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Tree breeding model to assess financial performance of pine hybrids and pure species: deterministic and stochastic approaches for South Africa

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Abstract Financial performance of the *P. patula* × *P. tecunumanii*, *P. greggii* × *P. tecunumanii*, *P. taeda* × *P. tecunumanii* hybrids and their parental species was studied for South Africa. A model was developed for use in determining the profitability of a tree-breeding program (TBP) with pine hybrids in commercial plantations. Growth measurement data were collected in four, 12-year-old genetic trials on Mondi and Sappi land holdings in South Africa. Growth models developed for *P. patula* and *P. taeda* in South Africa were used to infer models for the other taxa and to calculate the optimal financial rotation age at discount rates of 6 and 8%. Financial data on pine plantations were collected from different sources in South Africa. Optimal rotation lengths in this study were found to be between 12 and 16 years for pulpwood and 17 years for sawtimber. The model output shows the net present value (NPV), the internal rate of return, and the minimum area that a tree grower has to plant every year in order to justify the investment in a TBP. A stochastic approach with Monte Carlo simulation showed that the sensitivity of NPV to uncertainty in the wood price was greater than that for the planting, harvesting, and transport costs.

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Introduction

Interspecific pine hybrids are a promising alternative to pure pine species in plantation forestry. They may grow more quickly than the parental species and combine economically important complementary traits. Pine hybrids might be viewed as "new (synthetic) species" better adapted to specific environmental conditions than their parents. Despite the great promise they hold for commercial plantations, pine hybrids have so far seen very limited use, with focus on only a few species combinations. For example, the forestry sector in Queensland, Australia, has been commercially planting the *Pinus elliottii* × *P. caribaea* var. *hondurensis* hybrid for more than 50 years and has established approximately 90,000 ha of hybrid plantations (Personal communication from Dominic Kain with HQPlantations Pty Ltd in Australia). Smaller extensions of this hybrid have been planted in South Africa and Argentina. *Pinus rigida* × *P. taeda*, which was initially field tested in the United States from 1970 to the 1980s (Kuser et al. 1987 cited by Dungey 2001), has been planted in South Korea for over 30 years (Hyun 1976; Byun et al. 1989).

The testing of pine hybrids in South Africa started on a small scale in the 1970s with the establishment of several hybrid trials in Zululand (van der Sijde and Roelofsen 1986). In these early trials, *P. elliottii* × *P. caribaea* var. *hondurensis*, *P. elliottii* × *P. caribaea* var. *bahamensis*, *P. elliottii* × *P. oocarpa* and *P. taeda* × *P. oocarpa* were tested as hybrids, and *P. elliottii* and *P. taeda* were included as controls. The result was the initiation of small hybrid programs of the *P. elliottii* × *P. caribaea* hybrid in some locations in the country. The effort to create and test additional pine hybrids began in earnest as a cooperative project with Camcore (International Tree Breeding and Conservation Program) at North Carolina State University (NCSU). Early results of this research indicated that hybrid crosses within the closed-cone pine group, such as *Pinus patula* × *P. tecunumanii* and *P. patula* × *P. oocarpa*, offered the opportunity to increase productivity and overcome disease problems in plantations (Mitchell et al. 2013). These hybrids have been shown to be a viable option to replace commercial plantations of *Pinus patula* at the low and mid-elevations to reduce the risk of high mortality caused by *Fusarium circinatum* (Pitch canker) in South Africa (Kanzler et al. 2014). South Africa has very limited options to expand the area of commercial pine plantations because of limited rainfall, and pine hybrids provide a way to increase wood productivity over a finite growing area.

Most of the work published on hybrid studies considers questions of genetics, productivity, adaptation, and wood properties. Attempts to assess the economic value of pine hybrids in plantation forestry are limited. Herrick (1981) used a least-total-cost model for Pitch × Loblolly pine hybrid to find the combination of annual planting area, seed orchard capacity, and expenditures that increased forest yields at different interest rates.

For pure species, economic value of TBP has been reported by several authors (Ivkovic et al. 2006a, b; McKeand et al. 2006; Talbert et al. 1985). Talbert et al. (1985) showed that rates of return for investment in loblolly pine tree improvement depend on seed orchard yields, but appear to be on the order of 17–19% after taxes. McKeand et al. (2006) show that forest landowners in the South of the U.S. can realize large financial benefits from planting the best loblolly pine (*Pinus taeda* L.) genotypes. Ivković et al. (2006a, b) developed economic breeding objectives for production of *Pinus radiata* structural timber in Australia. They calculated weights for different traits (MAI, stem straightness, branch

Table 1 Location and environmental conditions of the pine trials used for this study. *Source* Internal reports Mondi South Africa and Sappi Forests

Company	Trial	Taxa	Location	Lat. (S)	Long. (E)	Alt. (m)	MAP (mm)	MAT (°C)
Mondi	Pine hybrids	*P. greggii* 1st gen mix *P. greggii* unimproved *P. greggii* × *P. tecunumanii* *P. taeda* × *P. tecunumanii* *P. tecunumanii* unimproved *P. patula* 2nd gen mix	KwaZulu-Natal, South Africa	30°08′	29°53′	1197	976	16.9
Mondi	*Pinus taeda* progeny	*P. taeda* 2nd gen	KwaZulu-Natal, South Africa	30°09′	29°53′	1197	976	16.9
Sappi	Pine hybrids	*P. patula* 2nd gen mix *P. patula* OP BSO mix *P. patula* × *P. tecunumanii*	Usutu Forest, Swaziland	27°32′	31°05′	1097	1350	16.8
Sappi	*Pinus tecunumanii* progeny	*P. tecunumanii* unimproved *P. patula* unimproved	Usutu Forest, Swaziland	26°32′	31°03′	1040	900	17.2

size and MOE) were based on a bio-economic model that they constructed using data from industry and published sources.

To address this informational gap, the main objective of this manuscript is to build a functional model that provides estimates of the potential economic profits of pine hybrids at the plantation level, not the stand level. The specific objectives are as follows: (1) measure profitability of TBP for pine hybrids and pure species at the optimal financial rotation age for sawtimber and pulpwood; (2) determine the minimum annual planting area (MAPA) required by a tree grower to justify the investment in a TBP with pine hybrids; and (3) assess the effects of stochastic operational and financial inputs on the NPV of a plantation forestry project.

Materials and methods

Description of the genetic trials

Four genetic field trials of different pine species and hybrids were established by Mondi South Africa in eastern South Africa and Sappi Forests Research in Swaziland. Two of the trials, one at Mondi and one at Sappi, were pine hybrid trials; the others were pure species trials of *Pinus taeda* and *Pinus tecunumanii* (Table 1).

The volume growth of *P. taeda* in the Mondi progeny trial was compared to the volume growth of the other taxa in the Mondi pine hybrid trial because the environmental conditions of both trials are the same, and no *P. taeda* control was planted in the hybrid trial. The distance between these two trials was 550 m. Because the Sappi pine hybrid trial did not have *P. tecunumanii*, the estimated volume growth for this species in the hybrid trial was extrapolated from the Sappi *P. tecunumanii* progeny trial. The relative difference found in the measured volume yield between *P. patula* and *P. tecunumanii* in the *P. tecunumanii* progeny trial was used to infer the difference in volume yield between these two species in the pine hybrid trial. The distance between these trials in Sappi was 5.6 km and the environmental conditions were very similar (Table 1).

The Mondi trials

The pine hybrid trial at Mondi, which was planted in December 1997, contained nine polymix families of *P. greggii* var. *australis* × *P. tecunumanii* and seven polymix families of *P. taeda* × *P. tecunumanii*, all of which were analyzed in this study. Bulk commercial seeds of *P. greggii* var. *australis* from Mexico and *P. tecunumanii* seed from Rio Chiquito in the highlands of El Salvador were used in the trial as controls. Other improved taxa included and analyzed in the study were *P. greggii* first-generation mix and *P. patula* second-generation mix (Table 1). The pollen of *P. tecunumanii* that was used in the crosses to create the hybrids was collected in natural stands in Central America by Camcore. The design of the trial was a randomized complete block with 4 replicates and 18 treatments, with 6-tree row plots per treatment.

The Mondi P. taeda trial was established in March 1998, it was a second-generation, open-pollinated progeny trial planted in a randomized complete block design, comprising 242 treatments that were placed in 20 replicates of single-tree plots.

The Sappi trials

The Sappi pine hybrid trial which was planted in March 1999, was established in an area where *P. patula* has been planted since the 1950s as the commercial species. The trial included several hybrids and pure species, but only the *P. patula* × *P. tecunumanii* hybrid, a second-generation *P. patula*, and *P. patula* from a breeding seed orchard (BSO), were assessed.

To generate the *P. patula* × *P. tecunumanii* hybrids, five second-generation *P. patula* clones were pollinated with a single-pollen source of *P. tecunumanii* from low elevation (LE) at Culmí, Honduras. The pollen source came from unimproved trees.

The trial had a randomized complete block design with 48 treatments; only three treatments were used for this analysis, with three replicates and 7 × 7 tree-square plots per treatment.

The growth of *P. tecunumanii* was assessed in a *Sappi P. tecunumanii progeny trial* planted in June 1990 (Table 1). Measurement data of 49 ten-tree line plots from 17-polymix families of *P. tecunumanii* LE from Culmí and 24 ten-tree line plots from eight families of unimproved *P. patula* from Usutu Forest were assessed in this trial. This trial had a randomized complete block design, with three replicates and 10 tree-row plots per treatment for the two species (Sappi Forest Research Internal Document 1996).

For clarity, hereafter these two trials will be referred to as a single one, the "Mondi trial." Information on the two trials at Sappi will be presented separately, and referred to as the "Sappi hybrid trial" and the "Sappi progeny trial."

Volume yield calculations for all trials

Diameter at breast height (DBH at 1.3 m in cm) and height (H in m) of the trees were measured for all the trees of the trials at different ages. The Mondi trial was measured at 9.5 years of age. The Sappi hybrid trial was measured annually between years 5 and 11, while the Sappi progeny trial was measured at 7.3 years only. Individual tree volume was estimated using an equation developed by Ladrach and Mazuera (1978) for juvenile trees.

$$Volume\ per\ tree = 0.00003 \times DBH^2 \times H \qquad (1)$$

Volume in m^3/ha was estimated by multiplying the mean tree volume (Eq. 1) by stand density.

ORA and NPV at the stand level

In order to calculate the NPV and the ORA at two discount rates (6 and 8%) in South African plantations, cost data as well as wood prices and growth curves were required for all the species. Plantation establishment, management, harvesting, and transportation costs for South Africa were provided by Forestry Economics Services (2010) and by Cassie Carstens and André van der Hoef at Mountain to Ocean—MTO in South Africa. Wood prices were obtained from Craig Norris with NCT Forestry Cooperative Limited in Pietermaritzburg, South Africa. The growth curves for *Pinus patula* and *Pinus taeda* were taken from Kotze et al. (2012). Because growth and yield models have not yet been made public for *P. tecunumanii*, *P. greggii*, or the hybrids included in this project, the first author has used his field experience and judgment to amend the available models for *P. patula* and

P. taeda for these taxa. It was assumed that the growth curves of *P. tecunumanii* and *P. greggii* are relatively similar to *P. patula*, for which published growth models exist. The *Pinus taeda* model exhibits a different developmental pattern than the Mesoamerican pines, showing slower growth in the early years and more robust growth in the later years (Fig. 2c).

For the species in the Mondi trial, the volume yield at 9.5 years was used as the basis to make projections of volume growth at later ages, following the shape of the curve. At the Sappi trials, the volume yield projections were made using the average yield obtained in the four annual measurements between years 5 and 8 in the Sappi hybrid trial and the Sappi progeny trial at 7.3 years.

Growth and yield models for *P. patula* and *P. taeda*

Pinus patula and *P. taeda* grown for sawtimber in South Africa are commonly planted at stand densities of 1111 trees per ha (3.0 m × 3.0 m), while the same species grown for pulpwood are mainly planted at 1667 trees per ha (2 m × 3 m). Site index used for pine sawtimber stands was at reference age 20 years. Site index is defined as the top height at the reference age, where top height is the regression height depending on the quadratic mean diameter of the 20% largest diameter trees in a sample of at least 30 height/dbh pairs (Bredenkamp 1993).

Because the number of trees per ha planted in the Mondi trial was 1111 (3.0 m × 3.0 m), it could be expected that the results of this analyses would be more closely related to those of a sawtimber regime than those of a pulpwood regime.

The planting density in the Sappi Usutu Forest trials was 1370 trees per ha (2.7 m × 2.7 m), which is an intermediate value between the traditional stocking used for both regimes. Therefore, the output values of the analysis in this case would be an intermediate estimate, equally close to the expected results for each one of the management regimes.

The yield tables used in this study were developed for *P. patula* and *P. taeda* in South Africa and estimate utilizable wood volume to an 8 cm minimum diameter (pulpwood) and 18 minimum diameter (saw logs) (Kotze et al. 2012). For the purposes of this study, it is assumed that only the size of the logs would be used as the main criteria to define the sawtimber utilization, and large logs, independent of age, would be purchased at the sawtimber market price. Results on wood properties assessed in this study as well as references found by other authors to support this assumption are included in the following explanations of methodology and the discussion section of this article.

Deterministic financial model at the forest level

The following assumptions were considered for the development of the model and will be analyzed in detail in the discussion section of this manuscript.

The model was conceived for a vertically integrated company (VIC), owner of commercial plantations and the pulp mill. The woodlands division is set as a profit center with the wood transfer price equivalent to the wood market price.

The cash flow of the model assumes costs and revenues for a forestry company that is just starting operational planting from year zero, without any hectare of land planted. The financial analysis is made for a regulated forest where the annual cut area is the same as the annual planted area and is managed to perpetuity.

The optimal financial rotation age defined by the greatest NPV at the stand level obtained for the two regimes was applied in the development of the tree-breeding model (TBM) in Excel^{TM}. The TBM was run for each taxa at the forest level.

In a VIC the annual harvest is determined by the MAI. In this analysis, it was assumed that the ORA is set at the beginning of the project and the harvest scheduling will be planned based on this rotation age. In other words, the MAI and the annual cut resulting from the ORA will be similar. There is also the presumption that change in wood prices and technological advances will not be great enough to alter the ORA significantly.

It is also supposed that the more tropical forestry species and hybrids will have good wood properties and have a shorter rotation age than commercial pine species being planted and harvested in South Africa.

In this study, no adjustments were made to the volume yield per hectare based on the type of plots used in the trials. Under ideal conditions, genetic gain trials with large block plots would be evaluated to obtain better prediction of growth gain. However, genetic trials more often use small plot sizes (small square blocks, row plots or single trees) to accommodate the testing of a number of treatments (families) in a trial at one time. In this case, the Mondi hybrid trial had row plots, the Sappi hybrid trial had block plots, the *P. taeda* trial at Mondi had single tree plots and the *P. tecunumanii* trial at Usutu had row plots.

Production of trees for commercial planting in the nursery will be from F2 seeds and not from rooted cuttings.

Extra costs of 50% in the pine hybrids TBP will be used to compare profitability against breeding of pure species.

The model covers all the cost components: site preparation, planting, periodic stand treatments, harvesting, as well as transportation and management. The pulpwood management regime does not include any thinning. In addition to the operational costs, the model includes the research costs of the TBP.

The model is flexible, and changes can be made to the strategy of the TBP. For calculations and illustration purposes in this document, the area covered by field trials is 86 ha in progeny trials and seed orchards for the first 20 years, and 56 ha thereafter. Included in the research costs are 50% of the research manager salary, the salary of a tree breeder, the salary of a technician, and three vehicles. The average total research cost per year on tree breeding was approximately U.S. $260,000. As part of the research costs, U.S. $36,000 per year were included for the membership to an industrial cooperative program like Camcore.

Genetic gains of 15% in volume productivity every 10 years were included for all the varieties. Revenues from pulpwood (U.S.$39.42/m^3) and sawtimber (U.S.$78.84/m^3) sales at the mill gate were the income used in the model.

The profitability of the TBP was determined through calculation of the IRR and the NPV at discount rates of 6 and 8% over a time horizon of four rotations (similar to perpetuity). The minimum area required to justify the investment on the TBP was calculated for each taxa.

Stochastic financial model at the forest level

The deterministic approach uses fixed values for the variables as inputs and also draws outputs with fixed values. A more complete method would include the uncertainty in the value of the inputs. The @RISK 6 software in Excel^{TM} by Palisade Corporation (2016) was used to add stochasticity to the model. The utilization of a probability distribution function (PDF) and their parameters for uncertain inputs show the chances of obtaining outputs within certain values. The software uses Montecarlo simulation.

A sensitivity analysis was conducted to measure the effects on NPV of uncertainty in several inputs, using a triangular PDF within a range of variation of ±10% between the minimum and the maximum values for the input variable. This exercise is used for the *P. greggii* × *P. tecunumanii* hybrid when managed for sawtimber at an 8% discount rate and for *P. taeda* when managed for pulpwood production at the same discount rate. The purpose is the comparison of a profitable versus a less profitable choice of species with different levels of financial risk.

Results

Growth and yield

Mondi KwaZulu-Natal trial

In the Mondi trial volume was calculated for all the species and the ANOVA procedure (SAS 9.3™) was used to compare volume yield among taxa. Significant differences at the $p = 0.01$ level were found between the two hybrids and the pure species. The *Pinus*

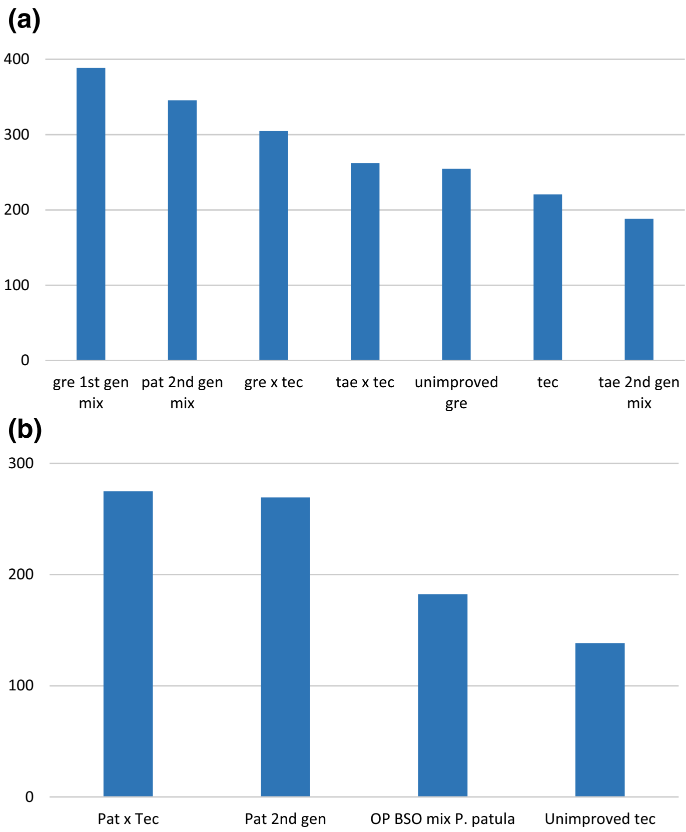

Fig. 1 Volume yield (m³/ha) for pine hybrids and pure species in the pine hybrid trials at **a** Mondi and **b** Sappi

greggii × *Pinus tecunumanii* hybrid had 20% greater volume than the unimproved *P. greggii*, but it was 27% below the improved *P. greggii* and 13% below the second-generation *P. patula*. The volume of pure *P. tecunumanii* was 39% less than that of the *P. greggii* × *P. tecunumanii* hybrid. The *P. taeda* × *P. tecunumanii* hybrid was 19% superior to *P. tecunumanii*, the better performer of the two taxa in the cross and 39% greater than pure *P. taeda*. The volume yield of the *P. taeda* × *P. tecunumanii* was 16% below the volume yield of *P. greggii* × *P. tecunumanii* (Fig. 1a).

The values for survival and growth of the different taxa in the study reflected their level of adaptability to the site. Survival at 9.5 years ranged from 83% for *P. greggii* × *P. tecunumanii* to 97% for *P. taeda*.

(a) Volume yield (m^3/ha) of six taxa in the Mondi trial at 9.5 years of age.
(b) Volume yield (m^3/ha) of three taxa in the Sappi Usutu Forest trials at 11.0 years of age.

Sappi Usutu Forest trials

The pine hybrid of *P. patula* × *P. tecunumanii* assessed in the Sappi Usutu Forest trial showed volume growth similar to the *P. patula* second-generation control, while it was 51% superior to the *P. patula* control from the BSO mix (Fig. 1b). Volume yield for the hybrid at 11 years of age was approximately 39% greater than volume yield for *P. tecunumanii*. Survival was 78% for the hybrid and 80% for *P. patula*.

Growth projections

Projections of growth curves for pulpwood and sawtimber are shown in Figs. 2a, b, c and 3a, b, c.

(a) Growth curves for taxa in the Sappi Usutu Forest trials projected from the measurement data and the pulpwood model developed for *P. patula* by Kotze et al. (2012).
(b) Growth curves for taxa in the Mondi trial projected from the measurement data and the pulpwood model developed for *P. patula* by Kotze et al. (2012).
(c) Growth curves for taxa in the Mondi trial projected from the measurement data and the pulpwood model developed for *P. taeda* by Kotze et al. (2012).
(a) Growth curves for taxa in the Sappi Usutu Forest trials projected from the measurement data and the sawtimber models developed for *P. patula* by Kotze et al. (2012).
(b) Growth curves for taxa in the Mondi trial projected from the measurement data and the sawtimber model developed for *P. patula* by Kotze et al. (2012).
(c) Growth curves for taxa in the Mondi trial projected from the measurement data and the sawtimber model developed for *P. taeda* by Kotze et al. (2012).

ORA and NPV at the stand level

Estimated growth curves, the establishment and management costs at the stand level, and the pulpwood and sawtimber prices were the basis used to calculate the NPV and the financial ORAs for all the hybrids in both trials at discount rates of 6 and 8% for pulpwood

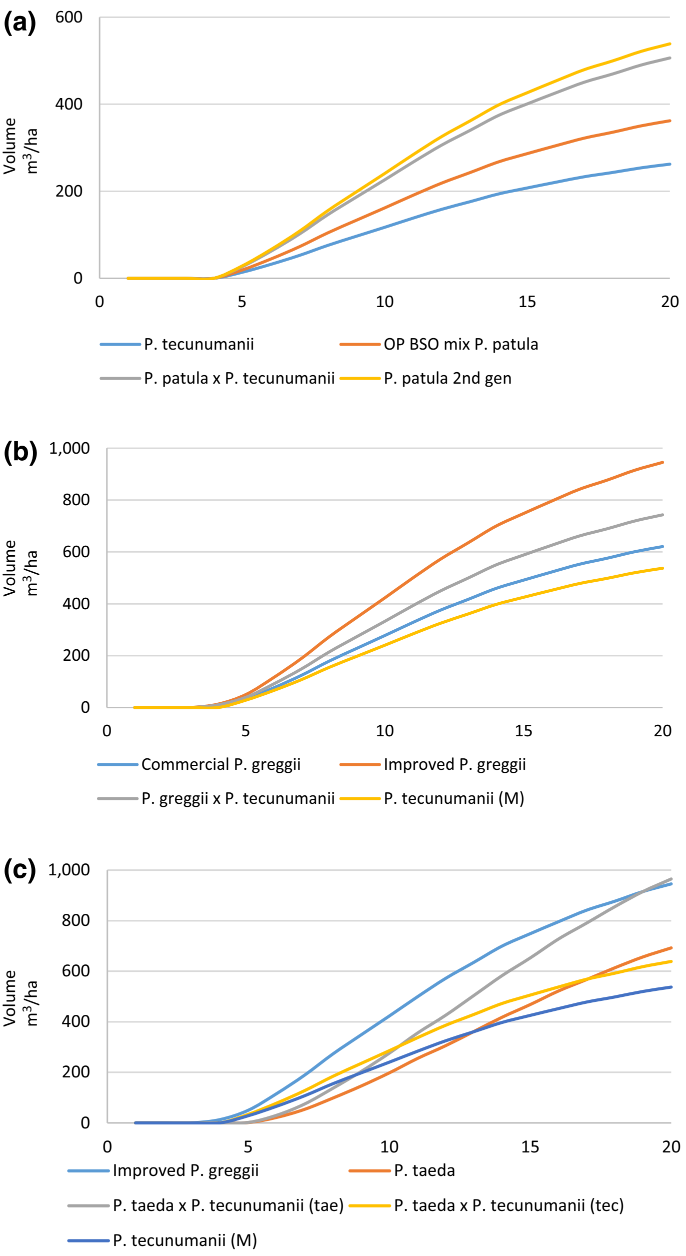

Fig. 2 Projected growth curves for pine hybrids and pure species under a pulpwood management regime in the pine hybrid trials at **a** Sappi and **b**, **c** Mondi

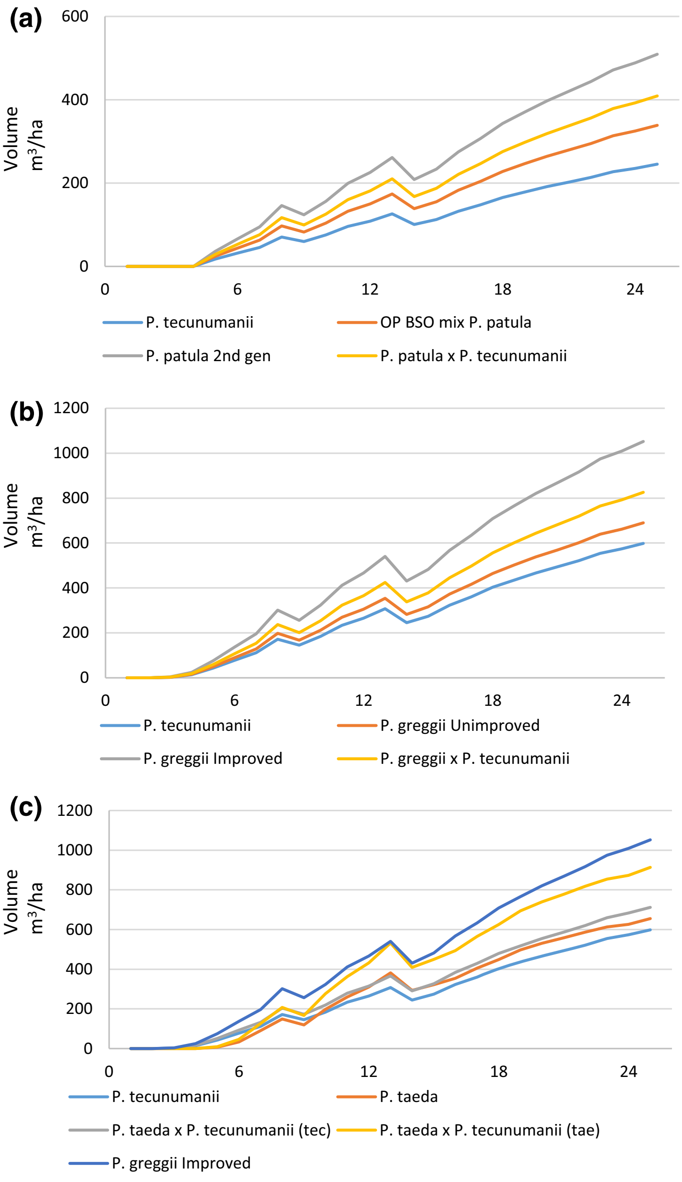

Fig. 3 Projected growth curves for pine hybrids and pure species under a sawtimber management regime in the pine hybrid trials at **a** Sappi and **b**, **c** Mondi

and sawtimber. For the purpose of illustration in Table 2, the calculations were made with hauling costs at 50 km from the pulp mill.

For pulpwood and sawtimber regimes, the NPV was very sensitive to the 2% difference in discount rate (6 and 8%). The ORA for sawtimber, 17 years, is the same for all of the taxa, while it is different for pulpwood, as seen in Table 2.

Table 2 ORA, NPV and IRR for ten taxa of pines grown in two sites for pulpwood and sawtimber at 6 and 8% discount rates

Trial	Taxon	ORA @ 6%		NPV @ 6%		ORA @ 8%		NPV @ 8%		IRR (%)	
		PW	ST	PW	ST	PW	ST	PW	ST	PW	ST
Usutu Forest—Sappi	Patula OP BSO mix	14	17	(1131)	6540	14	17	(1429)	3570	3.3	14.7
	Patula 2nd gen	14	17	982	10,424	13	17	(30)	6005	7.9	17.2
	Patula × tec	14	17	577	8555	13	17	(298)	4869	7.1	16.4
	Tec	14	17	(2323)	3916	14	17	(2205)	1881	(0.5)	12.1
KwaZulu-Natal—Mondi	Commercial greggii	14	17	1960	15,692	12	17	632	9386	9.8	20.2
	Improved greggii	13	17	6508	23,336	12	17	3702	14,178	16.0	22.7
	Greggii × tec	14	17	3424	19,791	12	17	1626	12,039	12.1	22.2
	Tec	14	17	961	12,915	12	17	(46)	7588	7.9	18.6
	Taeda	16	17	1606	13,994	16	17	251	8213	8.6	18.7
	Taeda × tec (from taeda)	16	17	4323	21,525	16	17	1977	13,058	11.7	22.2
	Taeda × tec (from tec)	14	17	2173	15,893	12	17	777	9504	10.1	20.2
	Tec	14	17	961	12,915	12	17	(46)	7588	7.9	18.6

Table 3 MAPA in commercial plantations to justify the economic investment in a TBP at a discount rate of 6% (Taxa at the Mondi trial)

Taxon	Rotation age ST (years)	MAPA for sawtimber (has)	NPV total forest ST (million US$)	IRR (%)	Rotation age PW (years)	MAPA for pulpwood (has)	NPV total forest PW (million US$)	IRR (%)
Tae × tec from tae	17	1128	223.6	17.2	16	2775	118.6	10.4
Gre × tec	17	1142	220.2	17.8	14	2332	72.6	10.0
Commercial greggii	17	1366	207.3	16.5	14	3544	90.8	9.6
Improved greggii	17	896	234.0	19.6	14	2327	154.2	13.2
Tae × tec from tec	17	1376	207.8	16.2	14	3443	67.0	8.8
Taeda	17	1568	198.4	15.1	16	3867	58.4	7.9
Tecunumanii	17	1575	195.4	15.4	14	4095	33.0	7.3

The faster growth rate at later ages of the *P. taeda* makes it financially desirable (greater NPV) for long rotations as a pure species and as a hybrid when the growth projection of the hybrid is similar to that of the pure species.

The *P. tecunumanii* provenance Rio Chiquito, El Salvador used as the control in the Mondi trial has been shown to be a below average source for growth in South Africa (Hodge and Dvorak 2012). Highly productive provenances of the species, like San Jeronimo Guatemala, or seeds from an advanced generation breeding orchard would provide much better volume growth than the Rio Chiquito provenance and would be more competitive when compared to *P. taeda*.

Deterministic tree-breeding model at the forest level

Table 3 shows estimates for the MAPA required to justify the investment in the TBP for pulpwood and sawtimber production at a discount rate of 6% and a haul distance of 50 km from the pulp mill. The ORA determined to the stand level was used for calculation at the forest level. Profitability at the break-even point for both regimes is very consistent, with the genetically improved taxa, the pine hybrids, and *P. greggii* always ranking higher than *P. taeda* and *P. tecunumanii*.

When tested in the model, the sensitivity of the MAPA to a 2% change in the discount rate (6–8%) was 51% and the NPV decreased 17% on average for all the varieties.

As previously mentioned, F2 seedlings were utilized in the financial analysis for the pine hybrids. The production cost per seedling in South Africa is $0.12, while per cutting is $0.24 (personal communication from André van der Hoef). In order to quantify the effect of using cuttings, instead of seedlings, on the profitability and the position of hybrids over pure species, the value of rooted cuttings was used in the model. The results of this assessment are illustrated in Table 4.

In the previous example, one observes that the relative change of the NPV for the pulpwood project with a discount rate of 8% was greater than the relative change on the NPV for the sawtimber project at a 6% discount rate. In none of the projects was there change in the ranking of hybrids versus pure species, but the economic advantage of the hybrids was reduced.

Another possible scenario when working with pine hybrids might be that the TBP is more expensive because improving the two parental should require more research effort and cost than working with one species.

When 50% additional costs are necessary to develop a TBP with hybrids, the forestry projects require more commercial areas to be planted annually in order to reach the break-

Table 4 Relative effect of propagation method used for pine hybrids between a highly profitable project and a less profitable project

Taxon	NPV (6%) sawtimber regime (million US$)		NPV (8%) pulpwood regime (million US$)	
	Seedlings	Cuttings	Seedlings	Cuttings
Improved greggii	234.0	–	84.6	–
Tae × tec from tae	223.6	221.1	76.9	66.5
Gre × tec	220.2	217.7	52.9	42.8
Commercial greggii	207.3	–	23.8	–
Tae × tec from tec	207.8	204.8	20.8	12.2
Taeda	198.4	–	11.7	–
Tecunumanii	195.4	–	−1.9	–

even point for the TBP. Because the capital investment is larger, the NPV is also larger, as depicted in Table 5. Ignoring market effects and land availability, as long as pine hybrids have a greater volume growth than pure species, there is always the possibility to make profits by increasing the commercial planting area, even if the tree breeding costs of hybrids are higher than those of the pure species.

This is a practical and flexible model that can be used as a tool for forest companies with TBP to assess profitability under different scenarios. Wood prices, discount rates, transportation costs, harvesting costs, management and operational costs, growth curves, research costs, genetic gains, and uncertainty are the main values that can be managed in the model.

Stochastic approach with @Risk™ (Montecarlo simulation)

P. greggii × P. tecunumanii for Sawtimber at 8% discount rate

Having run the simulation with 5000 iterations, the impact on the NPV (8%) generated by the uncertainty in the input variables is illustrated in Fig. 4. It is observed that the NPV at a discount rate of 8% will always be positive, with 100% probability that the value will vary between $152.01 and $222.44 million under the assumption of the model. This outcome suggests that the investor should be willing to invest funds in this project because it is financially safe and will obtain the expected return. In this simulation the mean NPV was $186.42 million.

As depicted in Fig. 5, the NPV is very sensitive to the dispersion of the sawtimber price. A small variation of ±10% in the sawtimber price within a range of probabilities (triangular PDF with mean $78.84/m^3$, minimum $70.96/m^3$ and maximum $86.72/m^3$), causes a high dispersion of the NPV at 8% discount rate.

Table 5 Results of the analysis for a pine hybrid TBP with 50% additional annual costs under a sawtimber management regime at rate discounted 6% and a pulpwood regime at rate discounted 8%

Taxon	Sawtimber management regime—NPV 6% (million US$)			Pulpwood management regime—NPV 8% (million US$)		
	NPV (6%) No additional TB costs	NPV (6%) with 50% additional TB costs	Increase in MAPA to the new break-even point (has)	NPV (8%) No additional TB costs	NPV (8%) with 50% additional TB costs	Increase in MAPA to the new break-even point (has)
Tae × tec from tae	223.6	333.8	556	76.9	114.7	2084
Gre × tec	220.2	328.7	563	52.9	78.9	2033
Commercial greggii	207.3	–	–	23.8	–	–
Improved greggii	234.0	–	–	84.6	–	–
Tae × tec from tec	207.8	310.1	678	20.8	30.9	1706
Taeda	198.4	–	–	11.7	–	–
Tecunumanii	195.4	–	–	−1.9	–	–

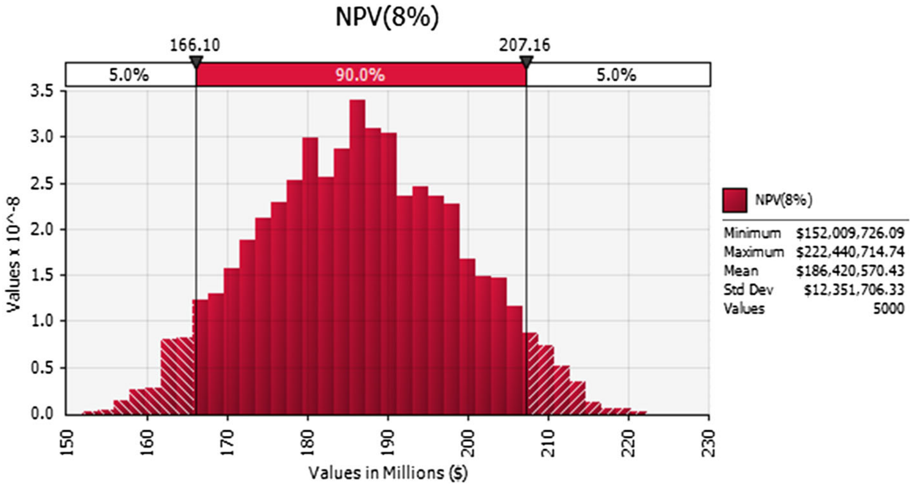

Fig. 4 Range of possible outcomes for the NPV (8%) and the probabilities that they will occur for a sawtimber management project with *P. greggii* × *P. tecunumanii*, when the input variables have a variation of ±10%

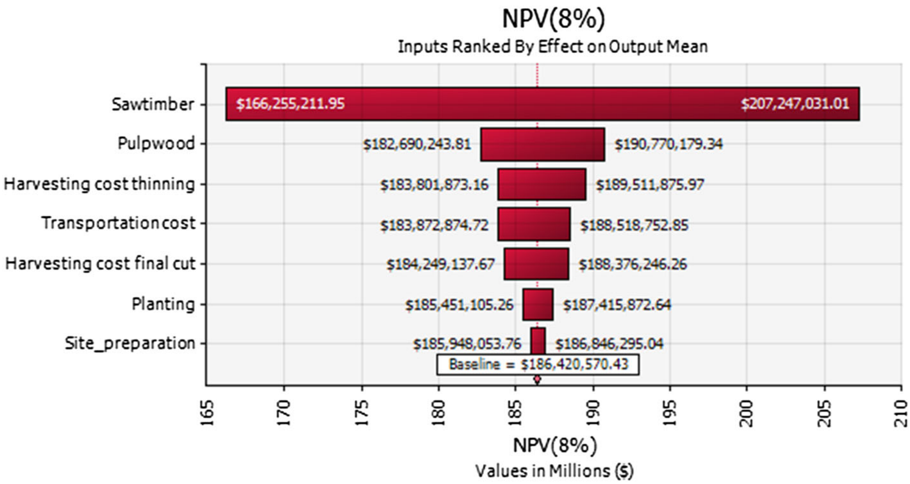

Fig. 5 Tornado graph illustrating the sensitivity of the NPV (8%) to the uncertainty of the input variables in the *P. greggii* × *P. tecunumanii* plantation project

P. taeda for pulpwood at 8% discount rate

P. taeda pulpwood production was analyzed the same way as the previous pine hybrid. The range of NPV (8%) in this investment project varied between −$42.25 and $76.75 million. In this simulation the mean NPV was $11.87 million. The probability that the NPV would be negative was 30.8%. A project that seemed to be very profitable when assessed with the deterministic model, with a NPV (8%) of $11.7 million (Table 5), turned into a highly risky project when uncertainty was added to the model.

Discussion

Volume growth and plot types

Considering that the hybrid crosses of *P. greggii* × *P. tecunumanii* were made on improved mother trees of *P. greggii* (first-generation orchard mix), it makes more sense to compare the hybrid results with those of the improved *P. greggii* than with those of the unimproved *P. greggii*. In this particular case, the growth of this hybrid is intermediate between the pure species.

Results of volume growth for the *P. taeda* × *P. tecunumanii* hybrid are different than in the previous case, with the controls of both parents in the trial having lower volume than the hybrid. The *P. taeda* mother trees used to produce the hybrids were located in a second-generation orchard, and the pollen of *P. tecunumanii* came from unimproved trees. The genetic quality of the pure species in the trial was comparable to the genetic quality of the hybrid, with a second-generation *P. taeda* control and an unimproved *P. tecunumanii* control.

Temperature and precipitation at the site of the study were favorable to *P. greggii*, which could explain the strong growth of the species and its hybrid with *P. tecunumanii*. Environmental conditions may not have been ideal for either *P. tecunumanii* or *P. taeda*, which makes the performance of their hybrid more surprising, with higher growth than that of unimproved *P. greggii*. The growth of *Pinus tecunumanii* was better than *P. taeda* at 9.5 years of age, which should be expected at this site. In addition to its rapid growth, the *P. tecunumanii* also brings pitch canker resistance to the hybrid, compensating for the susceptibility of *P. greggii* to the disease (Hodge and Dvorak 2000). *Pinus greggii* should provide the hybrid with intermediate frost resistance, and to a lesser extent, better drought hardiness than *P. tecunumanii*.

Because the mother trees used for crosses of the *P. patula* × *P. tecunumanii* hybrid seed production were second-generation clones, the results should be compared to the growth of the *P. patula* second-generation control.

In the Sappi hybrid trial, the hybrid had very similar growth to the growth of the best of the parents, *P. patula* second-generation, and better growth than the *P. patula* from the BSO. The *P. tecunumanii* progeny trial at Usutu Forest was located at an elevation of 1040 m, which is a better climatic match to maximize the development of *P. patula* growth and explains in part the lower performance of *P. tecunumanii*.

Pinus patula × *P. tecunumanii* LE has been tested in other locations in South Africa. The mean tree volume (m^3) of a series of trials planted on six sites over a large range in elevation by Sappi showed that the hybrid was more productive across all sites and that the average growth improvement over *P. patula* was 46% at 4 years (Hongwane et al. 2016; Kanzler et al. 2014).

In regard to the type of plot in the trials and its effect on growth, the comparisons among taxa are within each trial not between trials. At Mondi, the *P. taeda* progeny trial has single tree plots while the pine hybrid trial has row plots. In the first case, the species growth is well represented regardless of the plot shape because the advantage of the fast growing families are counter-balanced by the poor growth of the worse families. No adjustment was made for the hybrid yield in the Mondi hybrid trial; it was assumed that the growth in the trial was the same as the growth expected in commercial plantations. Even though some overestimation in volume growth was possible for the fast growing taxa, their ranking should have been the same as the ranking that might have been obtained in block plots. The Sappi hybrid trial in Usutu had block plots with a similar growth to that expected in operational plantings. A comparison was made for the height growth of *P. patula* at 5.5 years of age in the trial with the adjusted growth reported by Evans (2005) at the same age in Swaziland and the difference was less than 1%. The *P. tecunumanii* progeny trial with row plots in Usutu was used to compare *P. patula* with *P. tecunumanii* and apply the relative difference in volume yield to estimate the growth of *P. tecunumanii* in the hybrid trial. The relative difference should have not been significantly affected by the plot type.

Wood properties and rotation length

In this study, wood density and pulp yield were measured (data not published) for all the taxa. Volume growth and wood density were superior for the hybrids, while pulp yield was intermediate between the parents. This indicates that hybrids between species have the potential for faster growth and greater wood density within the same trees. Several studies have shown how wood properties vary at different ages (Evans 2005; Ivković et al. 2006a, b; Morris et al. 1997; Wang et al. 2000; Wessels et al. 2015). As shown by Morris et al. (1997), even though the age was important, the combined effect of species, altitude, and level of fiber refinement was greater on pulp yield. This supports the idea that criteria other than age can be used for selections in a TBP to obtain desirable wood or pulp properties. In study by Wang et al. 2000, the wood density of lodge pole pine (*P. contorta* var. *latifolia*) decreased less from the pith to the bark in both overall and early wood densities in the subpopulation selected for fast growth and high density wood, resulting in denser, more homogeneous wood, than in the other subpopulations. This suggests that it is possible to increase wood density and homogeneity in juvenile wood of pine species by selecting families with fast growth. In an accompanying paper (to be submitted) to this study, the authors show the financial impact on a hypothetical South African pulp mill and commercial plantation investment for wood density, pulp yield and volume growth. A sensitivity analysis is also presented, showing the relative weight of each one of these properties when their values change $\pm10\%$ on the NPV of the investment. Pine wood properties (MOE, Micro-fibril angle and wood density) measured at Camcore have shown to be consistently greater for *P. maximinoi* and *P. tecunumanii* (LE) than for *P. patula* and *P. tecunumanii* (HE) (unpublished data). In studies conducted in Mpumalanga, South Africa with subtropical species like *P. maximinoi* and *P. tecunumanii*, it was found that tree volume and the physical wood properties (early-wood density, pith to bark wood density gradient, modulus of elasticity etc.) are often superior to *P. patula* and *P. taeda* through 16 years of age when planted below 1100–1200 m elevation (Malan and Hoon 1991; Malan 2006). Assuming that pine hybrids with at least one subtropical pine parent also produce high-quality wood at early ages, the rotation length does not necessarily have to be as long as 28 years; it could be much shorter. As explained, it was assumed that the size of the tree was the only criterion for the sawtimber analyses in this paper, not the wood properties. However, some adjustment to shorten rotation age for sawtimber regimes, including amending the timing of commercial thinning, most likely needs to be made with the faster-growing taxa. It is realized that the average growth of commercial plantations is usually lower than the MAI observed in the genetic trials, but in our opinion, shortening rotation ages by even a few years when planting the faster growing hybrids will not adversely affect wood quality of the final product over what is produced with the current sawlog regime and would increase profitability.

F2 seedlings

Several authors (Powell and Nikles 1996; Harding et al. 1996 cited by Kain 2003) have said that for the *P. elliottii* × *P. caribaea* hybrid in South-East Queensland, Australia, outcrossed F2 progeny are typically almost indistinguishable from the F1, both visually and statistically, and have been used to successfully afforest an area of 12,500 ha (Nikles 2000). Hyun (1976), cited by Kain (2003), stated that in South Korea, the *P. rigida* × *P. taeda* outcrossed F2 hybrid, generated by crossing F1 s from different seed sources, had performed at least as well as its F1 parents on average. For the purpose of this project, it was assumed that the pine hybrids would be grown from F2 seedlings and not from rooted cuttings.

Future research

More precise growth and yield curves for the pure species and hybrids in this study would improve the results of the modelling approach. More comprehensive studies like the one by Hongwane et al. (2017), testing the same taxa at several sites with different environmental conditions should be part of future research. Information of genotype × environment interaction at the taxa level would give more complete results.

Conclusions

Our results indicated that pine hybrids may have economic potential when they grow faster and show greater survival than pure species. Considering only volume growth with the data used for this project, optimal rotation lengths were found to be between 12 and 16 years for pulpwood and 17 years for sawtimber.

The financial criteria outputs calculated in this project were also based on volume increase only. The TBM developed at the forest level drew profitability for the pine hybrids and for the pure species. At a 6% discount rate, the MAPA among varieties changed between 896 ha and 1575 ha for sawtimber production. For pulpwood production, a variation of the MAPA among varieties went from 2327 to 4095 ha. For the 8% discount rate, the MAPA changed from 1356 to 2390 ha for sawtimber and from 3197 to 5905 ha for pulpwood. Ignoring market effects and land availability, as long as pine hybrids exhibit greater volume growth than the pure species, there is always the possibility to make profits by increasing the commercial planting area, even if the tree-breeding costs of hybrids are higher than those of the pure species.

The sensitivity analysis with the stochastic approach illustrates the different profitability and risk level between two plantation projects associated with the uncertainty in the value of some input variables. Variation in wood prices, highly correlated with the financial outcomes, had a large impact on the NPV. A project that was apparently very profitable when the deterministic model was run turned into a high-risk project when uncertainty of wood prices varied ±10%.

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