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ORIGINAL ARTICLE

Adaptation of tropical and subtropical pine plantation forestry to climate change: Realignment of *Pinus patula* and *Pinus tecunumanii* genotypes to 2020 planting site climates

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Abstract

Pinus patula and *Pinus tecunumanii*, two pines native to Mexico and Central America, are important plantation species for the forestry sector in the tropics and subtropics. In recent decades, members of the International Tree Conservation & Domestication Program (CAMCORE), North Carolina State University, have established large, multisite provenance trials for these pine species. The data provide valuable information about species and provenance choice for plantation establishment in many regions with different climates. However, since climate is changing rapidly, it may become increasingly difficult to choose the right species and provenance to plant. The aim of this study is to test the suitability of seed material under changing climate of two *P. patula* varieties (*P. patula* var. *patula* and *P. patula* var. *longipedunculata*) and two *P. tecunumanii* ecotypes (highland and lowland). For each variety and ecotype, a site quality model was developed that statistically relates growth to environmental factors and couples the predictions to the average 2020 climate prediction of four general circulation models. Three developed models were significant and robust. Provenances of *P. tecunumanii* from lowland areas in Central America are expected to be most productive in 2020 because of their promising performance under rather hot and wet climates.

Keywords: *Climate change impact predictions, height growth, management decision support tools, provenance trials, site quality modelling.*

Introduction

Global climate alterations are likely to affect the productivity of plantation forestry in the coming decades. Forest growth models suggest a substantial loss of production in the core area of current forestry if no appropriate action is taken (Fairbanks, 1999; Spittlehouse & Stewart, 2003; Savolainen et al., 2007). At the same time planted forests are becoming increasingly important to satisfy global wood demand (Carle & Holmgren, 2008). Planted forests may also indirectly reduce pressures in natural forests and are potential sources for carbon sequestration (Carle & Holmgren, 2008), and in that way contribute to the mitigation of climate change. To ensure the supply of the expected products and services from planted forests in the future under a changing climate, plantation forest management needs to be adapted accordingly (Kremer, 2007).

The selection of species and provenances that are most suitable to grow under the new climates that are expected to occur is an important aspect of a management plan that aims to adapt plantation forests (Spittlehouse & Stewart, 2003). It can be anticipated that seed material used in the past to establish new plantations will not be optimal under

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the changing climate in the future. New sources of seed will need to be found to optimize wood productivity.

In recent decades multisite provenance trials have been established to identify the most suitable species and provenances to plant in different climates (e.g. Dvorak et al., 1995; Hodge & Dvorak, 1999; Kanzler, 2002). Site growth modelling has proven to be a practical and accurate method to predict the performance of species and provenances in these experiments (Louw & Scholes, 2006). Support decision models that couple site growth modelling to future climate predictions based on general circulation models (GCMs) can be a useful tool for forest managers to choose which provenances and species to plant today in order to yield optimal growth during the rotations in future decades.

Significant areas of planted forests are grown in tropical and subtropical areas of Colombia, Brazil and South Africa (FAO, 2007). *Pinus patula* and *Pinus tecunumanii*, two pine species native to Mexico and Central America, are important plantation species for the forestry sector in the tropics and austral regions. Members of the International Tree conservation & Domestication Program (CAMCORE) have established multisite provenance trials on a global level that include 74 trials and 79 trials of *P. patula* and *P. tecunumanii*, respectively, to identify the growth and survival of these species and provenances across different environments. The results from these trials represent a treasure trove of data suitable for understanding how trees are adapted to their abiotic environment, and how they adapt to different conditions.

Pinus patula is one of the most important pine plantation species in tropical and subtropical regions, with close to 1 million ha established in plantations (Birks & Barnes, 1991). It is of primary importance in South Africa, where the pine is the most commonly planted species, accounting for 25% of the country's entire forest plantation area (FAO, 2007). Lesser amounts of *P. tecunumanii* are used in plantations, but it is an important plantation species in Colombia, and owing to its favourable growth characteristics and comparatively high resistance against pitch canker (Hodge & Dvorak, 2006) the species is also gaining importance in Brazil and southern Africa (Dvorak et al., 2000).

Pinus patula occurs naturally in the mountainous regions of eastern and southern Mexico. Two varieties can be distinguished: *P. patula* var. *patula*, which occurs in the eastern mountain ranges of the Sierra Madre Oriental, and *P. patula* var. *longipedunculata*, which occurs in the southern Mexican states of Guerrero and Oaxaca in the Sierra Madre del Sur (Dvorak et al., 2000). The geographical distribution of *P. patula* var. *longipedunculata* borders with the western distribution range of *P. tecunumanii*. The distribution of *P. tecunumanii* extends from Chiapas, Mexico, in the north to Honduras in the south and can be divided into two ecotypes based on altitude: a highland ecotype found in cloud forests at altitudes between 1500 and 2900 m, and a lowland ecotype that occurs at altitudes between 450 and 1500 m (Dvorak et al., 1989).

This study aims to contribute to the development of management plans to adapt existing planted forests in Colombia, Brazil and South Africa to the expected climate changes in the next few decades. It is hypothesized that in several areas, species and provenance choice of seed material will have to be changed in order to sustain the productivity of these planted forests. The objective of this study is to develop a decision support model that (1) predicts the impact of climate change on wood productivity for new rotation cycles that have an expected harvest time around 2025, and (2) identifies the most suitable variety and ecotype of *P. patula* and *P. tecunumanii*, respectively, to optimize wood productivity in the period of these new rotation cycles.

Materials and methods

To develop the decision support model, 8-year-old *P. patula* and *P. tecunumanii* height growth data were retrieved from a database of 153 provenance trials that were established by CAMCORE members in Colombia, Brazil and South Africa during 1981 and 1997 (Dvorak et al., 1995, 2001*b*). For each of the two *P. patula* varieties, *P. patula* var. *patula* and *P. patula* var. *longipedunculata*, and the two *P. tecunumanii* ecotypes, lowland and highland *P. tecunumanii*, three different site quality model types that examined relations between height growth and environmental conditions were developed. The models were cross-validated with an independent set of test data as an indication of model robustness. The model types that scored best in the cross-validation were used in the final growth prediction. Geographical Information Systems (GIS) were used to spatialize model predictions to other plantation areas and project them into the future. The average of four GCM climate projections for the year 2020 were used to calculate the expected impact of climate change on a plantation's growth performance in a time span that falls below the common rotation cycle of 17 years.

Study area

The study area comprises areas suitable for *P. patula* and *P. tecunumanii* plantations in current and future (2020) climates in Colombia, Brazil and South Africa. The areas include a topographic range from 25 to 2850 m of altitude and diverse climates that range from tropical conditions in the Colombian highlands, where annual rainfall frequently exceeds 3000 mm, to the dry, subtropical conditions characterized by cold and dry winters in South Africa, where the maximum annual mean temperature exceeds 20°C but temperature seasonality is more than 10 times as high as in Colombia. In South Africa in the coldest quarter of the year the temperature drops below 1°C. The trials were planted in parts of the northern tropical Andes in Colombia, and in southern Brazil, where trials are established in the states of Minas Gerais, Epirito Santo, Paraná and Santa Catarina. Trial sites in South Africa are located in the country's eastern escarpment from the Eastern Cape Province to the Northern Province. Management (site preparation, spacing of trees, weed control, etc.) among trials was as similar as practical in the field.

Data

The aim was to predict average observed height growth at the age of 8 years and select through stepwise regression the environmental variables that best explain height performance at trial sites. The pool of variables that were used as input consisted of grid-based climate, soil and topographical variables (Table I). Data for the 153 provenance trial locations were extracted using ArcInfo (ESRI, 2006). The 19 Bioclim candidate variables (Busby, 1991) were chosen to describe the climate in the study area. The data were derived from the WorldClim database developed by Hijmans et al. (2005). In addition, two water balance variables, water availability and potential to actual evapotranspiration, were calculated using satellite-based observation of rainfall from the Tropical Rainfall Measurement Mission (TRMM). Soil conditions (topsoil) were described by variables of the Harmonized World Soil database (FAO, 2009). Topographical variables were derived from the Shuttle Radar Topography Mission 90m Digital Elevation Data (Jarvis et al., 2008). All variable grids were scaled to the same spatial resolution of 30 arc-seconds, except for the TRMM-based variables, which have a resolution of 15 arc-minutes.

Model selection

Single regression analyses showed that some environmental variables predicted height growth best following a linear relation, while others did so

Table I. List of climatic, edaphic and topographic variables that were incorporated in the data table for the stepwise regression runs.

Climate	Soil	Topography
Temperature variables	*Structure variables*	*General variables*
Annual mean temperature (°C)	Available water capacity (mm m^{-1})	Elevation (m a.s.l.)
Mean diurnal range (°C)	Reference bulk density (kg dm^{-3})	Slope (degree)
Isothermality (unitless)	Clay fraction (% wt)	Aspect (degree)
Temperature seasonality (%)	Gravel fraction (% wt)	
Max. temperature of warmest period (°C)	Sand fraction (% wt)	
Min. temperature of coldest period (°C)	*Chemical composition variables*	
Temperature annual range (°C)	Organic carbon (% wt)	
Mean temperature of wettest quarter (°C)	pH (H_2O) ($-\log(H^+)$)	
Mean temperature of driest quarter (°C)	Cation-exchange capacity (cmol kg^{-1})	
Mean temperature of warmest quarter (°C)		
Mean temperature of coldest quarter (°C)		
Precipitation variables		
Annual precipitation (mm)		
Precipitation of wettest period (mm)		
Precipitation of driest period (mm)		
Precipitation seasonality (%)		
Precipitation of wettest quarter (mm)		
Precipitation of driest quarter (mm)		
Precipitation of warmest quarter (mm)		
Precipitation of coldest quarter (mm)		
Water balance variables		
Consecutive dry months (no. months)		
Actual to potential evapotranspiration (%)		
Water availability (%)		

Note: The table lists the environmental variables that were used to build the site growth prediction models.

through a quadratic relation (data not presented). Since it was not known beforehand which type of relations would weigh more in a multiple linear regression (MLR) model, three different types of MLR models were compared, all three using stepwise regression for the selection of model variables. The first model type, "Linear", consisted of standard linear relations between height growth and environmental variables. The second model type, "Squared", consisted of linear relations with centred-squared variables. In the third model type, "Mixed", the environmental predictors were either linear or centred-squared, depending on which type of relation explained best height growth in a single regression analysis. The development of squared centred variables is a recommended method to improve linear regression models (Bedrick, 2000). The value of the original environmental variable is centred by subtracting the variable's mean from each value and then squared. The transformed variables are then again related linearly to the dependent variable. Figure 1 exemplifies this variable transformation by showing the *P. tecunumanii* high-elevation population height growth linear, centred quadratic and centred-squared linear response to the annual mean temperature at the trial sites.

For each variety and ecotype, cross-validation of all three model types was carried out as an indicator of how the model could be extrapolated to larger areas. After Hurvich and Tsai (1990), 20% of the initial data set was used to validate the model types developed using the remaining 80% of data. As an indicator of robustness the coefficient of determination (R^2) was calculated based on the comparison between observed and predicted height of the test data. For each of the two *P. patula* varieties and the two *P. tecunumanii* ecotypes, the model type that scored best in the cross-validation was selected to perform the definitive growth prediction of the respective variety and ecotype, using all data.

Variable selection

To find the subset of predictors that best explain height growth, the stepwise regression algorithm was used. This is a common method in variable selection for site growth models (Huston, 1980; Dise & Wright, 2000). The stepwise algorithm defines the best possible set of variables to explain the variability in height growth at the age of 8 years. As variables are added during the model run there is continuous reappraisal of the existing set of included variables. If, in the light of the most recently added variable, an included variable no longer satisfies the retention criteria, it is deleted from the model (MacNally, 2000). The retention criterion of variables in the model runs was set on a probability value (p) of below 0.05. The coefficient of determination (R^2) was used to express the model's fit.

Multicollinearity among the explanatory variables (Xs) means that causal Xs may be lost from ultimate models because other, non-causal Xs are correlated with those causal variables and may be retained in models at their expense. To guard against the negative effect that multicollinearity has on the stability of regression coefficients and significance levels (MacNally, 2000), variance inflation (Vif) was calculated to indicate the rate of multicollinearity.

Variables were taken out of the modelling process if their Vif score exceeded 30, which is a common threshold to test for multicollinearity (O'Brien, 2007).

Model spatialization

To identify suitable seed material for plantation sites, Arcmap's grid calculator (ESRI, 2006) was used to project spatially the developed multiple linear regression equation for each variety and ecotype. Height growth of the respective variety and ecotypes is calculated for each grid in the study area based on the values of the environmental variables in those grids. The equations have the general form:

$$\text{pht8} = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots \beta_n x_{in} \text{ for } i = 1, 2, \cdots n$$

where pht8 = predicted average height performance at age 8, β_0 = intercept, β_1 = Pearson's correlation coefficient with the dependant of first environmental variable, x_{i1} = value of first environmental variable [...], β_n = Pearson's correlation coefficient with the dependant of nth environmental variable, and x_{in} = value of nth environmental variable.

Current and future climate projections

The study area for which the site growth prediction models were developed was restricted to the environments that resemble the actual environmental niche in which the provenance trials are established. This avoids an extrapolation of the regression functions to environments where no empirical information was available and impedes the prediction of unrealistic and impossible height growths. A mask grid was calculated that comprises only the study area that has a similar bioclimatic set-up to the climatic niche in which the trials were established. The mask used the minimum and maximum values of the 19 BIOCLIM variables at the trial sites. All model operations use this mask as a template for their predictions. By substituting the climate grids for current conditions with climate grids for the

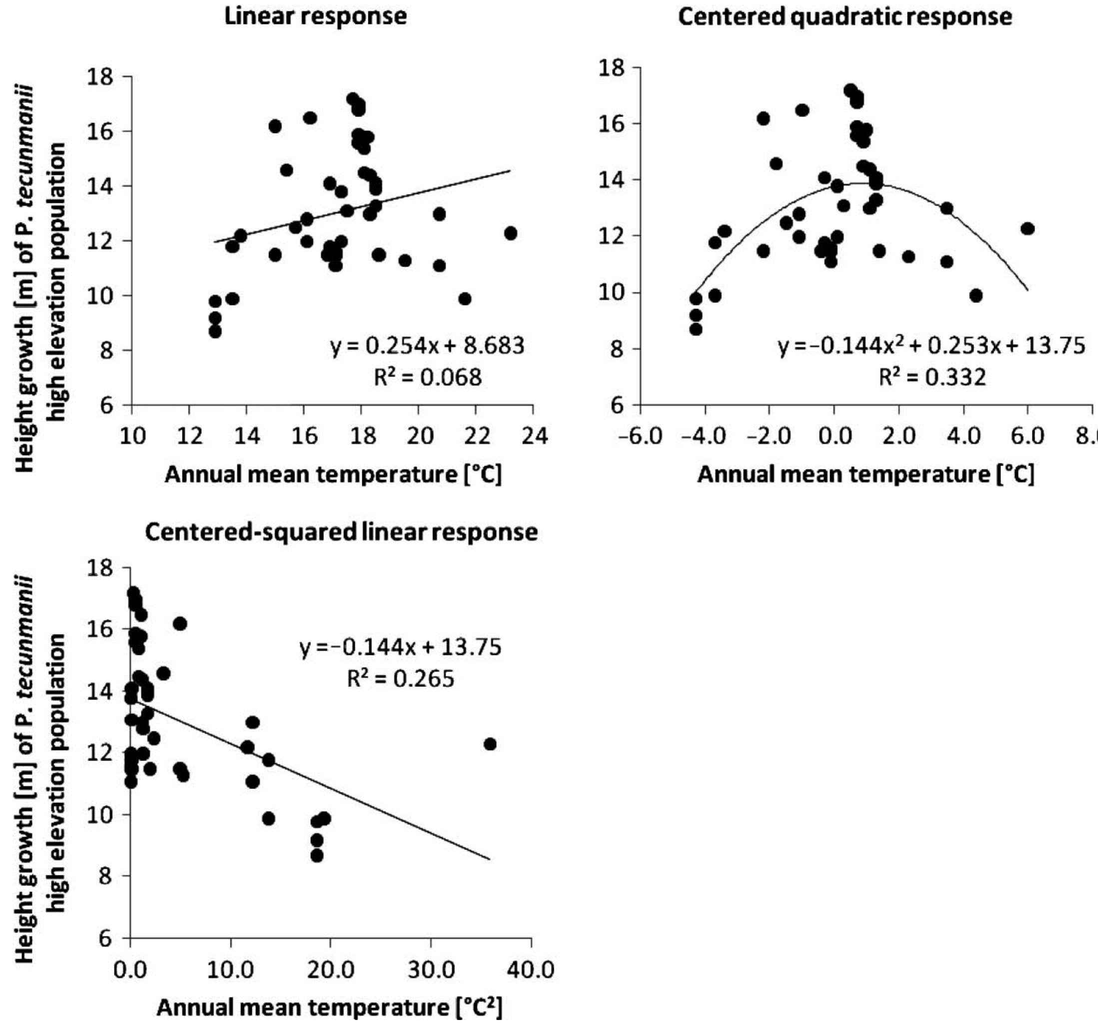

Figure 1. Linear, centred and centred-squared response of *Pinus tecunumanii* high-elevation subpopulation trial's height growth to annual mean temperature. A regression line is drawn through the points. For each plot the coefficient of determination R^2 and according regression equation are given. The sample size n for all three plots is 45.

future, the impact of climate change on the height performance of the plantings by 2020 under the emission scenarios A2a and B2a was inferred. Four 4th assessment GCM runs from the Canadian Centre for Climate Modeling and Analysis (CCCMA), Commonwealth Scientific & Industrial Research Organization (CSIRO), Hadley Centre Coupled Climate Model (HADCM) and National Institute for Environmental Studies (NIES) models were used for the future climate.

To compare height growth of the three taxa under current climate and future climate by 2020, independent t tests were carried with the predicted values at the field trials.

To address variation in projected climate brought about by GCM model uncertainty, the standard deviation of height growth for each variety and ecotype under the four GCM model projections was calculated.

To see whether an adapted planting decision results in a significant improvement in height growth, an independent t test was carried out. The height growth of the three taxa under current and future climate by 2020 was calculated and changes in performance for the best seed choice under current and future climate conditions were tested for their significance.

Results

Model selection and performance

Based on the results of the cross-validation, the most robust model types to predict height growth were selected (Table II). The Linear model type is the most confident model type to predict height growth of *P. patula* var. *patula* and the *P. tecunumanii* lowland ecotype. The Mixed model type proved to be the

Table II. Summary table of cross-validation R^2 scores for the relation between observed and predicted height of test set trials.

	Linear R^2	Squared R^2	Mixed R^2
High	0.096	0.201	0.337
Low	0.512	0.001	0.073
Varpat	0.832	0.812	0.38

Note: The cross-validation results are given for the three modelled genotypes High (*Pinus tecunumanii* high-elevation population), Low (*Pinus tecunumanii* low-elevation population) and Varpat (*Pinus patula* var. patula).

most successful in predicting height growth of the *P. tecunumanii* highland ecotype.

In none of the three model types could a regression equation be developed that significantly predicted 8-year-old height growth of *P. patula* var. *longipedunculata*; coefficient of determination scores (R^2) were 0.22 or lower. Therefore, no site growth predictions were made for this variety. The multiple regression equations for *P. patula* var. *patula*, the *P. tecunumanii* highland and lowland ecotypes yielded R^2 scores of 0.61, 0.62 and 0.56, respectively (and p values of < 0.001, < 0.001 and 0.008, respectively). Variance inflation scores for the three developed models ranged from 5 to 26. The equations are as follows:

Predicted height of the *P. tecunumanii* highland ecotype at age $8 = (-9.3600) + 0.0617^\star$ Cation-exchange capacity of topsoil $+0.1399^\star$ Mean diurnal temperature range $+0.0502^\star$ Annual mean temperature $-0.0545^\star$ Precipitation seasonality.

and

Predicted height of *P. patula* var. *patula* at age $8 = (-19.0058) + 0.0046^\star$ Annual precipitation $+$ $0.2054^\star$ Mean diurnal temperature range.

Expected impact of climate change on wood productivity and seed material choice

Under current climate *P. tecunumanii* low-elevation provenances are predicted to exhibit a superior growth performance in the majority of the study area (Figure 2). In Colombia high-elevation provenances of *P. tecunumanii* outperform the other two seed choices at altitudes above 1800 m. In southern Brazil, in the near-coastal areas of the southern Brazilian states of Santa Catarina, Paraná, Sao Paula and Rio de Janeiro, the high-elevation seed sources of *P. tecunumanii* show best height growth. *Pimus patula* var. *patula* is predicted to reach competitive growth rates in the interior of Brazil and South Africa and is able to surpass the fast growing provenances from the low and high-elevation populations of *P. tecunumanii*.

In the overall study area 8-year-old height growth in all three countries is predicted not to change significantly by 2020 (t test, $n = 94$, $m = 49$, $p = 0.4152$). Still, the models predict that in 7.3% of the study area the choice of seed material today should be changed to adapt plantation forestry adequately by 2020.

In Colombia 9.3% of the study area is subject to change, while in South Africa 8.6% and in Brazil 7.4% of the study area is subject to change. Height growth in year 8 is predicted to decline by 0.39 m if seed material is not changed. In those areas height at 8-year-old plantations is predicted to be diminished by 0.39 m if seed material is not changed. A change to the superior choice between the three species/subspecies under future climate will significantly improve this situation by minimizing height loss at year 8 to only -0.04 m (t test, $n = 14$, $m = 14$, $p < 0.0004$).

In 95% of cases the new best choice of seed material is from provenances of the *P. tecunumanii* low ecotype. In Colombia, for example, the area where *P. tecunumanii* lowland ecotypes is predicted to perform best by 2020 moves 80 m higher in altitude. The height of the *P. tecunumanii* low ecotype is predicted to increase by 0.28 cm in 8-year-old plantings by 2020. Provenances from high-elevation seed sources are predicted to be most seriously affected by climate, reducing their average height growth by 1.16 m. *Pinus patula* var. *patula* exhibits comparatively stable growth responses to the environmental changes, losing an average of only 0.14 m in the study area (Table III).

Uncertainty in climate change projections

The standard deviation (σ) of the predicted mean mapped values calculated for the four GCMs serves as an additional indicator for the variability between GCM predictions (Table III). σ and therefore uncertainty of the GCM projections is highest for the site quality model of *P. tecunumanii* low-elevation population. σ values for the studied ecotypes and variety range from 0.25 to 0.4. The evaluation of uncertainty in climate change projections should also take into account the spatial variability in uncertainty. σ between GCM projections calculated for Brazil, Colombia and South Africa independently shows a homogeneous σ of 0.32 for each country.

Discussion

Demand for wood from planted forests is expected to increase in the coming decades (Carle & Holmgren,

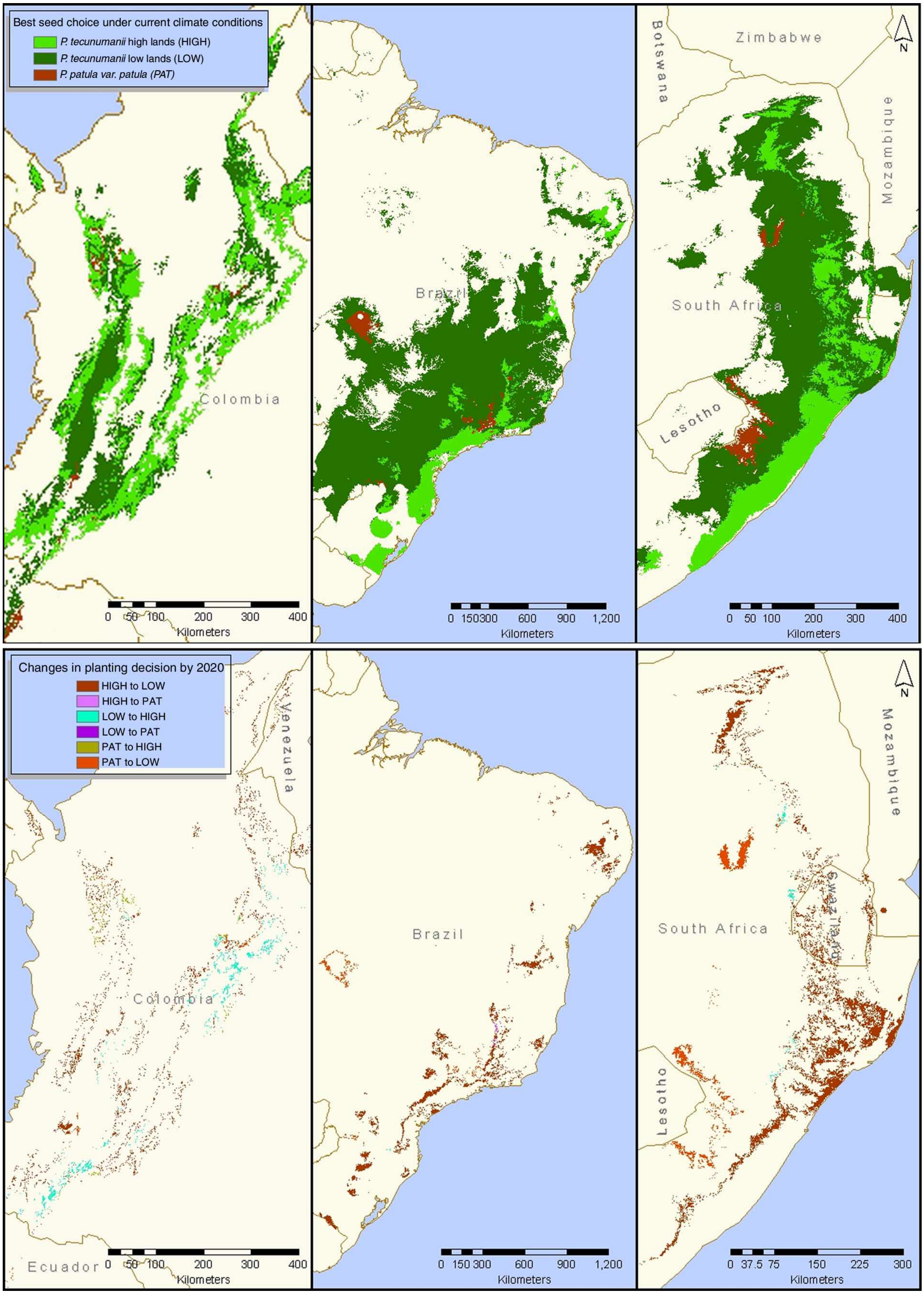

Figure 2. Map of optimal seed choice under current conditions and areas where the optimal planting decision is predicted to change by 2020. The results are based on the average of the results of four general circulation models.

Table III. Map mean values of predicted height growth at the age of 8 years (pht8) for the entire study area.

		CCCMA		CSIRO		HADCM		NIES			
pht8 (m)	Current	△ A2a	△ B2a	△ A2a	△ B2a	△ A2a	△ B2a	△ A2a	△ B2a	Mean △	SD
High	11.7	−0.88	−0.79	−1.04	−1.24	−1.30	−1.17	−1.39	−1.45	−1.16	0.25
Low	14.83	−0.39	−0.24	0.48	0.43	0.50	0.51	0.53	0.43	0.28	0.4
Varpat	11.63	−0.56	−0.51	0.05	0.11	0.08	0.08	−0.17	−0.23	−0.14	0.29

Note: The table shows map mean values for growth prediction models dependent on underlying general circulation model (GCM) and emission scenario—different outcomes of the regression models based on the results of four GCMs: Canadian Centre for Climate Modeling and Analysis (CCCMA), Commonwealth Scientific & Industrial Research Organization (CSIRO), Hadley Centre Coupled Climate Model (HADCM) and National Institute for Environmental Studies (NIES), for two emission scenarios each. The predicted height growth performance under current climate conditions is compared with the anticipated future height growth performance in 2020. Predictions are given for the three modelled genotypes High (*Pinus tecunumanii* high-elevation population), Low (*Pinus tecunumanii* low-elevation population) and Varpat (*Pinus patula* var. *patula*).

2008), while significant wood losses are expected if no appropriate action is undertaken to adapt plantation forestry to climate change (Fairbanks, 1999; Spittlehouse & Stewart, 2003; Kremer, 2007). The importance of selecting appropriate plantation seed material in the face of climate change has been pointed out by Persson (1998) for *Pinus sylvestris* in temperate and boreal plantation forestry. Optimal niches of *P. sylvestris* provenances' height growth are predicted to shift considerably during the next 90 years (Rehfeldt et al., 2002). Fairbanks (1999) points out that especially in *P. patula* and *Pinus radiata* plantations in South Africa a great loss of productivity will occur unless different seed sources are selected that are appropriate for future climate conditions. Through height growth models coupled with future climate scenarios the present report has shown that for 7–10% of areas in the study a change in the most suitable variety or subspecies will occur by 2020 (less than one production cycle away from the present).

Model performance

The developed site quality models for the two *P. tecunumanii* ecotypes and *P. patula* var. *patula* were significant; in particular, the goodness to fit ($R^2_{adj.}$) of the model for the *P. tecunumanii* lowland ecotype was excellent. No problems are expected in the extrapolation of the model predictions to the whole of study area because this area is within the climate ranges where the field trials are established and cross-validation for all three selected models was significant. The selected model for *P. patula* var. *patula* can be considered very robust since the cross-validation resulted in a high coefficient of determination. The model for the *P. tecunumanii* lowland ecotype was still fairly robust according to the cross-validation and the height growth model predictions also coincided with indicated elevations for optimal growth of this ecotype. Cross-validation of the model for the *P. tecunumanii* highland ecotype resulted in a moderate but still significant coefficient of determination.

In Colombia under current climate conditions a distinct altitude range can be identified at which the height growth of *P. tecunumanii* highland ecotype surpasses the *P. tecunumanii* lowland ecotype growth performance. This threshold ranges from 1300 to 1700 m, coinciding with the altitude that separates the two subpopulations inside their natural distribution range in Honduras (Dvorak et al., 2000). This demonstrates that both ecotypes are best adapted to divergent environments that in each case resemble their respective native niche. This underlines two facts: first, provenances are indeed adapted to their specific environmental conditions; and secondly, it is important to conserve a wide range of seed sources to sustain the value of diversity for plantation forestry in heterogeneous environments and in the face of a changing climate.

For *P. patula* var. *longipedunculata* no significant site quality model could be developed. From the four different taxa studied, the least amount of data was available for *P. patula* var. *longipedunculata*. To improve the prediction of the impact of climate change on height growth for this variety it is recommended to include height data from more field trials established over a wider climate range than could be accessed here.

Impact of climate change on wood productivity and choice of seed material

In general terms no significant changes are predicted by 2020 across the whole study area, but some specific areas important for wood productivity do show significant changes. At these sites a change in seed choice has been shown to adapt the existing planted forests with great effectiveness. Two trials in Santa Tereza, Brazil, for instance were established using seeds from high-elevation populations of *P. tecunumanii*. Observed and predicted heights on this site differ by just 0.05 m. The regression model predicts that on this site low-elevation seed sources would yield the same height growth under current climate conditions. Height growth predictions for the 2020 projections suggest that provenances from the low-elevation population of *P. tecunumanii* will reach 13.7 m in height at 8 years, while the high-elevation population will reach only 12.09 m. This is a significant difference and should be an important criterion used today in selecting seed material for this site.

Pinus tecunumanii lowland ecotype is expected to be the most suitable seed material to plant for the next rotation because of its promising performance under rather hot and wet climates. On sites in South Africa where *P. patula* var. *patula* is planted, seed material from *P. tecunumanii* lowland provenances is either already more suitable or will become more suitable by 2020 (Figure 2).

This analysis concentrated on 2020 climates in order to capture the climate during rotations being planted today. However, the impacts of climate change are expected to become more drastic in the second half of the twenty-first century. The results of this analysis could form the basis for exploring the longer term future of plantation forestry in tropical sites, and evaluate what seed materials are necessary to sustain plantation forestry in Colombia, Brazil and South Africa.

Implications for the conservation of genetic resources

In most plantation areas of Colombia, Brazil and South Africa, seed material of *P. tecunumanii* lowland ecotypes appears to be the best seed choice for wood productivity under the current climate and becomes even more important in the next two decades. However, the analysis also shows the value of diversity, at both the genetic and the species level. Unfortunately, the lowland ecotypes of *P. tecunumanii* in the wild are most threatened by predicted climate change (van Zonneveld et al., 2009*a*). This coincides with studies about the impact of climate change on the natural distribution of other tropical pines that demonstrate that lowland provenances will be most negatively affected by climate change (Sáenz-Romero et al., 2006; van Zonneveld et al., 2009*b*). Appropriate action needs to be taken to conserve these valuable genetic resources. Sáenz-Romero et al. (2006) propose seed transfer of lowland *P. oocarpa* provenances in the wild to higher altitudes in the natural distribution of this species. Another possibility is conservation outside its natural distribution ranges in climate-proofed conservation parks (van Zonneveld et al., 2009*a*). CAMCORE members are currently establishing conservation parks to protect provenances of economically important tree species (CAMCORE, 2009). Further studies could broaden the analysis to look at other factors, and link with economic models to evaluate the true cost of adaptation of plantation forestry and support management plans.

Evaluation criteria for tree performance

The site quality models in this study only incorporate height growth to assess the quality of the sites. This is one of the most important commercial characteristics, but other criteria are also important when evaluating the potential of different provenances. These include stem form, aberrant growth appearances, disease tolerance, resin content and branching or rooting characteristics. Of particular importance is the issue of frequent stem breakage, which is frequently observed in *P. tecunumanii* plantations, where on the worst sites 30–40% of the trees are affected. The propensity for the main stem to break in its upper crown is thought to be the greatest limitation to using *P. tecunumanii* in the tropics and subtropics (Dvorak et al., 2001*a*).

Disease tolerance is another critical characteristic that eventually determines the value of the seed material for future plantation projects. The success of exotic tree species has generally been attributed to effective species–site matching and their freedom from insect pests and diseases in tropical plantations. There is now the fear that climate change will induce catastrophic outbreaks of pests and diseases in native and exotic forest plantations. The consideration of biotic risk factors could greatly improve the applicability of future site quality models.

Conclusions

In this study the need to change the currently used seed material of *P. patula* and *P. tecunumanii* in the existing plantation areas was evaluated to optimize wood productivity in the face of climate change in the next rotations. Overall, no significant changes in wood productivity are predicted. Still, several forestry areas are substantially impacted. In those areas a change to a better adapted seed material is expected to sustain wood products under a changing climate. Provenances of *P. tecunumanii* low-elevation ecotypes are already important sources of seed material and are predicted to be become an even more important seed material by 2020 because of their good performance under the warmer and wetter climate conditions predicted for the future.

The models presented here form the basis for developing site-specific decision support models for selecting planting material under a dynamic climate.

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