content %		0.45				
N (LECO) %		0.03				
P (Bray 2) ppm		11				
K meq/100g		0.01				
Mg		0.11				

Table 4. Species survival for species at the six tests in the South African species-site trials. Sample size is 144 trees of every species at every site, and 10800 in total.

Species	Survival (%)					
	Ncalu	Weza	Wildebeest	Glen Cullen	Ruigtevlei	Brackenhill
P. elliottii	90	92	53	83	88	67
P. elliottii x caribaea MTO					92	89
P. elliottii x caribaea SAPPI					90	61
P. elliottii x caribaea SAPPIN	85					
P. elliottii x caribaea SAPPIX		93				
P. greggii var. *australis*	89	47	63	91	97	47
P. greggii var. *greggii*	90	53	47	83	79	17
P. maximinoi	83	51	0		85	
P. maximinoi OXF		67				
P. patula	96	43	36	74	88	37
P. patula KLFE		79				
P. patula KLFGF		77				
P. patula PGB			31	71		
P. patula x oocarpa KLF	86					
P. patula x tecunumanii LE KLF	90					
P. patula x tecunumanii LE YORK		90				
P. pseudostrobus	92	70	0	28	88	51
P. radiata	90		4	25	88	45
P. radiata MTOC					53	22
P. radiata MTOS					59	29
P. tecunumanii HE	81	38	3	6	90	44
P. tecunumanii LE	77	47	0	1	83	28
P. taeda	92	75	52		69	56
P. taeda MONDIB		79				

Table 5. Summary of F-tests for species differences for growth traits from single-site ANOVAs. Diameters were measured at 1.3 m (breast height, dbh).

TestID, Site, Region	Trait	DF	F value	Pr > F
991803C, Ncalu, KZN	Height	12	22.03	<0.0001
	Diameter	12	9.76	<0.0001
	Volume	12	13.00	<0.0001
994903D, Weza, KZN	Height	10	16.02	<0.0001
	Diameter	10	34.51	<0.0001
	Volume	10	23.41	<0.0001
995503E1, Wildebeest, Eastern Cape	Height	2	8.46	0.0141
	Diameter	2	1.45	0.2987
	Volume	2	1.28	0.3372
995503E2, Glen Cullen, Eastern Cape	Height	4	7.91	0.0023
	Diameter	4	0.71	0.6017
	Volume	4	2.01	0.1563
995503E3, Ruigtevlei, Western Cape	Height	13	11.04	<0.0001
	Diameter	13	17.23	<0.0001
	Volume	13	15.09	<0.0001
995503E4, Brackenhill, Western Cape	Height	4	7.76	0.0025
	Diameter	4	9.89	0.0009
	Volume	4	10.09	0.0008

Table 6. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for survival and growth traits for test 99-18-03C Mondi, Ncalu, KwaZulu–Natal. Species means followed by the same letter are not significantly different.

Survival (%)			**Height** (m)							**Diameter** (cm)							**Volume** (m^3)				
Species	**Mean**		**Species**	**Tukey**			**Mean**	**SE**		**Species**	**Tukey**			**Mean**	**SE**		**Species**	**Tukey**		**Mean**	**SE**
Pat	96		PatxTecL KLF		A		6.23	0.096		PatxTecL KLF		A		8.70	0.198		PatxTecL KLF		A	0.0159	0.0006
Pseu	92		PatxOoc KLF		B		5.61	0.089		PatxOoc KLF	B	A		8.33	0.185		PatxOoc KLF		B	0.0131	0.0006
Tae	92		Max		B		5.56	0.098		Pat	B	A		8.28	0.145		Pat	C	B	0.0123	0.0005
Ell	90		Pat		B		5.53	0.064		Rad	B			7.75	0.177		Max	C	B	0.0110	0.0006
GregN	90		Rad		B		5.29	0.090		Max	B	C		7.60	0.193		Rad	C		0.0109	0.0006
PatxTecL KLF	90		GregS		C		4.87	0.109		Ell	B	C	D	7.51	0.134		GregS	C	D	0.0104	0.0006
Rad	90		TecH	D	C		4.84	0.099		GregS	B	C	D	7.49	0.244		TecH	E	D	0.0084	0.0005
GregS	89		Tae	D	C	E	4.53	0.065		TecH	E	C	D	6.89	0.221		Ell	E		0.0081	0.0003
PatxOoc KLF	86		TecL	D		E	4.45	0.115		ECC SAPPIN	E	C	D	6.86	0.213		ECC SAPPIN	E		0.0076	0.0005
ECC SAPPIN	85		Ell			E	4.44	0.055		Tae	E	F	D	6.73	0.137		Tae	E		0.0068	0.0003
Max	83		ECC SAPPIN			E	4.31	0.103		Pseu	E	F		6.36	0.181		TecL	E		0.0063	0.0005
TecH	81		Pseu			E	4.29	0.0824		TecL	G	F		5.99	0.235		Pseu	E		0.0063	0.0004
TecL	77		GregN		F		3.56	0.0576		GregN	G			5.20	0.144		GregN		F	0.0034	0.0002

Table 7. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for survival and growth traits for test 99-49-03D Merensky, Weza, KwaZulu–Natal. Species means followed by the same letter are not significantly different.

Survival (%)		**Height** (m)					**Diameter** (cm)					**Volume** (m^3)					
Species	**Mean**	**Species**	**Tukey**		**Mean**	**SE**	**Species**	**Tukey**		**Mean**	**SE**	**Species**	**Tukey**			**Mean**	**SE**
ECC SAPPIX	93	ECC SAPPIX		A	3.67	0.074	ECC SAPPIX		A	6.52	0.156	ECC SAPPIX		A		0.0054	0.0003
Ell	92	Ell	B	A	3.42	0.061	Ell		A	6.50	0.146	Ell		A		0.0050	0.0002
PatxTecL Y	90	Pat KLFE	B	C	3.17	0.084	Tae		B	5.02	0.157	Tae		B		0.0028	0.0002
Pat KLFE	79	Tae	D	C	3.08	0.066	Tae MONDIB	C	B	4.81	0.170	Tae MONDIB	C	B		0.0026	0.0002
Tae MONDIB	79	MaxOXF	D	C	3.01	0.091	PatxTecL Y	C	B	4.40	0.147	Pat KLFE	C	B		0.0025	0.0003
Pat KLFGF	77	Tae MONDIB	D	C	3.01	0.064	Max	C	D	4.07	0.246	PatxTecL Y	C	B	D	0.0022	0.0001
Tae	75	PatxTecL Y	D	C	2.98	0.057	Pat KLFE	C	D	4.05	0.224	Max	C	B	D	0.0021	0.0002
Pseu	70	Max	D	C	2.98	0.091	MaxOXF		D	3.41	0.239	MaxOXF	C		D	0.0019	0.0002
MaxOXF	67	Pat KLFGF	D		2.86	0.057	Pat KLFGF		D	3.41	0.199	Pat KLFGF			D	0.0016	0.0001
GregN	53	GregN		E	2.04	0.054	GregN		E	1.80	0.233	GregN		E		0.0006	0.0001
Max	51	Pseu		E	1.83	0.074	Pseu		E	1.08	0.197	Pseu		E		0.0005	0.0001

Table 8. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for survival and growth traits for test 99-55-03E1 PG Bison, Wildebeest, Eastern Cape. Species means followed by the same letter are not significantly different.

Survival (%)		**Height** (m)				**Diameter** (cm)					**Volume** (m^3)				
Species	**Mean**	**Species**	**Tukey**	**Mean**	**SE**	**Species**	**Tukey**		**Mean**	**SE**	**Species**	**Tukey**		**Mean**	**SE**
GregS	63	Tae	A	2.25	0.043	Tae		A	2.45	0.145	Tae	A		0.0006	0.0001
Ell	53	GregS	A	2.23	0.053	GregS	B	A	2.03	0.131	GregS	B	A	0.0004	0.0000
Tae	52	Ell	B	1.86	0.045	Ell	B		1.60	0.173	Ell	B		0.0003	0.0000

Table 9. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for survival and growth traits for test 99-55-03E2 PG Bison, Glen Cullen, Eastern Cape. Species means followed by the same letter are not significantly different.

Survival (%)		**Height** (m)				**Diameter** (cm)					**Volume** (m^3)					
Species	**Mean**	**Species**	**Tukey**	**Mean**	**SE**	**Species**	**Tukey**		**Mean**	**SE**	**Species**	**Tukey**			**Mean**	**SE**
GregS	91	GregS	A	3.39	0.0707	GregS		A	4.40	0.1443	GregS		A		0.0025	0.0001
Ell	83	Pat	A	3.38	0.0701	Pat	B	A	4.26	0.1510	Pat	B	A		0.0023	0.0002
GregN	83	PatPGB	A	3.36	0.0594	Ell	B	A	4.11	0.1757	PatPGB	B	A	C	0.0020	0.0002
Pat	74	GregN	B	2.99	0.0484	PatPGB	B	A	4.03	0.1278	Ell	B		C	0.0019	0.0001
PatPGB	71	Ell	C	2.64	0.0595	GregN	B		3.77	0.1077	GregN			C	0.0015	0.0001

Table 10. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for survival and growth traits for test 99-55-03E3 PG Bison, Ruigtevlei, Western Cape. Species means followed by the same letter are not significantly different.

Survival (%)		**Height** (m)					**Diameter** (cm)					**Volume** (m^3)					
Species	**Mean**	**Species**	**Tukey**		**Mean**	**SE**	**Species**	**Tukey**		**Mean**	**SE**	**Species**	**Tukey**			**Mean**	**SE**
GregS	97	RadS MTO		A	3.26	0.082	RadS MTO		A	4.90	0.1692	RadS MTO		A		0.0028	0.0002
ECC MTO	92	RadC MTO	B	A	3.09	0.059	RadC MTO		A	4.79	0.1484	RadC MTO		A		0.0025	0.0002
ECC SAPPI	90	Rad	B	C	2.88	0.062	Rad		B	3.96	0.1290	Rad		B		0.0018	0.0002
TecH	90	ECC SAPPI	D	C	2.81	0.054	ECC SAPPI		B	3.93	0.1171	ECC SAPPI		B		0.0016	0.0001
Ell	88	Max	D	E	2.61	0.060	Ell		B	3.55	0.0831	Ell		C		0.0011	0.0001
Pat	88	Ell		E	2.55	0.039	ECC MTO		C	2.96	0.1134	ECC MTO	D	C		0.0009	0.0001
Pseu	88	TecH	F	E	2.46	0.050	Tae	D	C	2.75	0.1040	Tae	D	E		0.0007	0.0001
Rad	88	ECC MTO	F	E	2.43	0.587	Max	D	E	2.47	0.0910	Max	D	E		0.0006	0.0001
Max	85	Tae	F	E	2.41	0.056	TecH	D	E	2.37	0.0796	TecH	D	E	F	0.0005	0.0000
TecL	83	GregS	F	E	2.37	0.046	TecL	F	E	2.16	0.1083	TecL		E	F	0.0005	0.0001
GregN	79	TecL	F	G	2.23	0.066	GregS	F	E	2.11	0.0700	GregS	G	E	F	0.0004	0.0000
Tae	69	Pat		G	2.12	0.050	Pat	F		1.90	0.0781	Pat	G	E	F	0.0003	0.0000
RadS MTO	59	Pseu		H	1.55	0.042	Pseu		G	1.36	0.1028	Pseu	G		F	0.0002	0.0000
RadC MTO	53	GregN		H	1.51	0.042	GregN		G	1.00	0.0765	GregN	G			0.0001	0.0000

Table 11. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for survival and growth traits for test 99-55-03E4 PG Bison, Brackenhill, Western Cape. Species means followed by the same letter are not significantly different.

Survival (%)			**Height** (m)						**Diameter** (cm)					**Volume** (m^3)			
Species	**Mean**		**Species**	**Tukey**		**Mean**	**SE**		**Species**	**Tukey**	**Mean**	**SE**		**Species**	**Tukey**	**Mean**	**SE**
ECC MTO	89		ECC MTO		A	3.50	0.076		ECC MTO	A	6.29	0.1910		ECC MTO	A	0.0052	0.0003
Ell	67		Ell		B	3.11	0.565		Ell	A	5.71	0.1654		Ell	B	0.0035	0.0002
ECC SAPPI	61		Tae		C	2.73	0.075		Tae	B	4.05	0.2007		Tae	C	0.0018	0.0002
Tae	56		Pseu	D	C	2.57	0.077		Pseu	B	3.81	0.1832		ECC SAPPI	C	0.0016	0.0002
Pseu	51		ECC SAPPI	D		2.41	0.088		ECC SAPPI	B	3.55	0.2303		Pseu	C	0.0015	0.0002

Table 12. Summary of F-tests for species differences for growth traits from the three multi-site region ANOVAs. Diameters were measured at 1.3 m (breast height, dbh).

Region	Trait	Source	DF	F value	Pr > F
KwaZulu-Natal	Height	Species	18	1.99	0.2663
		Site x Species	4	10.56	<0.0001
	Diameter	Species	18	1.24	0.4617
		Site x Species	4	16.00	<0.0001
	Volume	Species	18	3.22	0.1342
		Site x Species	4	4.66	0.0022
Eastern Cape	Height	Species	5	3.11	0.4040
		Site x Species	1	2.68	0.1188
	Diameter	Species	5	15.60	0.1619
		Site x Species	1	0.06	0.8066
	Volume	Species	5	1.88	0.4999
		Site x Species	1	1.10	0.3083
Western Cape	Height	Species	13	1.19	0.4768
		Site x Species	4	8.44	<0.0001
	Diameter	Species	13	1.30	0.4363
		Site x Species	4	11.60	<0.0001
	Volume	Species	13	0.66	0.7470
		Site x Species	4	16.80	<0.0001

Table 13. Summary of F-tests for species differences for wood property traits[1] from single-site ANOVAs.

TestID, site, Region	Trait	DF	F value	Pr > F
991803C, Ncalu, KZN	Green density	12	4.21	0.0004
	Dry density	12	4.98	<0.0001
	Moisture content	12	4.75	0.0001
	MOE	12	16.67	<0.0001
	MOE2	12	18.41	<0.0001
	MOE3	12	16.97	<0.0001
994903D, Weza, KZN	Green density	4	2.10	0.1443
	Dry density	4	1.80	0.1938
	Moisture content	4	4.47	0.0192
	MOE	4	21.15	<0.0001
	MOE2	4	41.58	<0.0001
	MOE3	4	42.47	<0.0001
995503E2, Glen Cullen, EC	Green density	3	10.67	0.0025
	Dry density	3	6.41	0.0130
	Moisture content	3	2.04	0.1789
	MOE	3	66.82	<0.0001
	MOE2	3	127.25	<0.0001
	MOE3	3	131.86	<0.0001
995503E4, Brackenhill, WC	Green density	5	3.09	0.0398
	Dry density	5	4.07	0.0150
	Moisture content	5	10.43	0.0002
	MOE	5	15.44	<0.0001
	MOE2	5	22.85	<0.0001
	MOE3	5	23.20	<0.0001

[1] Densities calculated as kg/m^3. Modulus of elasticity (MOE) was calculated as a function of observed green density and acoustic velocity. MOE2 was calculated by using the overall mean green density for a particular species. MOE3 was calculated assuming a constant green density of 1000 kg/m^3 for all species. Green density, dry density, moisture content and MOE were measured on 16 trees per site, while acoustic velocity (and thus MOE2 and MOE3) measured on 32 trees per site.

Table 14. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for wood property traits[1] for test 99-18-03C Mondi, Ncalu, KwaZulu–Natal. Species means followed by the same letter are not significantly different.

Green density (kg/m^3)								Dry density (kg/m^3)							Moisture content (%)					
Species	**Tukey**				**Mean**	**SE**		**Species**	**Tukey**			**Mean**	**SE**		**Species**	**Tukey**			**Mean**	**SE**
Max			A		1059.8	14.56		TecL		A		395.5	6.84		Pseu		A		184.2	3.81
Pseu	B		A		1026.9	9.33		Max		A		394.1	7.57		Ell	B	A		181.6	5.35
Rad	B		A	C	1008.0	5.42		GregS	B	A		380.7	3.99		Rad	B	A	C	179.8	4.10
GregN	B		D	C	999.8	22.41		GregN	B	A	C	370.8	8.30		TecH	B	A	C	179.5	4.71
PatxOoc KLF	B		D	C	997.6	13.61		PatxOoc KLF	B	A	C	369.3	4.77		PatxTecL KLF	B	A	C	176.4	4.47
ECC SAPPIN	B		D	C	994.7	6.71		Pseu	B	D	C	363.8	4.82		ECC SAPPIN	B	A	C	174.3	3.74
GregS	B		D	C	993.3	7.69		ECC SAPPIN	B	D	C	362.6	4.43		Pat	B	A	C	172.9	4.32
PatxTecL KLF	B	E	D	C	987.3	15.51		Rad	B	D	C	361.4	5.62		PatxOoc KLF	B	A	C	170.6	4.38
TecH	B	E	D	C	980.8	15.34		PatxTecL KLF	B	D	C	358.4	7.72		GregN	B	A	C	170.1	4.37
TecL		E	D	C	965.0	14.21		Tae	B	D	C	357.2	6.96		Max	B	A	C	169.8	4.28
Pat		E	D	C	959.6	10.07		Pat	B	D	C	352.4	4.69		Tae	B	D	C	162.9	4.50
Ell		E	D		947.9	12.23		TecH		D	C	351.9	6.77		GregS		D	C	161.3	3.39
Tae		E			935.3	9.58		Ell		D		338.0	6.71		TecL		D		144.7	4.27

[1] Densities calculated as kg/m^3. Green density, dry density and moisture content were measured on 16 trees per site.

Table 15. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for MOE[1] variables for test 99-18-03C Mondi, Ncalu, KwaZulu–Natal. Species means followed by the same letter are not significantly different.

MOE (GPa)						
Species	**Tukey**				**Mean**	**SE**
PatxTecL KLF			A		6.40	0.248
Max			A		6.28	0.285
TecL	B		A		5.93	0.317
Pat	B		A	C	5.52	0.272
TecH	B		D	C	5.15	0.182
GregS	B		D	C	5.11	0.202
PatxOoc KLF	B	E	D	C	4.86	0.361
Pseu	F	E	D	C	4.44	0.213
Rad	F	E	D		4.35	0.249
GregN	F	E	D		4.11	0.167
Tae	F	E			4.01	0.107
Ell	F				3.74	0.159
ECC SAPPIN	F				3.34	0.122

MOE2 (GPa)					
Species	**Tukey**			**Mean**	**SE**
Max		A		6.36	0.211
PatxTecL KLF	B	A		6.23	0.186
TecL	B	C		5.50	0.247
Pat		C		5.44	0.185
TecH		C		5.24	0.158
GregS	D	C		5.01	0.132
PatxOoc KLF	D	C	E	4.85	0.211
Rad	D	F	E	4.40	0.174
Pseu	G	F	E	4.22	0.144
GregN	G	F	E	4.21	0.111
Tae	G	F	H	3.98	0.105
Ell	G		H	3.60	0.097
ECC SAPPIN			H	3.45	0.097

MOE3 (GPa)					
Species	**Tukey**			**Mean**	**SE**
PatxTecL KLF		A		6.31	0.188
Max	B	A		6.00	0.199
Pat	B	A	C	5.79	0.196
TecL	B	A	C	5.70	0.256
TecH	B	D	C	5.36	0.162
GregS	E	D	C	5.14	0.136
PatxOoc KLF	E	D	F	4.87	0.212
Rad	E	G	F	4.41	0.174
Tae		G	F	4.28	0.113
GregN	H	G	F	4.21	0.111
Pseu	H	G		4.11	0.140
Ell	H	G		3.79	0.102
ECC SAPPIN	H			3.46	0.097

[1] Modulus of elasticity (MOE) was calculated as a function of observed green density and acoustic velocity. MOE2 was calculated by using the overall mean green density for a particular species. MOE3 was calculated assuming a constant green density of 1000 kg/m^3 for all species. MOE was measured on 16 trees per site, while acoustic velocity (and thus MOE2 and MOE3) measured on 32 trees per site.

Table 16. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for wood property traits[1] for test 99-49-03D Merensky, Weza, KwaZulu–Natal. Species means followed by the same letter are not significantly different.

Green density (kg/m^3)						Dry density (kg/m^3)							Moisture content (%)			
Species	**Tukey**		**Mean**	**SE**		**Species**	**Tukey**			**Mean**	**SE**		**Species**	**Tukey**	**Mean**	**SE**
PatxTecL Y		A	965.9	14.39		PatxTecL YOR		A		396.3	10.23		Ell	A	170.1	2.79
ECC SAPPIX	B	A	962.7	8.71		Tae	B	A		381.2	3.52		ECC SAPPIX	A	164.5	3.17
Ell	B	A	953.1	9.68		Pat KLFE	B	A	C	377.7	10.49		Pat KLFE	B	150.0	4.89
Pat KLFE	B	A	937.3	10.40		ECC SAPPIX	B		C	364.7	5.22		PatxTecL Y	B	145.1	4.19
Tae	B		925.9	6.63		Ell			C	353.6	5.69		Tae	B	143.1	1.99

[1] Densities calculated as kg/m^3. Green density, dry density and moisture content were measured on 16 trees per site.

Table 17. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for MOE[1] variables for test 99-49-03D Merensky, Weza, KwaZulu–Natal. Species means followed by the same letter are not significantly different.

MOE (GPa)					**MOE2** (GPa)						**MOE3** (GPa)			
Species	**Tukey**	**Mean**	**SE**		**Species**	**Tukey**		**Mean**	**SE**		**Species**	**Tukey**	**Mean**	**SE**
Pat KLFE	A	5.08	0.221		Pat KLFE		A	5.19	0.132		Pat KLFE	A	5.54	0.141
PatxTecL Y	A	4.81	0.237		PatxTecL YOR		A	5.04	0.156		PatxTecL Y	A	5.22	0.162
Tae	B	3.70	0.125		Tae		B	3.64	0.115		Tae	B	3.91	0.123
ECC SAPPIX	B	3.32	0.196		ECC SAPPIX	C	B	3.21	0.115		ECC SAPPIX	C	3.34	0.119
Ell	B	3.14	0.172		Ell	C		3.04	0.115		Ell	C	3.20	0.121

[1] Modulus of elasticity (MOE) was calculated as a function of observed green density and acoustic velocity. MOE2 was calculated by using the overall mean green density for a particular species. MOE3 was calculated assuming a constant green density of 1000 kg/m^3 for all species. MOE was measured on 16 trees per site, while acoustic velocity (and thus MOE2 and MOE3) measured on 32 trees per site.

Table 18. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for wood property traits[1] for test 99-55-03E2 PG Bison, Glen Cullen, Eastern Cape. Species means followed by the same letter are not significantly different.

Green density (kg/m^3)						Dry density (kg/m^3)						Moisture content (%)			
Species	Tukey		Mean	SE		Species	Tukey		Mean	SE		Species	Tukey	Mean	SE
GregN		A	999.5	11.33		GregN		A	384.6	4.67		GregN	A	160.2	3.23
GregS		B	952.0	10.85		GregS		A	383.8	4.97		Pat	A	153.7	4.81
Ell	C	B	927.2	8.71		Ell	B	A	371.8	6.54		Ell	A	150.3	4.26
Pat	C		895.9	11.89		Pat	B		354.3	5.45		GregS	A	148.6	3.95

[1] Densities calculated as kg/m^3. Green density, dry density and moisture content were measured on 16 trees per site.

Table 19. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for MOE[1] variables for test 99-55-03E2 PG Bison, Glen Cullen, Eastern Cape. Species means followed by the same letter are not significantly different.

MOE (GPa)						MOE2 (GPa)					MOE3 (GPa)			
Species	**Tukey**		**Mean**	**SE**		**Species**	**Tukey**	**Mean**	**SE**		**Species**	**Tukey**	**Mean**	**SE**
Pat		A	4.37	0.136		Pat	A	4.50	0.107		Pat	A	4.78	0.114
GregS	B	A	3.95	0.135		GregS	B	3.97	0.092		GregS	B	4.07	0.094
GregN	B		3.81	0.110		GregN	B	3.77	0.090		GregN	B	3.78	0.090
Ell		C	2.21	0.095		Ell	C	2.39	0.070		Ell	C	2.51	0.074

[1] Modulus of elasticity (MOE) was calculated as a function of observed green density and acoustic velocity. MOE2 was calculated by using the overall mean green density for a particular species. MOE3 was calculated assuming a constant green density of 1000 kg/m^3 for all species. MOE was measured on 16 trees per site, while acoustic velocity (and thus MOE2 and MOE3) measured on 32 trees per site.

Table 20. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for wood property traits for test 99-55-03E4 PG Bison, Brackenhill, Western Cape. Species means followed by the same letter are not significantly different.

Green density (kg/m^3)					Dry density (kg/m^3)						Moisture content (%)				
Species	**Tukey**	**Mean**	**SE**		**Species**	**Tukey**		**Mean**	**SE**		**Species**	**Tukey**		**Mean**	**SE**
Rad	A	988.1	8.689		GregS		A	386.5	6.93		Rad		A	188.1	5.22
GregS	A	980.0	10.01		Ell		A	380.1	6.85		ECC MTO	B	A	171.9	3.77
TecH	A	975.8	14.53		TecH	B	A	371.5	8.03		TecH	B	C	163.7	4.66
Ell	A	975.6	11.02		Tae	B	A	370.8	8.59		Ell	B	C	157.4	3.61
ECC MTO	A	974.5	9.80		ECC MTO	B	A	359.3	5.53		GregS	B	C	154.3	3.53
Tae	B	928.4	10.83		Rad	B		344.6	6.72		Tae		C	151.7	4.58

[1] Densities calculated as kg/m^3. Green density, dry density and moisture content were measured on 16 trees per site.

Table 21. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for MOE[1] variables for test 99-55-03E4 PG Bison, Brackenhill, Western Cape. Species means followed by the same letter are not significantly different.

MOE (GPa)					MOE2 (GPa)						MOE3 (GPa)			
Species	Tukey	Mean	SE		Species	Tukey		Mean	SE		Species	Tukey	Mean	SE
TecH	A	4.54	0.225		TecH		A	4.43	0.157		TecH	A	4.53	0.160
GregS	A	4.09	0.223		GregS		A	4.13	0.119		GregS	A	4.23	0.122
Tae	B	3.41	0.105		Tae		B	3.43	0.092		Tae	B	3.69	0.099
ECC MTO	B	3.26	0.102		ECC MTO	C	B	3.11	0.092		ECC MTO	C	3.19	0.094
Ell	B	3.01	0.137		Rad	C		2.80	0.112		Ell	C	2.89	0.099
Rad	B	2.88	0.167		Ell	C		2.74	0.095		Rad	C	2.81	0.112

[1] Modulus of elasticity (MOE) was calculated as a function of observed green density and acoustic velocity. MOE2 was calculated by using the overall mean green density for a particular species. MOE3 was calculated assuming a constant green density of 1000 kg/m^3 for all species. MOE was measured on 16 trees per site, while acoustic velocity (and thus MOE2 and MOE3) measured on 32 trees per site.

Table 22. Wood ANOVA results[1] combined sites for species and site x species.

Trait	Source	DF	F value	Pr > F
Green density	Species	16	6.00	0.0076
	Site x Species	8	1.04	0.4177
Dry density	Species	16	1.82	0.1970
	Site x Species	8	2.43	0.0218
Moisture content	Species	16	2.49	0.0960
	Site x Species	8	2.75	0.0105
MOE	Species	16	11.46	0.0008
	Site x Species	8	2.41	0.0230
MOE2	Species	16	16.30	0.0002
	Site x Species	8	2.19	0.0379
MOE3	Species	16	16.53	0.0002
	Site x Species	8	2.11	0.0450

[1] Densities calculated as kg/m^3. Modulus of elasticity (MOE) was calculated as a function of observed green density and acoustic velocity. MOE2 was calculated by using the overall mean green density for a particular species. MOE3 was calculated assuming a constant green density of 1000 kg/m^3 for all species. Green density, dry density, moisture content and MOE were measured on 16 trees per site, while acoustic velocity (and thus MOE2 and MOE3) measured on 32 trees per site.

Table 23. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for wood property traits[1] across all four sites where wood properties were measured (99-18-03C Mondi, Ncalu, KwaZulu–Natal, 99-49-03D Merensky, Weza, KwaZulu–Natal, 99-55-03E2 PG Bison, Glen Cullen and Eastern Cape, 99-55-03E4 PG Bison, Brackenhill, Western Cape). Species means followed by the same letter are not significantly different.

Green density (kg/m^3)								
Species	**Tukey**					**Mean**	**SE**
Max				A		1059.8	14.56
Pseu		B		A		1026.9	9.33
GregN		B		C		999.7	12.35
Rad		B		C		998.0	5.35
PatxOoc KLF		B		C		997.6	13.61
ECC SAPPIN		B		C	D	994.7	6.71
PatxTecL KLF		B		C	D	987.3	15.51
TecH		E		C	D	978.3	10.40
GregS		E	F	C	D	975.1	5.98
ECC MTO		E	F	C	D	974.5	9.80
PatxTecL Y	G	E	F	C	D	965.9	14.39
TecL	G	E	F	C	D	965.0	14.21

Dry density (kg/m^3)							
Species	**Tukey**				**Mean**	**SE**
PatxTecL Y			A		396.3	10.23
TecL	B		A		395.5	6.84
Max	B		A		394.1	7.57
GregS	B		A	C	383.7	3.09
Pat KLFE	B	D	A	C	377.7	10.49
GregN	B	D	A	C	377.7	4.85
Tae	B	D		C	369.7	4.05
PatxOoc KLF	B	D		C	369.3	4.77
ECC SAPPIX		D		C	364.7	5.21
Pseu		D		C	363.8	4.82
ECC SAPPIN		D		C	362.6	4.43
TecH		D		C	361.7	5.46

Moisture content (%)					
Species	**Tukey**			**Mean**	**SE**
Pseu		A		184.2	3.81
Rad		A		183.9	3.35
PatxTecL KLF	B	A		176.4	4.47
ECC SAPPIN	B	A		174.3	3.74
ECC MTO	B	A		171.9	3.77
TecH	B	A		171.6	3.56
PatxOoc KLF	B	A	C	170.6	4.38
Max	B	A	C	169.8	4.28
GregN	B	D	C	165.2	2.82
Ell	B	D	C	164.9	2.51
ECC SAPPIX	B	D	C	164.5	3.17
Pat	B	D	C	162.3	3.64

Table 23. Continued

ECC SAPPIX	G	E	F	C	D	962.7	8.71		Ell		D		C	360.9	3.77		GregS	E	D	C	154.7	2.19
Ell	G	E	F		D	951.0	5.56		ECC MTO		D		C	359.3	5.53		Tae	E	D		152.6	2.49
Pat KLFE	G	E	F			937.3	10.40		PatxTecL KLF		D		C	358.4	7.72		Pat KLFE	E	D		150.0	4.89
Tae	G		F			929.9	5.22		Pat		D			353.4	3.56		PatxTecL Y	E			145.0	4.19
Pat	G					926.7	9.65		Rad		D			353.0	4.57		TecL	E			144.7	4.27

[1] Densities calculated as kg/m^3. Green density, dry density and moisture content were measured on 16 trees per site.

Table 24. Species means, standard errors and Tukey-Kramer's multiple comparison difference tests for MOE[1] variables across all four sites where wood properties were measured (99-18-03C Mondi, Ncalu, KwaZulu–Natal, 99-49-03D Merensky, Weza, KwaZulu–Natal, 99-55-03E2 PG Bison, Glen Cullen and Eastern Cape, 99-55-03E4 PG Bison, Brackenhill, Western Cape). Means Species means followed by the same letter are not significantly different.

MOE (GPa)					
Species	**Tukey**			**Mean**	**SE**
PatxTecL KLF		A		6.40	0.248
Max		A		6.28	0.285
TecL		A		5.93	0.317
Pat KLFE		B		5.08	0.222
Pat		B		4.93	0.180
PatxOoc KLF		B		4.86	0.361
TecH		B		4.84	0.152
PatxTecL YOR		B		4.81	0.237
Pseu	C	B		4.44	0.213
GregS	C	B		4.38	0.132
GregN	C	D		3.96	0.102
Tae	C	D	E	3.71	0.073

MOE2 (GPa)						
Species	**Tukey**				**Mean**	**SE**
Max			A		6.36	0.211
PatxTecL KLF			A		6.23	0.186
TecL			B		5.50	0.247
Pat KLFE	C		B		5.19	0.131
PatxTecL YOR	C		B		5.04	0.156
Pat	C		B		4.96	0.121
PatxOoc KLF	C		D		4.85	0.211
TecH	C		D		4.84	0.122
GregS	E		D		4.37	0.081
Pseu	E		F		4.23	0.144
GregN	E		F	G	3.99	0.076
Tae	H		F	G	3.68	0.064

MOE3 (GPa)					
Species	**Tukey**			**Mean**	**SE**
PatxTecL KLF		A		6.31	0.188
Max	B	A		6.00	0.199
TecL	B	C		5.70	0.256
Pat KLFE	B	C		5.54	0.141
Pat	D	C		5.28	0.128
PatxTecL YOR	D	C		5.22	0.162
TecH	D	E		4.95	0.124
PatxOoc KLF	D	E		4.87	0.212
GregS	F	E		4.48	0.083
Pseu	F	G		4.11	0.140
GregN	F	G	H	3.99	0.076
Tae	F	G	H	3.96	0.069

Table 24. Continued

Rad	C	D	E	3.62	0.198		Rad	H		I	G	3.61	0.145		Rad	I	G	H	3.62	0.145
ECC SAPPIN		D	E	3.34	0.122		ECC SAPPIN	H	J	I	G	3.45	0.097		ECC SAPPIN	I		H	3.46	0.097
ECC SAPPIX		D	E	3.32	0.196		ECC SAPPIX	H	J	I		3.21	0.115		ECC SAPPIX	I			3.34	0.119
ECC MTO		D	E	3.26	0.102		ECC MTO		J	I		3.11	0.092		ECC MTO	I			3.19	0.094
Ell			E	3.03	0.098		Ell		J			2.94	0.062		Ell	I			3.09	0.065

[1] Modulus of elasticity (MOE) was calculated as a function of observed green density and acoustic velocity. MOE2 was calculated by using the overall mean green density for a particular species. MOE3 was calculated assuming a constant green density of 1000 kg/m^3 for all species. MOE was measured on 16 trees per site, while acoustic velocity (and thus MOE2 and MOE3) measured on 32 trees per site.

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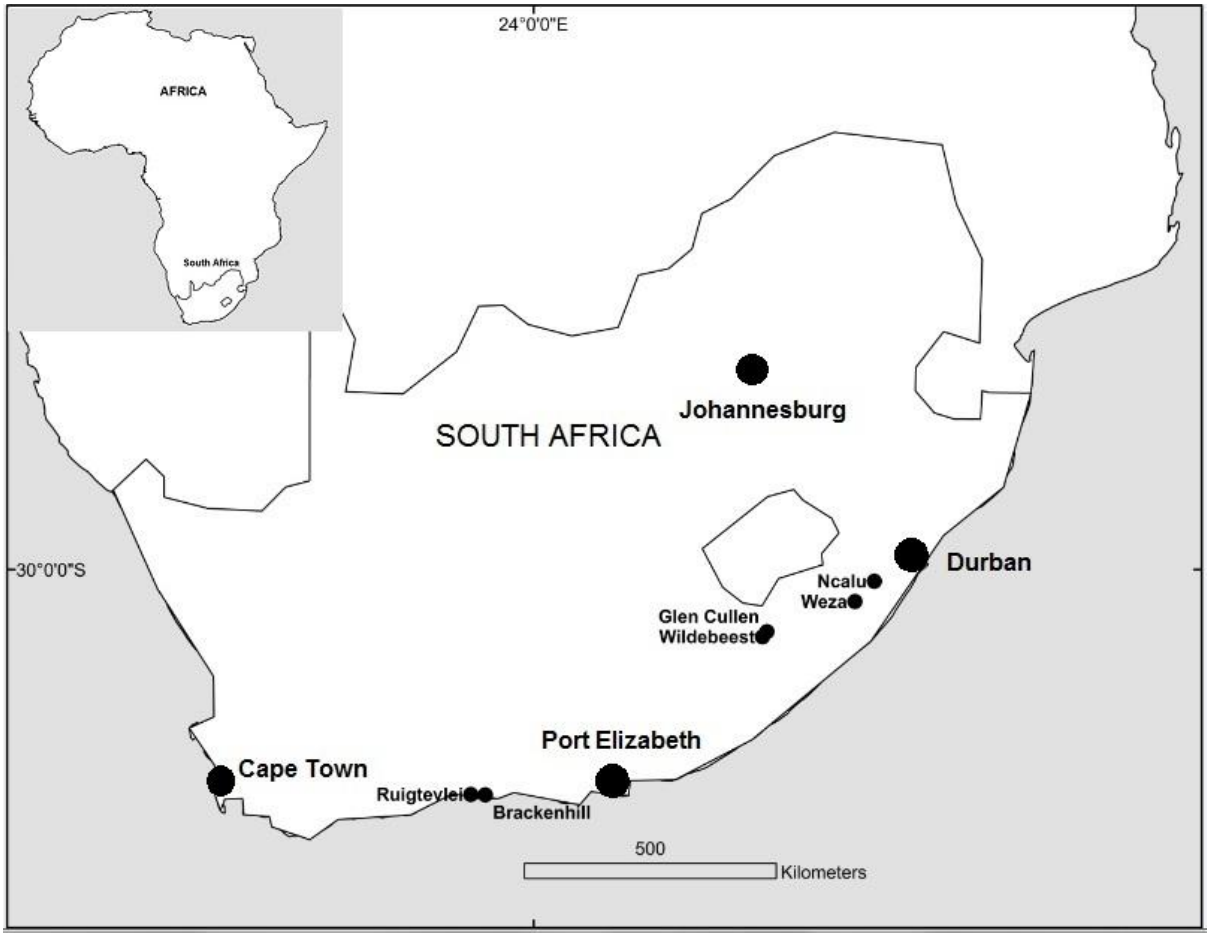

Figure 1. Map of study sites within South Africa.

Figure 2. Using the TreeSonic time-of-flight tool in the field.