

South African Country Study on Climate Change: Vulnerability and Adaptation Assessment for Plantation Forestry

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EXECUTIVE SUMMARY

1. The South African forestry industry is sensitive to climate, for better or for worse. Only 1.5% of the country is suitable for tree crops under the current climate. Much of this area is relatively marginal. The relatively long period between planting and harvest makes tree plantations vulnerable to environmental change. Shifts in the optimum tree-growing location can have a big impact on the profitability of fixed capital investments, such as sawlog and pulp mills.
2. Significant climate change is likely within the next 50 years, as a consequence of human-induced changes in the composition of the atmosphere. An increase in the atmospheric concentration of carbon dioxide is already apparent, and will continue to grow. The predicted changes are of a sufficient magnitude to affect the plantation forestry industry. Many of the potential impacts are negative, and some are positive. Climate change will become an increasingly important issue to the forestry industry, but will remain secondary to the more important changes brought about by political, economic and land-use changes.
3. General Circulation Models (GCM) predict scenarios of mean annual temperature increases of 2.5 - 3.5° C and reduced rainfall during the 21st century. The rainfall predictions are less reliable than temperature predictions. These changes have the potential to alter the distribution of optimum planting areas for current cultivars of the major tree crop species (e.g. *Pinus patula*, *Pinus elliottii*, *Pinus taeda*, *Pinus radiata*, *Eucalyptus grandis*, *Eucalyptus saligna*, *Eucalyptus nitens*, *Accacia mearnsii*), and the competition for land with other potential users (e.g. subtropical fruits, dryland agriculture, biodiversity conservation, etc.) will increase. Greater clarity on the location and intensity of climate change will be forthcoming in the next decade as better models become available. Immediate action to alter the current distribution of tree plantation land is premature. Instead increased effort should be focused on developing new genetic hybrids (e.g. resistance to heat stress and drought tolerance) and in understanding site-species-climate relationships needed to take rational planning decisions once better climate predictions become available.
4. The results of forest growth models suggest that if the climate changes to the degree predicted, and if no action is taken to select and plant heat tolerant cultivars, there will be substantial loss of production in the core area of current forestry, particularly in *Pinus patula* and *Pinus radiata* plantations.

1. TERMS OF REFERENCE

This analysis and report was commissioned by the National Research Foundation (NRF) for the Department of Environmental Affairs and Tourism as part of the National Climate Change Commission (NCCC) studies on vulnerability and adaptation of South African ecosystems and economic sectors to potential climate change. It is part of a process of examination of the potential impacts of possible climate change on all aspects of the South African environment, and economy. This process is being coordinated by the NCCC and will lead to recommendations to the South African government regarding future risks, opportunities and policy actions.

The following were required of this contract:

1. Database collation of relevant bioclimatic information for the following forestry species: *Pinus patula*, *Pinus elliottii*, *Pinus taeda*, *Pinus radiata*, *Eucalyptus grandis*, *Eucalyptus saligna*, *Eucalyptus nitens* and *Acacia mearnsii*.
2. Utilise afforestation potential models to simulate shifts in current optimal forestry areas due to potential climate change effects.
3. Conduct climate sensitivity studies on selected individual species, i.e. *Pinus patula* and *Eucalyptus grandis*.
4. Assess the productive output of the forest industry under climate change and enhanced CO₂ conditions.

The remainder of this report details the current issues in the industrial tree plantation sector, the biological effects of climate change and CO₂ enrichment on forestry species, provides results of the climate shift scenario, and provides preliminary conclusions and adaptation recommendations.

2. THE IMPORTANCE OF THE FORESTRY INDUSTRY TO THE NATIONAL ECONOMY

Indigenous forests occupy only 0.3% (401 369 ha) of the South African land surface (Fairbanks et al., 1999), and contribute a negligible amount to the timber industry. The other major indigenous wooded biome, savannas, occupies 26.1% (31 642 193 ha) of South Africa, and has a sparse to dense cover of low stature trees and bush (Fairbanks et al., 1999; Low and Rebelo, 1996). They are important suppliers of a variety of goods and services, such as firewood, medicinal plants and wildlife habitat. Tree plantations of exotic species supply the bulk of South African sawlog and pulp needs, and support a major export industry. They occupy 1.5% (1 790 269 ha) of South Africa (Fairbanks et al., 1999), of which roughly half is softwood, and half hardwood. This area has expanded by roughly +/- 60 000 ha per year since 1985 and at substantially higher rates before that (Fairbanks et al., 1999). The industry produces 3 853 000 m³ of sawlogs, 6 421 000 tons of pulpwood, 2 371 000 tons of mining timber, and smaller quantities of matchwood, firewood, and treated poles per annum. The value of timber products is R 1 201.21 million (for 1996; Hassan, 1999). The sector's contribution to GDP amounts to 4.4% of total value added in South Africa. About 70% of its income is derived from export sales.

3. THE 21ST CENTURY AND GLOBAL CHANGE

The most certain aspect of global change is that the atmospheric concentration of carbon dioxide (CO₂) is increasing currently at a rate of 0.4% per year. Even if controls are implemented under the Kyoto Protocol (1998), this rise will continue into the next century, since human emissions will continue to exceed the capacity of the biosphere to absorb them. Under optimistic control scenarios, it will have doubled from the pre-industrial level of 280 ppm by the year 2100. The current atmospheric CO₂ level is 360 ppm, which is higher than it has been at any time in the past 160 000 years (Barnola et al., 1987). A consequence of the accumulating 'greenhouse' gases is a projected increase in global temperature, estimated to be about 2.0 - 3.5° C by the time the CO₂ level reaches double its pre-industrial level. Higher temperatures will lead to changes in precipitation and atmospheric circulation, which are currently hard to predict with acceptable accuracy.

The effect of an elevated CO₂ atmospheric environment is presented here as it affects plant functioning, and how the increased CO₂ causes climate changes with its further effect on the biosphere. The sections present natural systems and their probable changes under a doubled CO₂ environment.

3.1 Plant Functioning and Climate Change

An increase in the atmospheric concentration of CO₂ has effects on net photosynthesis, respiration, development, tissue chemistry and plant water use. It therefore affects the growth rate of the plant (Field et al., 1992). The increase in whole-plant production which is achieved under elevated CO₂ is much less than the increase in photosynthesis.

The amount of growth stimulation that occurs depends on the ability of the plants to use the extra carbohydrates productively. This is controlled by such factors as nutrient availability (including water) and high night temperatures. Recent reviews of the input of doubled CO₂ suggest that under field conditions a growth rate increase of round 10 - 20% is probable (de Lucia et al., 1999), although much higher rates can be achieved in the laboratory (Mooney et al., 1999).

Along with an increase in biomass production, there are many other physiological changes in a plant grown at elevated CO₂. The photosynthetic apparatus generally acclimates partially to the surplus carbon assimilation by reduced enzyme activity, per unit leaf area reduced quantum efficiency or reduced leaf area (Idso, 1999). The allocation of photosynthates shifts in favor of the below-ground organs (roots). This is interpreted as a control mechanism to bring the plant nutrient supply back into balance with the enhanced carbon supply. The higher CO₂ concentrations mean that the stomatal conductance can be lower, while still permitting an adequate CO₂ flux to the mesophyll. This and the reduction in leaf size have the benefit of reducing plant water loss, and thus increasing water use efficiency. Nutrient use efficiency (the dry matter produced per unit of nutrient assimilated) also increases, due to a decrease in tissue nutrient concentration.

It is clear that integrated data over the whole season are necessary to evaluate the complete effect of increased CO₂ concentration. To that single factor has to be added possible climatic change, such as increased temperature and changes in rainfall, which presents a major challenge in ecological research. It is really not clear what the rainfall changes will be at this stage.

3.2 Impacts on Agriculture and Forestry

The world's terrestrial ecosystems constitute a continuum from virtually pristine to intensively managed and highly modified systems devoted to production. Agro-ecosystems fall at the latter end of the spectrum and are essential to human survival. They supply the bulk of humanity's food and fibre, and they cover a large portion of the planet's land area.

Rising temperatures will stimulate crop and forest production in the areas currently cooler than the growth optimum for the species concerned, and reduce it where the crops are already above their optimum. Increased rainfall will almost always increase tree and crop production, and reduced rainfall will decrease it. Increased CO₂ will stimulate crop and tree production to a small degree. Warmer climates will encourage the movement of tropical pests and diseases into temperate regions.

3.3 General Circulation Models

General Circulation Models (GCMs) are computer simulations of the global climate, atmospheric chemistry and oceanic circulation, and are used to explore possible future climates given scenarios of greenhouse gas emissions. At a local scale their predictions are still very crude, but at a regional to global scale they capture the main features of the global climate remarkably accurately, and are improving all the time. All the GCM outputs available to this study (Genesis, CSM, and HADCM2) suggest a general aridification over southern Africa. Predicted scenarios give increased annual mean temperatures of 2.5 - 3.5° C and reduced rainfall.

Greater incidence of drought is relevant to the risks associated with tree plantations. General aridification, due to lower rainfall and higher air temperatures, will affect the optimal areas for the countries primary tree species, and impact the marginal costs associated with planting in sub-optimal areas. Drying and higher temperatures may increase the area lost to fires. The potentially positive effects of increased minimum temperature (reduction in the area prone to killing frosts) and the fertilizing effect of higher atmospheric CO₂ are important ameliorating influences. Temperature, atmospheric CO₂ and rainfall predictions are all critical in forecasting changes in tree plantation yield.

The model results presented are from the United Kingdom Meteorological Office - Hadley Center Unified Model¹ (HadCM2), using the scenario where sulphate emissions drop in the 21st century. The Hadley 'no sulphates' model was used in this study because it is considered to be the most reliable and accepted model in the science community, but it is also considered to provide the most pessimistic of outputs. Thus, it provides us with a worst case scenario. The 'no sulphates' option was chosen because it is likely that increased global regulation of sulphate emissions beginning in the late 1980s will decrease the influence of sulphate aerosols on future global climates.

4. THE SENSITIVITY OF TREE PLANTATIONS TO CLIMATE CHANGE

¹ http://www.metu.gov.uk/sec5/NWP/NWP_sys.html

The South African tree plantation industry is vulnerable to climate change for three reasons:

1. It is a plant-based industry, and plants respond sensitively to climate and atmospheric conditions;
2. The area climatically suitable for exotic tree plantations in South Africa is extremely limited and subject to other land and water use pressures; and
3. Tree cropping has a long planning horizon (+/- 25 years), a long period between the commitment of investment and the realization of profit, and a high sensitivity to transport costs.

This sensitivity is both positive and negative. Small improvements in forest growth rate, or decreases in forest use, could be very beneficial.

4.1 Timber Production

The productivity of plants, including agricultural crops and plantations species, will be affected in two ways: firstly by the 'CO₂ fertilisation effect', and secondly through climate change. The first is certain to occur to some degree, the second is likely, but of uncertain magnitude and direction.

The CO₂ concentration in the atmosphere has a strong positive effect on photosynthesis. A doubling of CO₂ increases carbon assimilation in C3 plants (such as *Pinus* and *Eucalyptus*) by about 10-20% (Curtis and Wang, 1998). This does not necessarily translate into increased harvestable yield. Except in the most fertile soils, plant growth is usually limited by available nutrients, so increasing the carbon supply does not necessarily lead to increased growth. Secondly, the response of a plant to increased carbon supply relative to nutrient supply is to increase the allocation of growth to roots, as described earlier. It is therefore likely that tree crop yields will increase only marginally, and then only on the sites of highest potential. Exploitation of the increased yield potential would require extensive fertilisation of plantations, with concomitant costs and environmental risks. Plants which rely on mycorrhizal associations for their nutrient supply (such as most pine species) could benefit from the additional carbon availability, with which to promote mycorrhizal growth.

In the absence of an increase in CO₂ and rainfall, increasing temperature would decrease timber yields in South Africa, largely because of increased water stress. Elevated CO₂ will increase plant water use efficiency and tend to cancel this effect.

5. DISTRIBUTION OF COMMERCIAL TREE PLANTATION SPECIES IN RELATION TO CLIMATE

To model the shifts in species optimal envelopes a database of the selected species growth parameters was developed (Appendix 1). These parameters were used in a bioclimatic analysis (along with available broad soils information (ARC Institute for Soil, Climate and Water, 1995)). A fuzzy logic technique was used to determine the optimum growth regions for each species (as described by Fairbanks and McKelly, 1994; Fairbanks, 1995; Fairbanks and Smith, 1995; Fairbanks, 1997; Fairbanks et al., 1997; Fairbanks *to be subm.*). It is widely accepted that the distribution of species shows a unimodal response to environmental variables. This basic ecological observation, popularised as the ‘Gaussian curve’ (Gauch and Whittaker, 1972) states that each species thrives best at a particular optimum value of an environmental variable and cannot survive when the value is either too low or too high. Plant species distribution and their associated abundance typically operate along lines of climatic gradients from which plot data can be obtained, and the resultant smoothed curves (Gaussian or sigmoidal) taken as species response functions (Whittaker, 1967; Westman, 1991). Fuzzy set logic as a method in geographic distribution analysis can characterize the climatic response of species by approximating the Gaussian curves commonly found from direct gradient analysis. Thus, the approach is able to mimic ecological niche theory and provide an improved surface of potential distribution of a species over simple Boolean overlay logic (Fairbanks *to be subm.*), potential growth matrices (Louw, 1995), or regression analysis (Smith, 1996).

As the resolution of the climate change scenarios are quite crude in comparison to the available climatic data, the computer simulation approach is most useful in demonstrating the areas of climatic sensitivity, rather than making detailed predictions of future growth areas. For this analysis the current climatic data from the Computer Center for Water Research (CCWR) was shifted up or down using the GCM model coarse-scale output. All species except *Pinus radiata* were modelled with shifts in temperature and precipitation, as these species are considered to be summer rainfall trees of the Northern, Mpumalanga, KwaZulu-Natal and Eastern Cape provinces. *Pinus radiata* is a winter rainfall pine grown in the Western province, where rainfall and soils are the most important factors limiting its production (Fairbanks and Smith, 1995; Joshua Louw pers. comm. 1995), therefore a change in temperature was not applied in its

analysis.

Application of the climate shift method with the available modelling technique to *Pinus patula*, *Pinus elliottii*, *Pinus taeda*, *Pinus radiata*, *Eucalyptus grandis*, *Eucalyptus saligna*, *Eucalyptus nitens* and *Acacia mearnsii* indicates that the optimum growing areas for the eight tree species are sensitive to climate change within the range predicted for next century. Two scenarios from the Hadley no sulphate model were applied to each species. In the first scenario the temperature is shifted with no change in precipitation, and in the second both a change in temperature and a (generally decreasing) shift in precipitation is simulated (Appendix 2).

The analysis which follows applies to current cultivars. There is substantial potential for selecting more temperature-tolerant cultivars within these species, and sufficient time and expertise to do so.

The climate thresholds used in these simulations are limits of economic viability, rather than absolute biological limits (Fairbanks, 1995; Fairbanks and Smith, 1995; Fairbanks, 1997). It may still be possible to grow plantation species in their current areas under altered climates, especially if the cultivars are adapted, but at lower yields.

This may remain profitable if the global price of wood products rises faster than the rise in input costs. It is highly probable that more lucrative land uses, such as sub-tropical fruits, may under altered climate compete for land currently under tree plantations. Human and de Munnik (1996) found that sub-tropical fruits such as, avocado and pecan nuts, show large positive increases in area with increasing temperature, which corresponds to a westward and uphill shift in potential distribution. Therefore, a changing climate would seem to favor subtropical fruits rather than pure strain tree plantation species.

Pinus patula

This species is sensitive to both temperature and rainfall. An increase in average air temperature or a decrease in rainfall results in a severely reduced optimum growth area for this tree species. The potential for this species is almost completely removed from the Northern and Eastern Cape provinces under this scenario. Its remaining areas of production include the northern KwaZulu-Natal Drakensberg, Vryheid and Empangani areas and smaller higher portions of the Mumpalanga Drakensberg escarpment.

Pinus taeda

An increase in temperature results in only a slight decrease in optimum growth areas for Northern, Mpumalanga, and KwaZulu-Natal provinces. There is a slight increase in optimum growth areas for the Eastern Cape province. A future decrease in rainfall almost eliminates this species from the Eastern Cape province, except along the Lusikisiki coast. The majority of the much reduced optimal areas are in the higher altitude regions of the KwaZulu-Natal midlands and northern Drakensberg, as well as the Mpumalanga escarpment, Tzaneen and Soutpansberg regions. This species is more sensitive to rainfall than temperature.

Pinus elliottii

This species had a positive increase in optimum growth areas with an increase in temperature with the loss of coastal growth areas compensated by new growth areas in the interior, especially in the southern KwaZulu-Natal Drakensberg region. A decrease in rainfall with temperature has a large decrease in the optimum growth areas, evident in the eastern portion of the Eastern Cape province, the southern KwaZulu-Natal Drakensberg and midlands, and in southern Mpumalanga around Piet Retief. This species seems more sensitive to changes in rainfall than the other two summer rainfall species.

Pinus radiata

This species has a small optimum area for growth under the current climate. It has been planted in many sub-optimum areas in the Western Cape. The region is considered to be of low productivity for this species internationally (Gary Drobnack, Weyerhaeuser Intl., pers. comm. 1998). Current production of this species reflects an historical anomaly, rather than a profitable land-use decision. A future decrease in precipitation will eliminate the current optimum areas and make this species even less financially rewarding in the Western Cape.

Eucalyptus grandis

An increase in temperature significantly favors this species in Mpumalanga and KwaZulu-Natal provinces. However, a decrease in rainfall significantly lessens the positive result. This species is sensitive to both changes in temperature and rainfall.

Eucalyptus saligna

A temperature increase has a sharp negative response in KwaZulu-Natal, Mpumalanga, Eastern Cape and especially the Northern provinces. A decrease in rainfall restricts this species mainly to the KwaZulu-Natal central and northern Drakensberg and Vryheid areas and to a small strip along the Mpumalanga escarpment. The species would no longer be commercially viable in the Northern Province. This species is both temperature and rainfall sensitive.

Eucalyptus nitens

An increase in temperature would radically restrict this species to the northeastern Eastern Cape province and to the southern and central KwaZulu-Natal Drakensberg regions, with small pockets near Volksrust and Belfast. The species would not be viable in any of the high altitude areas of the Northern province. A decrease in rainfall only slightly reduces the singular temperature scenario. This species is very sensitive to changes in temperature.

Acacia mearnsii

This species shows only a strong decrease in its optimum growth area with an increase in temperature. A decrease in rainfall shrinks the optimum area to mainly the KwaZulu-Natal midlands, central and southern Drakensberg, Vryheid and along the Mpumalanga escarpment. This species is sensitive mainly to temperature and less so with changes in precipitation.

5.1 Simulated impacts under climate change and CO₂ enrichment

The model used for this analysis was CENTURY (Metherell et al., 1998; Parton et al., 1998). It is a model of carbon and nitrogen dynamics in grassland and forest biomes, and has been extensively used and validated around the world. The representative study site chosen represents a typical tree plantation on the Mpumalanga escarpment near to Sabie.

Monthly rainfall, maximum and minimum temperature data for the simulation site were obtained from the CCWR. The predicted changes in mean monthly rainfall, maximum and minimum temperature in 2050

relative to the simulated present from the Hadley model (no sulphates) were then used to construct a linear climate change ramp for these variables, starting in 1990 and leveling out in 2050, then continuing until 2250. The historical data (1955 to 1983; Dr R de Wet weather station) was used as a repeating template to ensure that realistic variability was preserved in the simulated data.

The initial soil carbon values, corresponding to the montane grasslands which existed before the plantations were established, were obtained by running a 2000 year equilibration using the mean present climate for the sites. The simulations were performed beginning in 150 AD, and running to 1954 assuming a fire regime of triennial winter burning and light grazing. From 1955 onwards the grassland was converted to either *Pinus patula* or *Eucalyptus grandis* plantations. Simulations were conducted with and without the CO₂ effect enabled. This is a theoretical exercise, since rising CO₂ will always accompany changes in climate, but is performed to understand the different mechanisms at work.

The physiological responses of the needle leaf (*Pinus*) and broad leaf (*Eucalyptus*) trees to elevated CO₂ were mimicked within CENTURY by adjusting certain key parameters. The change in these parameters at 700 ppm relative to 350 ppm is automatically scaled to the prevailing CO₂ by the model. Assimilation rate at 700 ppm was set to 1.2 times the rate at 360 ppm, transpiration rate to 0.7, and the C:N ratio was widened by 1.3 times. When the effect of rising CO₂ was simulated, it was linearly increased from 360 ppm in 1990 to 550 ppm in 2050, and then kept at that level until 2250. This corresponds to the IPCC 92e scenario up until 2050, followed by an equilibration period to investigate longer-term phenomena.

Pinus patula: Frankfort plantation, Sabie, Mpumalanga

The data, on which this analysis was based, was supplied by Dr. Peter Dye, CSIR Division of Water, Environment and Forestry, Pietermaritzburg. He has conducted a soil water holding capacity experiment on Safcol's Frankfort plantation, east of Sabie (-24.8167 S, 30.7167 E, 1400m). The mean annual rainfall at the site is 960 mm, of which 80% falls in October to March. The mean annual temperature is 15.0° C, with a July nighttime mean minimum of 3.6° C and a January daytime mean maximum of 23.6° C. The site is on granite geology, with soil texture of sand 78%, silt 9%, and clay 13%.

From 1955 to 2250, a 25 year rotation was simulated with a 1 year rest in between harvest and planting. *Pinus patula* was simulated using two different sets of operating temperature regimes to understand the temperature sensitivity of the species. Simulation one was set with an optimum temperature of 18° C and a 30° C limiting temperature at which the point the plant theoretically shuts down photosynthesis.

Simulation two was set with an optimum temperature of 18° C and a 25° C limiting temperature.

The predicted changes in climate are given in Table 1. Note that according to the Hadley (no sulphates) model, the temperature is predicted to increase substantially (~3° C) and the rainfall total decreases by 54mm (4%). The winter rainfall increases while the late summer rainfall decreases.

Table 1. Predicted absolute changes (2050 minus 1990) in rainfall (mm) and temperature (°C) at Frankfort plantation over the period 1990-2050 using the Hadley simulation (no sulphate).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain	-3.4	-1.5	3	-34	-15	8.5	2.3	8.9	-13.1	-4.7	-8.3	3.4
Tmin	2.7	2.8	2.7	4.2	4.2	2.8	2.5	2.4	2.4	3.3	3.1	1.9
Tmax	2.9	2.8	2.7	4.2	4.2	2.8	2.5	2.4	2.4	3.3	3.1	1.9

The simulated productivity results (Table 2) show how sensitive the outcome is to the temperature limit for *Pinus patula*. A 30° C limit and higher temperatures would lead to a 23% increase in wood production and a gain of soil organic matter (Appendix 3). The rising CO₂ almost exactly mimics the climate impacts (Appendix 3). Production increases by 25% by 2050 (this increase must be evaluated against an interannual variability of 30%). The stabilization in production after CO₂ and climate are stabilized indicate that the soil carbon and nitrogen content are in approximate equilibrium with the altered climate by 2050. The inference which can be drawn from this is that increased nitrogen mineralization from the increase in soil temperature will create a spurt of yield between now and 2050, and will stabilise in the long term once CO₂ levels have been stabilised. The carbon stored in the system will increase by 41% in the short-term, and 37% in the long term if atmospheric stabilisation occurs at 550 ppm.

Table 2. Summarised results of the two simulations for altered climate, and altered climate plus altered [CO₂], at Frankfort plantation for *Pinus patula*. Means for 25 year rotation periods.

Period	Climate change only (limits 30° C / 25° C)	Climate change and CO ₂ enrichment (limits 30° C / 25° C)
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	Aboveground NPP (gC/m ² /y)	Soil organic carbon(gC/m ²)	Aboveground NPP (gC/m ² /y)	Soil organic carbon (gC/m ²)
1955-1980	94.4 / 31.4	2960 / 2316	94 / 31.4	2960 / 2316
2050-2075	123 / 0.83	4120 / 1528	126 / 1.7	4194 / 1606
2225-2250	121 / 0.34	3980 / 700	124 / 0.35	4066 / 704

A 25° C limit and higher temperatures would lead to a severe (97%) decrease in wood production and a concomitant decrease of soil organic matter (Appendix 3). The same pattern is shown when CO₂ is involved (Appendix 3). Production decreases by 94% by 2050, and continues to drop for the next two centuries. The continued drop in production is because the soil carbon and nitrogen content are not in equilibrium with the altered climate by 2050, and continue to fall, releasing nitrogen. The inference which can be drawn from this is that carbon sequestration will drop between now and 2050, and will continue to drop in the long term once CO₂ levels have stabilised. The carbon stored in the system will decline by 30% in the short term, and 69% in the long term.

The site studied on the Frankfort plantation is shown to no longer be an optimal area for economic *Pinus patula* production after a climate change (Appendix 2). The exact magnitude of loss of production depends on the upper temperature limit for *Pinus patula* growth.

This is not known precisely. Current cultivars are *economically* unsuitable above about 25°C, but will continue to grow at higher temperatures. Genetic selection for temperature tolerance could increase the upper limit.

Eucalyptus grandis: Frankfort plantation, Sabie, Mpumalanga

Eucalyptus grandis was simulated using one operating temperature regime. Simulation was set with an optimum temperature of 22° C and a 30° C limiting temperature at which the point the photosynthesis is equal to plant respiration. From 1955 to 2250, a 12 year rotation was simulated with a 1 year rest in between harvest and planting.

Table 3. Summarised results of the simulation for altered climate, and altered climate plus altered [CO₂], at Frankfort plantation for *Eucalyptus grandis*. Means for 12 year rotation periods.

Period	Climate change only (limits 30° C)		Climate change and CO ₂ enrichment (limits 30° C)	
	Aboveground NPP (gC/m ² /y)	Soil organic carbon(gC/m ²)	Aboveground NPP (gC/m ² /y)	Soil organic carbon (gC/m ²)
1955-1967	206	3186	206	3197
2050-2062	107	1509	105	1503
2225-2237	102	1106	100	1099

The simulated productivity results (Table 3) show that the higher temperatures would lead to a 48% decrease in wood production and loss of soil organic matter (Appendix 3), even under elevated CO₂ (Appendix 3). Production decreases by the same amount by 2050 (this decrease is of similar magnitude to the interannual variability of 30%), and continues to decrease for the next two centuries until finally stabilising in 2250. The continued drop in production is because the soil carbon and nitrogen content are not in equilibrium with the altered climate by 2050, and continue to fall, releasing nitrogen. The carbon stored in the system will decline by 53% in the short term, and 65% in the long term. As with *Pinus patula*, this finding is highly dependent on the unknown upper temperature limit for *Eucalyptus grandis*. *Eucalyptus grandis* is a montane species in Australia, and not highly adapted to high temperatures. Selection of heat tolerant cultivars, and crossing with warm-area species such as *Eucalyptus terreticornis* or *Eucalyptus urophylla* could allow this upper limit to be shifted somewhat higher than 30° C.

6. POLICY ADAPTATIONS FOR THE FORESTRY INDUSTRY

In examining the implications of possible global change for forest policy, two broad questions were addressed:

1. What processes in tree cropped ecosystems are sensitive to physical and chemical changes in the atmosphere?
2. How will future physical and chemical climate changes influence the structure, function, and productivity of forests (How serious is the problem)?

It is clear from the analyses presented here that climate change will pose challenges to the South African tree plantation industry and the consequences should be viewed in a serious manner. There are several implications for management in designing alternative activities to achieve long-term sustainable yield.

A sound strategy should be developed with regards to the future afforestation of higher altitude cooler sites, keeping in mind the serious direct impacts on water supply and biodiversity. Plantation forestry is a stream flow reduction activity (Scott et al., 1998) and creates reduced biodiversity landscapes (Armstrong et al., 1998), thus the likely future release of forestry permits in these higher cooler areas of the country is limited. Instead the emphasis should be placed on tree breeding techniques that directly address plant stress physiology through new species hybrids and gene selection. The results presented here, although preliminary, show quite clearly that the pure species breeds will have reduced bioclimatic niche spaces and their current areas will provide an environment of decreased wood yields. Forestry companies that are not already active with genetic engineering programmes should do so within the next decade with an increased emphasis on trees withstanding higher temperatures and less intercepted rainfall. The purchasing of new lands would be too reactive and premature, especially based on the crudeness of the GCM models currently in practice.

The forestry industry should actively pursue the opportunity, which may become available in terms of the Joint Implementation of Clean Development Mechanism provisions of the Kyoto Protocol, to market the carbon sequestration potential of afforestation projects (Christie and Scholes, 1995).

7. CONCLUSION

It will be important to maintain a strategic watching brief on developments in the field of global climate prediction and provide research support for those projects in the area of climate change which are tree plantation-forestry related and where research cannot be imported without local adoption. Any strategic planning should include a tree breeding programme which has higher temperatures as a selection criterion.

It will be important to advance the study done here to understand the response of the tree species and weeds to changes in climate. This will entail the identification of the mechanisms of inter- and intra-specific interactions, both above and below ground for trees and competing vegetation.

An understanding of the possible impacts of plantation pests and diseases under altered temperature and moisture regimes is required. The impact of water availability on tree growth and landscape patterns must be evaluated.

These further research requirements relating to global climate and atmospheric change within the South African tree plantation industry must be prioritised and a sound research, development and implementation plan based on well-defined objectives instituted in cooperation with the corporations and communities affected.

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Appendix 1. *Pinus* spp., *Eucalyptus* spp., and *Accacia mearnsii* tree growth parameters and modeling technique (after Fairbanks 1995; Fairbanks & Smith 1995; Fairbanks 1997; Fairbanks et al., 1997; Fairbanks, to be submitted).

Pinus patula

VARIABLES	Low end - 50% suitability	100% suitability	High end - 50% suitability
Mean annual precipitation (mm)	850	1050	18.5
Mean annual temperature (°C)	12	15-18	
Mean January (°C)			
Mean July (°C)		< 22	
Mean minimum July (°C)			

Pinus taeda

VARIABLES	Low end - 50% suitability	100% suitability	High end - 50% suitability
Mean annual precipitation	850	1050	22
Mean annual temperature	13	15-20	
Mean January		< 26	
Mean July		> 8	
Mean minimum July			

Pinus elliottii

VARIABLES	Low end - 50% suitability	100% suitability	High end - 50% suitability
Mean annual precipitation	800	950	22.5
Mean annual temperature	14	15-20	
Mean January		< 27	
Mean July		> 10	
Mean minimum July			

Pinus radiata

VARIABLES	Low end - 50% suitability	100% suitability	High end - 50% suitability
Mean annual precipitation	750	1000	
Mean annual temperature			
Mean January			
Mean July			
Mean minimum July			

Note: Due to the complex nature of soils in the winter rainfall regions, relatively little emphasis is placed on climatic variation. The influence of the latter on tree growth seems to be overridden by soil variation. Although strong gradients in rainfall do occur, temperature variation is not as conspicuous as in the other regions, mainly because of the Mediterranean climate type and limited variation in altitude. For this reason, temperature does not form part of the proposed climatic classification for these regions.

Eucalyptus grandis

VARIABLES	Low end - 50% suitability	100% suitability	High end - 50% suitability
Mean annual precipitation	850	1000	24
Mean annual temperature	17	18-22	
Mean January		< 30	
Mean July		>= 11	
Mean minimum July		> 4	

Eucalyptus saligna

VARIABLES	Low end - 50% suitability	100% suitability	High end - 50% suitability
Mean annual precipitation	800	850	20
Mean annual temperature	14.5	15.5-19	
Mean January		=< 21.5	
Mean July			
Mean minimum July		> 1	

Eucalyptus nitens

VARIABLES	Low end - 50% suitability	100% suitability	High end - 50% suitability
Mean annual precipitation	650	850	16.5
Mean annual temperature	10	13-16	
Mean January			
Mean July			
Mean minimum July		> -2	

Acacia mearnsii

VARIABLES	Low end - 50% suitability	100% suitability	High end - 50% suitability
Mean annual precipitation	650	750-1200	1400
Mean annual temperature	13	16-19	22
Mean January		10-22	
Mean July			
Mean minimum July		> 2	
Mean maximum January		=< 28	

Appendix 2. Species climate shift sensitivity diagrams.

Fig. 1. Current and future distributions of *Pinus patula*.

Fig. 2. Current and future distributions of *Pinus taeda*.

Fig. 3. Current and future distributions of *Pinus elliottii*.

Fig. 4. Current and future distributions of *Pinus radiata*.

Fig. 5. Current and future distributions of *Eucalyptus grandis*.

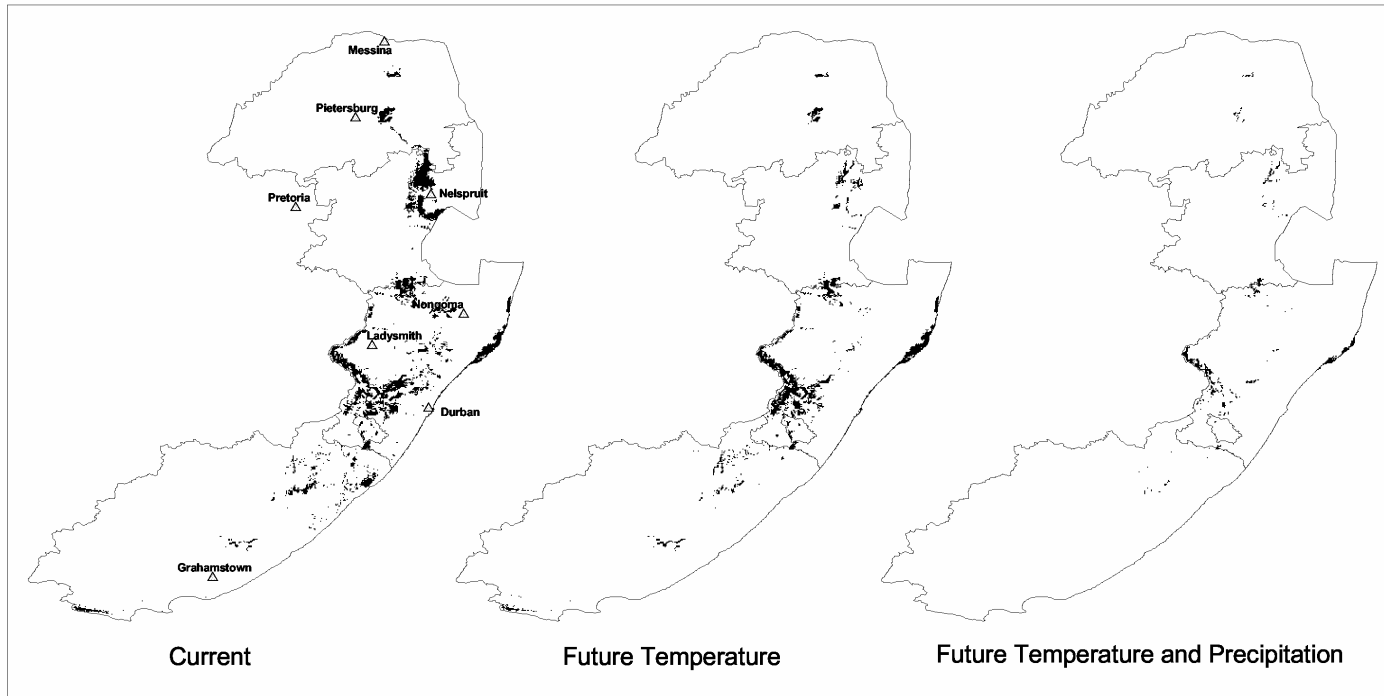
Fig. 6. Current and future distributions of *Eucalyptus saligna*.

Fig. 7. Current and future distributions of *Eucalyptus nitens*.

Fig. 8. Current and future distributions of *Acacia mearnsii*.

Pinus patula

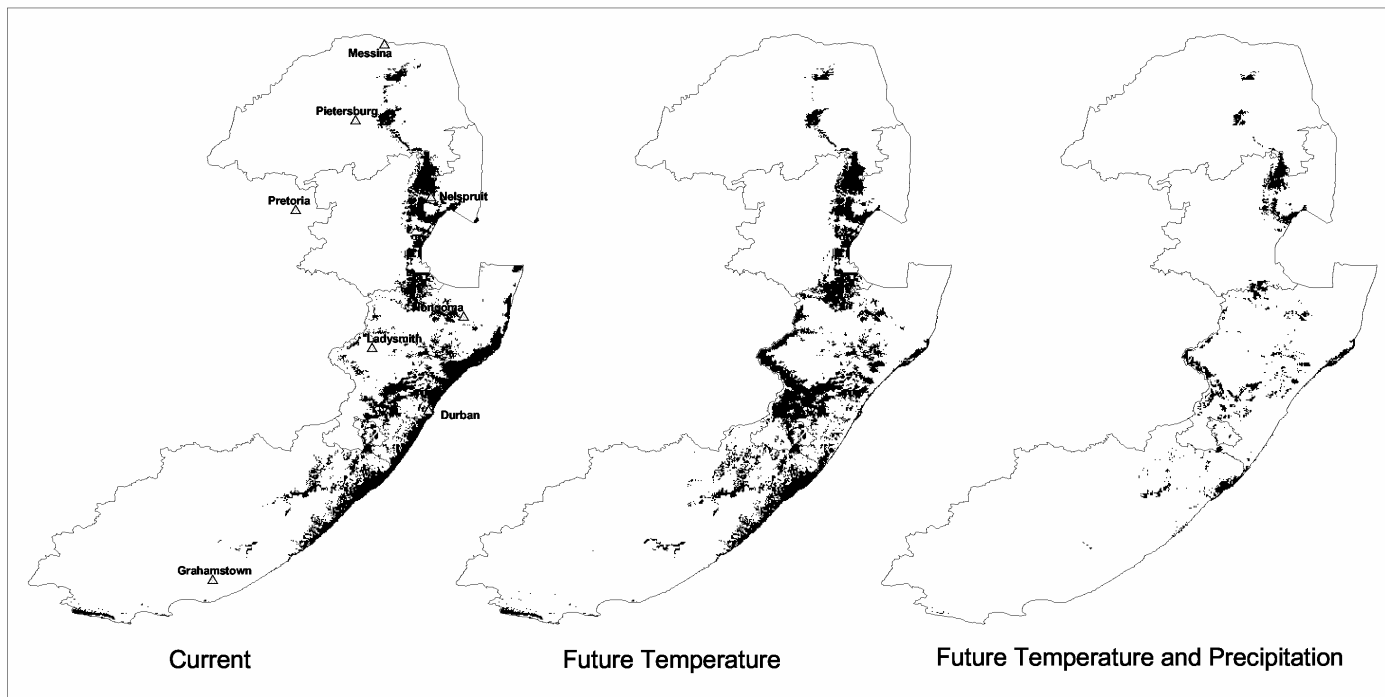
Optimal Afforestation Suitability Potential: Current, Under Future Temperature, and Under Future Temperature and Precipitation Conditions (Hadley no sulphates)



100 0 100 200 300 400 500 600 700 800 900 1000 Miles

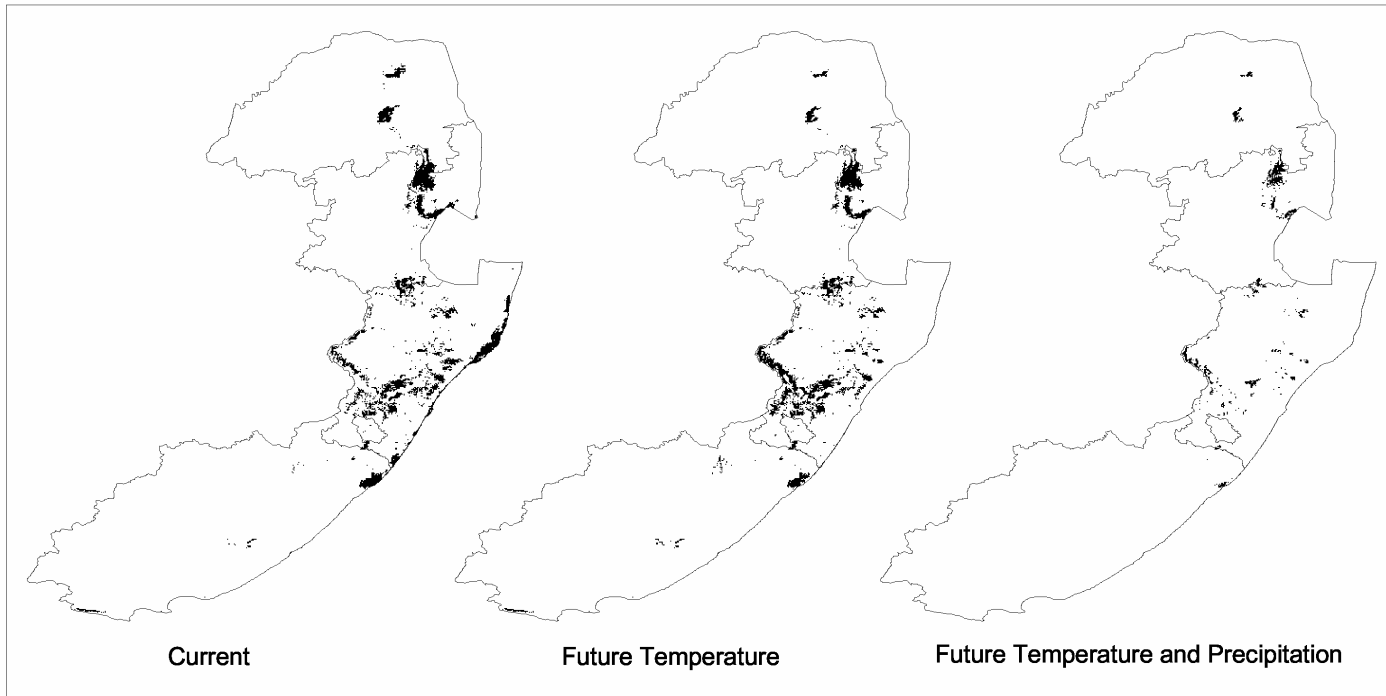
Pinus elliottii

Optimal Afforestation Suitability Potential: Current, Under Future Temperature, and Under Future Temperature and Precipitation Conditions (Hadley no sulphates)



Pinus taeda

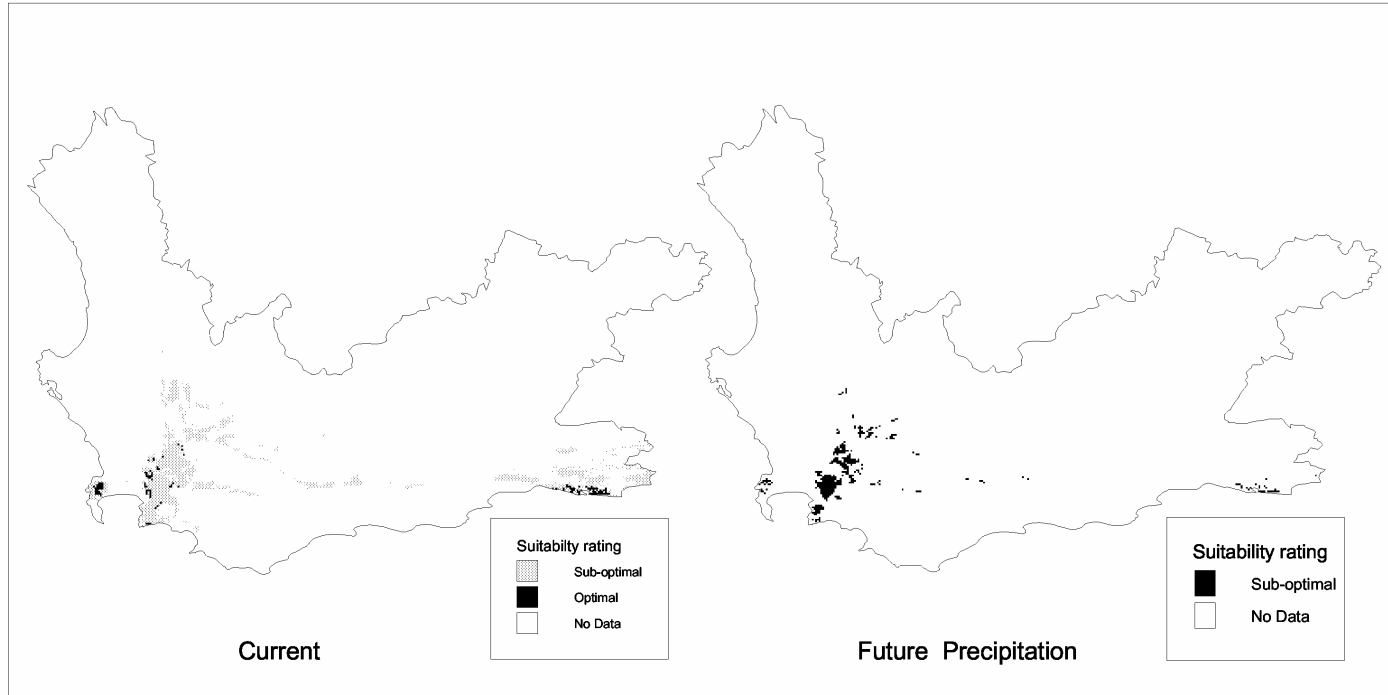
Optimal Afforestation Suitability Potential: Current, Under Future Temperature, and Under Future Temperature and Precipitation Conditions (Hadley no sulphates)



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Pinus radiata

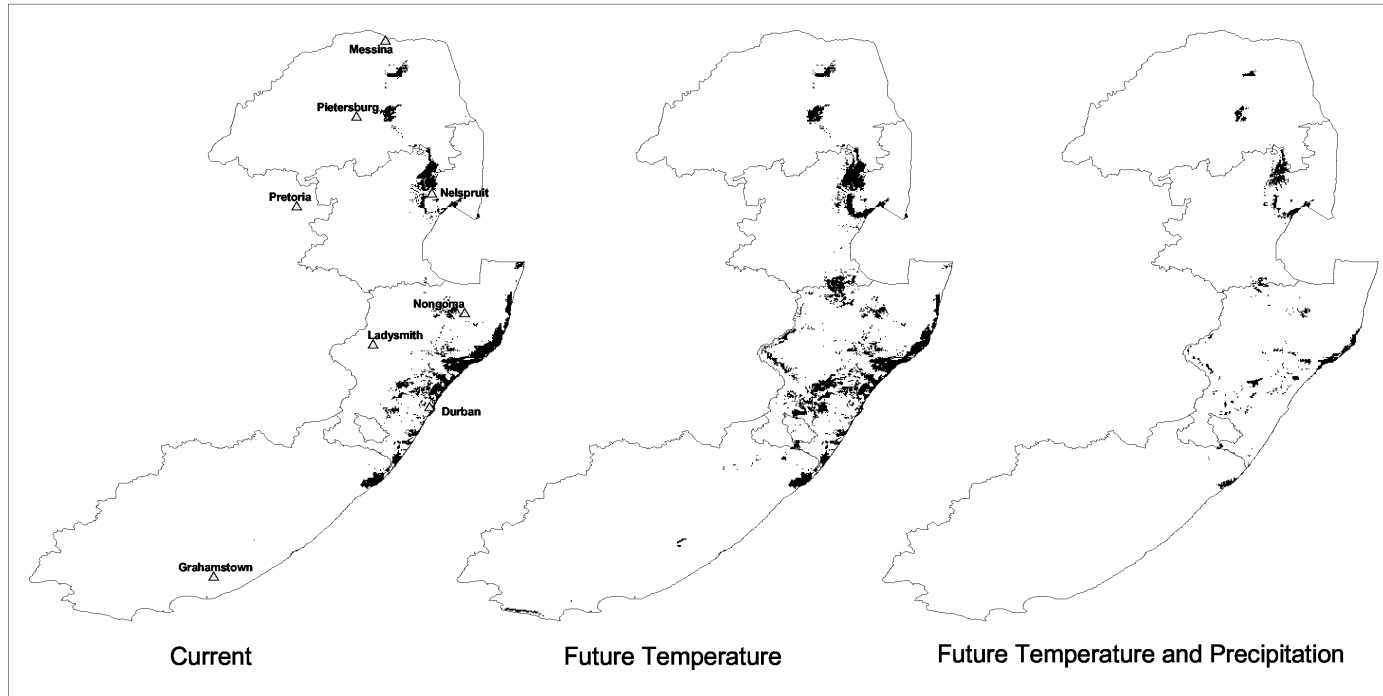
Afforestation Suitability Potential: Current and Under Future Precipitation Conditions (Hadley no sulphates)



100 0 100 200 300 400 Kilometers

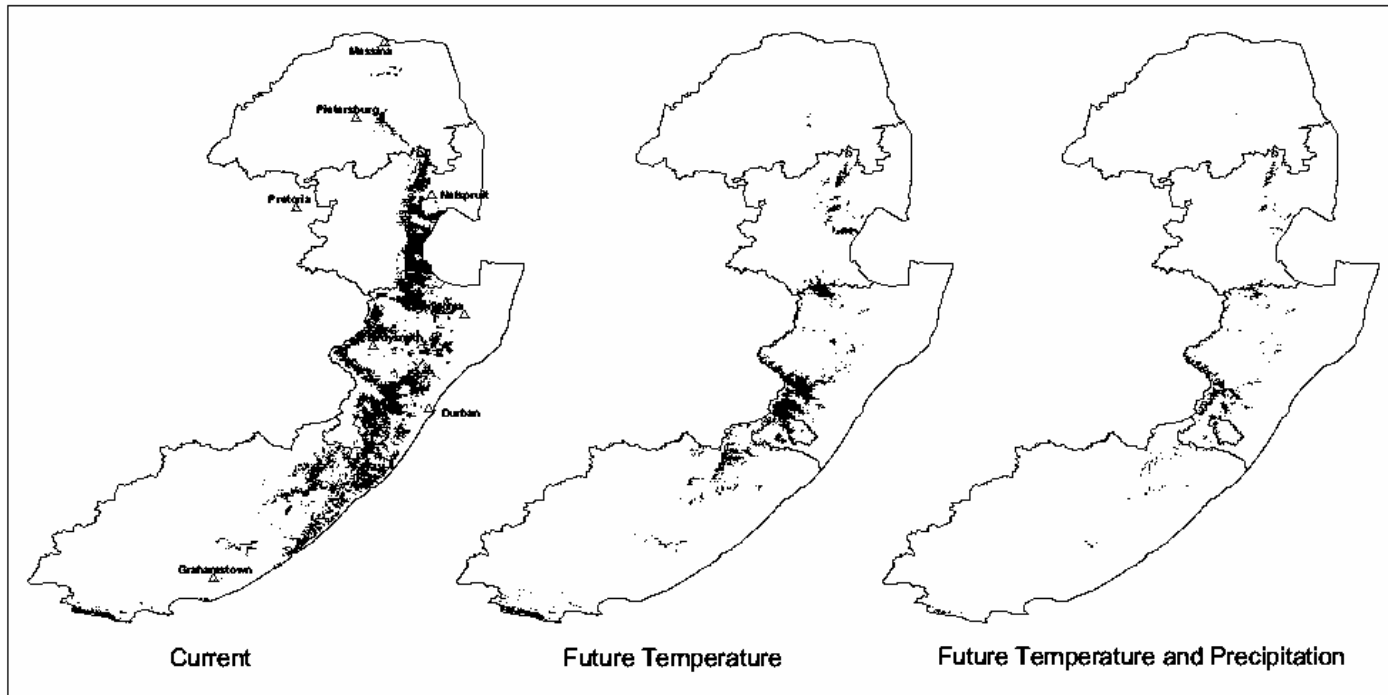
Eucalyptus grandis

Optimal Afforestation Suitability Potential: Current, Under Future Temperature, and Under Future Temperature and Precipitation Conditions (Hadley no sulphates)



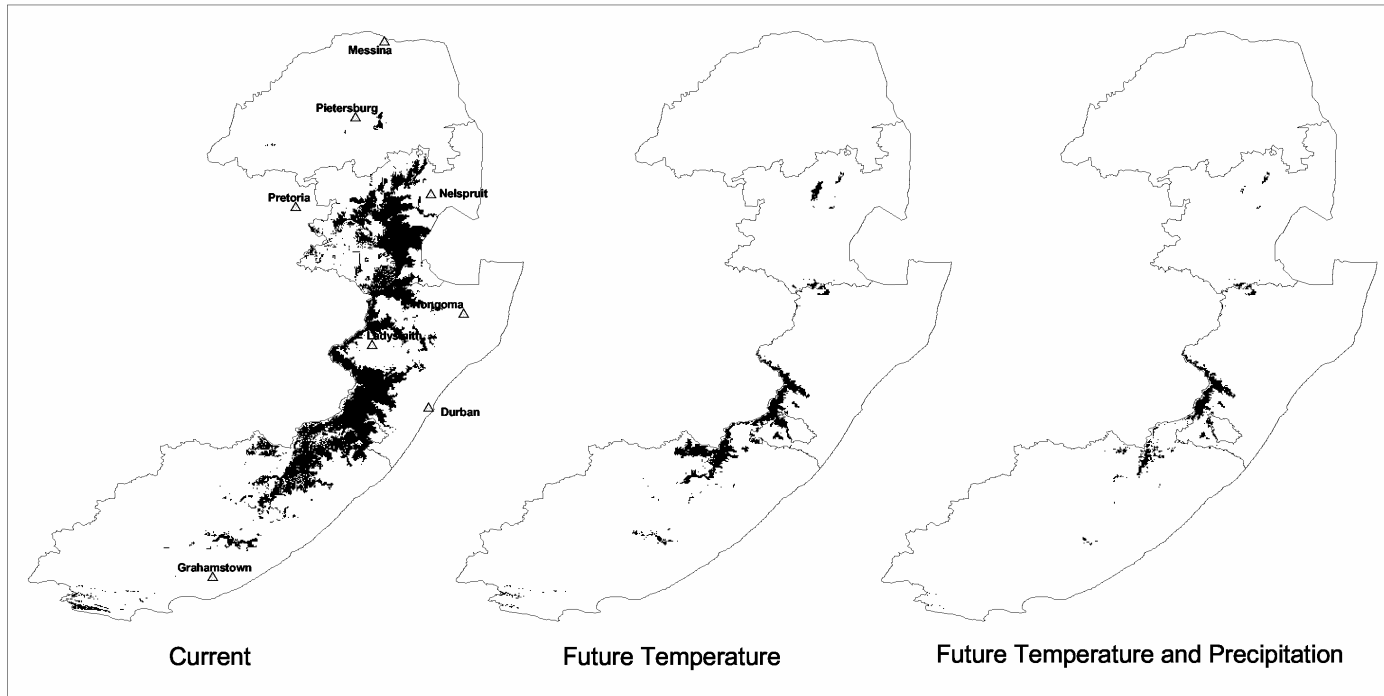
Eucalyptus saligna

Optimal Afforestation Suitability Potential: Current, Under Future Temperature, and Under Future Temperature and Precipitation Conditions (Hadley no sulphates)



Eucalyptus nitens

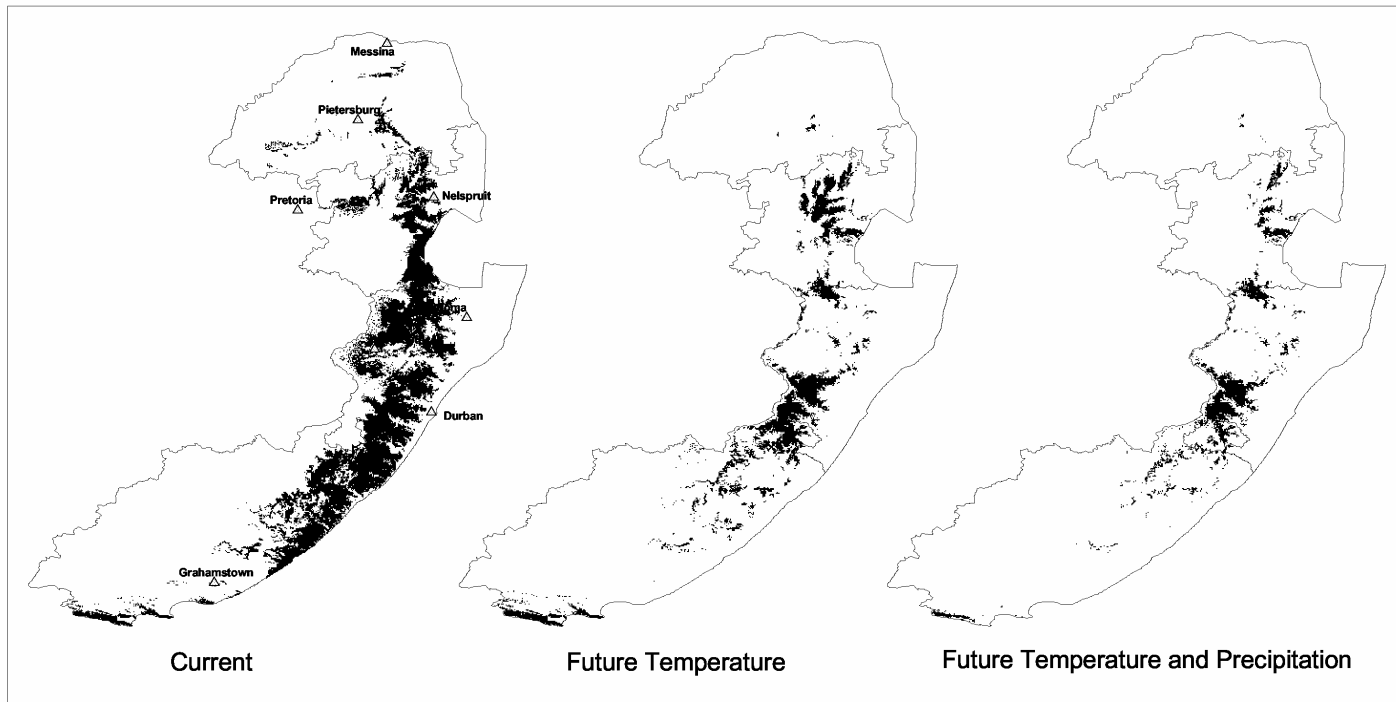
Optimal Afforestation Suitability Potential: Current, Under Future Temperature, and Under Future Temperature and Precipitation Conditions (Hadley no sulphates)



100 0 100 200 300 400 500 600 700 800 900 1000 Miles

Acacia mearnsii

Optimal Afforestation Suitability Potential: Current, Under Future Temperature, and Under Future Temperature and Precipitation Conditions (Hadley no sulphates)



100 0 100 200 300 400 500 600 700 800 900 1000 Miles

Appendix 3. CO₂ and nutrient cycling for *Pinus patula* and *Eucalyptus grandis* under climate change and CO₂ enrichment.

Fig. 1. Simulated soil carbon for *Pinus patula* (30° C limit) with climate change.

Fig. 2. Simulated net primary productivity for *Pinus patula* (30° C limit) with climate change.

Fig. 3. Simulated soil carbon for *Pinus patula* (30° C limit) with climate change and CO₂ enrichment.

Fig. 4. Simulated net primary productivity for *Pinus patula* (30° C limit) with climate change and CO₂ enrichment.

Fig. 5. Simulated soil carbon for *Pinus patula* (25° C limit) with climate change.

Fig. 6. Simulated soil carbon for *Pinus patula* (25° C limit) with climate change.

Fig. 7. Simulated soil carbon for *Pinus patula* (25° C limit) with climate change and CO₂ enrichment.

Fig. 8. Simulated net primary productivity for *Pinus patula* (25° C limit) with climate change and CO₂ enrichment.

Fig. 9. Simulated soil carbon for *Eucalyptus grandis* (30° C limit) with climate change.

Fig. 10. Simulated net primary productivity for *Eucalyptus grandis* (30° C limit) with climate change.

Fig. 11. Simulated soil carbon for *Eucalyptus grandis* (30° C limit) with climate change and CO₂ enrichment.

Fig. 12. Simulated net primary productivity for *Eucalyptus grandis* (30° C limit) with climate change and CO₂ enrichment.

