18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Use of a spatial process-based model to quantify forest plantation productivity and water use efficiency under climate change scenarios

Almeida, A.C.[1], P.J. Sands[2], J. Bruce[1], A.W. Siggins[3], A. Leriche[4], M. Battaglia[1], T. R. Batista[5]

[1] CSIRO – Sustainable Ecosystems, Hobart, TAS, Australia.
[2] 39 Oakleigh Av, Taroona, Tasmania, Australia.
[3] CSIRO – Sustainable Ecosystems, Clayton, VIC, Australia.
[4] CSIRO – Entomology, Black Mountain, ACT, Australia.
[5] Aracruz Celulose, Aracruz, ES, Brazil.
E mail: Auro.Almeida@csiro.au

Abstract: The area of commercial Eucalyptus plantations has expanded dramatically in many countries during the last three decades, and continues to do so. This is causing concerns about the potential impacts of these plantations on water resources and uncertainty about productivity under different environmental conditions.

We present a study where the effects of climate change on the spatial variation in climate are taken into account when predicting potential productivity in terms of dry mass (DM) of wood or mean annual volume of wood increment and water use efficiency (WUE) of hybrids of *Eucalyptus grandis and Eucalyptus urophylla* plantations across more than 32 million ha located near the Atlantic coast of Brazil. Our main objective was to estimate the effects of future climate and increasing CO_2 concentration on planted forests in this region. Predictions of mean annual increment in wood production and of water use efficiency were generated with an updated spatial version of the process-based growth model 3-PG (Landsberg and Waring, 1997). The model has been modified to include the direct effects of increasing levels of atmospheric CO_2 on the vegetation. We assume that light saturated assimilation rate and light use efficiency increase as atmospheric CO_2 concentration increases, while maximum stomatal conductance declines.

The study considered three climatic periods with different CO_2 concentrations: the historical scenario has 350 ppm, while the 2030 and 2050 scenarios correspond to 450 ppm and 520 ppm, respectively. Sensitivity analyses quantified the effects of the parameters used in the model to account for the effects of atmospheric CO_2 on the predicted forest productivity. Stem mass is strongly sensitive to changes in canopy quantum efficiency, and hence to the effect of CO_2 on light use efficiency, but less so to changes in stomatal conductance, and hence to the effect of CO_2 on conductance. WUE, defined here as DM of wood per mass of water evapotranspired, is also sensitive to these parameters.

Analysis of the climatic data for the 2030 and 2050 scenarios in the study area suggests a reduction of 2% and 3% in annual precipitation and an increase of 8% and 15% in vapour pressure deficit in 2030 and 2050, respectively, compared with the period 1971 to 2000. Application of 3-PG with the 2030 and 2050 climates suggests that, averaged over the study area, forest productivity may increase by of the order of 6 $m^3\ ha^{-1}\ year^{-1}$ by 2030, and 10 $m^3\ ha^{-1} year^{-1}$ by 2050, corresponding to 17% and 26% increments compared with the historical period. WUE increases by an average of 1.0g DM kg^{-1} H_2O in 2030 and 1.7 g DM kg^{-1} H_2O in 2050 compared with the historical scenario, which is equivalent to increases of 29% and 51% in WUE, respectively. This shows that with increasing CO_2 the trees are more efficient in using water.

If these changes do occur it will increase the amount of land with higher potential productivity for *Eucalyptus* plantations in the study area. From the total area of 32 million hectares (Mha), 8.5 Mha currently have potential productivity above 40 $m^2\ ha^{-1}\ year^{-1}$. With increasing CO_2 this area increases to 20.5 Mha in 2030 and 26.0 Mha in 2050.

Keywords: *forest growth, process-based model, climate change, increasing CO_2, water use efficiency, Eucalyptus plantation.*

1. INTRODUCTION

Over the last three decades the area under commercial *Eucalyptus* plantations has markedly expanded in many countries, including Brazil where the current area of *Eucalyptus* plantations covers more than 3.7 million ha (Iglesias & Wilstermann, 2008). Concerns about impacts on water resources have been raised (Almeida et al., 2009). At the same time uncertainty of the effect of climate change on productivity has arisen.

Short rotation plantations (6 to 8 years) are particularly susceptible to loss of production, and even death, during drought periods (Almeida et al, 2009; Almeida et al., 2007). Adequate models are needed to quantify the impact of climatic variation on wood production. The effects of climate change, particularly if inter-rotation climate variation increases, may lead to considerable yield uncertainty. The process-based model 3-PG (Landsberg & Waring, 1997) was used to predict potential productivity of these plantations (Almeida et al., 2004b; Landsberg, 2003). However, it did not consider the effects increasing levels of atmospheric CO_2, which limits its application to climate change scenarios (Constable & Friend, 2000). While detailed process-based models do exist that allow exploration of changes in atmospheric CO_2 on production, they are not well suited to broad-scale spatial application.

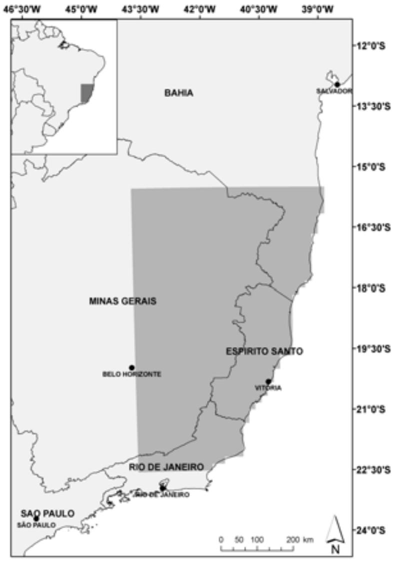

Figure 1 Study area (grey polygon) in Brazil.

Site selection and future management needs to be informed not only by existing biophysical constraints but also by the changes and interactions of these under climate change and elevated CO_2 conditions. Accordingly, 3-PG, which is frequently used to study spatial aspects of forest productivity, was generalised in an attempt to take effects of atmospheric CO_2 into account in a simple manner. A spatial version was then applied to an area on the coast of Brazil where *Eucalyptus* plantations have expanded over the last decade. Questions exist as to the productive potential of this region and the nature of water conflicts now and into the future under climate change scenarios. We estimated the potential productivity under the historical climate and climate scenarios for 2030 and 2050. In doing this we explore the complex pattern of future production in space and time.

2. STUDY AREA

The study area covers 32 million ha in eastern Brazil, covering parts of the states of Espirito Santo, Bahia, Rio de Janeiro, and Minas Gerais (see Fig. 1). More than 500,000 ha of this region is covered with *Eucalyptus* plantations, predominantly hybrids of *E. grandis* x *urophylla*. Plantations are normally grown for pulpwood on a 6-7 year rotation at an average stocking of 1100 trees ha^{-1}. Mean annual growth varies among plantations from 20 to 60 m^3 ha^{-1} $year^{-1}$. Soils are cultivated before planting and fertilizer is applied for the first two years after planting. Weeds are controlled until the canopy closes.

3. MODEL DESCRIPTION AND EFFECTS OF ATMOSPHERIC CO_2 IN 3-PG

The forest growth model 3-PG, described by Landsberg and Waring (1997) and modified and parameterised for *Eucalyptus globulus* by Sands and Landsberg (2002), was parameterised for, and applied to, *E. grandis* grown in part of the study area by Almeida et al (2004a). The spatial 3-PG is presented in Almeida et al. (2009).

Hitherto, 3-PG has not explicitly included effects of atmospheric CO_2 concentration (C_a) on growth or water use, and existing parameters sets are based on data obtained at C_a of about 350 ppm. Numerous experimental and theoretical studies suggest light saturated assimilation rate and light use efficiency increase as C_a increases, while maximum stomatal conductance declines (Ainsworth, & Rogers, 2007). These effects were incorporated into 3-PG through modifications of canopy quantum efficiency α_C and canopy conductance g_C in a manner similar to how other factors (e.g. vapour pressure deficit and soil water content) affecting growth are taken into account, i.e. through growth modifiers. A growth modifier is a function $f(X)$ of a factor X such that $f = 1$ when X is not limiting growth and f declines to zero when the limitation is extreme. However, in the case of C_a, growth increases with increasing C_a while stomatal conductance declines, so the CO_2 growth modifiers will not be bounded by 0 and 1. Separate modifiers are used for α_C and g_C as the effects of atmospheric CO_2 on these are distinct.

3.1. CO_2 growth modifiers for use in 3-PG

Results from gas exchange analyses (Constable & Friend, 2000) suggest light saturated assimilation rate (and hence also α_C) increases with increasing C_a but with a declining rate of increase. We assume this relationship saturates for high C_a. The same gas analyses suggest maximum stomatal conductance declines with increasing C_a, and we assume it declines to zero for high C_a.

Let the growth modifiers applied to the canopy quantum efficiency α_C be $f_{C\alpha}(C_a)$, and that to canopy conductance g_C be $f_{Cg}(C_a)$. These are the ratios of the variable to its value when $C_a = 350$ ppm, and it will be assumed current parameterisations of 3-PG apply to $C_a = 350$. We parameterise the CO_2 growth modifiers by their values $f_{C\alpha 700}$ and f_{Cg700} at $C_a = 700$ ppm and assume the growth modifiers have the form

$$f_{C\alpha}(C_a) = \frac{f_{C\alpha x} C_a}{350(f_{C\alpha x} - 1) + C_a}, \quad f_{Cg}(C_a) = \frac{f_{Cg0}}{1 + (f_{Cg0} - 1)C_a / 350}, \tag{1}$$

where $f_{C\alpha x}$ is the saturated value of $f_{C\alpha}$ for large C_a, and f_{Cg0} is the value of f_{Cg} when $C_a = 0$, and

$$f_{C\alpha x} = \frac{f_{C\alpha 700}}{2 - f_{C\alpha 700}}, \qquad f_{Cg0} = \frac{f_{gx700}}{2 f_{gx700} - 1} \tag{2}$$

express the parameters $f_{C\alpha x}$ and f_{Cg0} in terms of the values $f_{C\alpha 700}$ and f_{Cg700} at $C_a = 700$ ppm.

These relationships were applied to predicted data for α and g_C obtained from runs of a detailed forest growth model CABALA (Battaglia et al., 2004) for a range of different values of C_a at three contrasting sites. Equation (1) gave excellent fits when fitted to these data. This is illustrated in Fig. 2 where α and g_{Sx} have been scaled by their values at $C_a = 350$ ppm at each site. The fitted curves are based on Eq. (1) and (2) applied to the scaled data, and the resulting parameter values are

$$f_{C\alpha 700} = 1.39, \quad f_{Cg700} = 0.69 \tag{3}$$

3-PG has been well tested across a wide range of conditions and species, and the parameter values we used here for *E. grandis x urophylla* hybrids are those developed under current atmospheric CO_2 and applied in the study area by Almeida et al. (2004a, 2009). We also assume the values in Eq. (3) apply for this species.

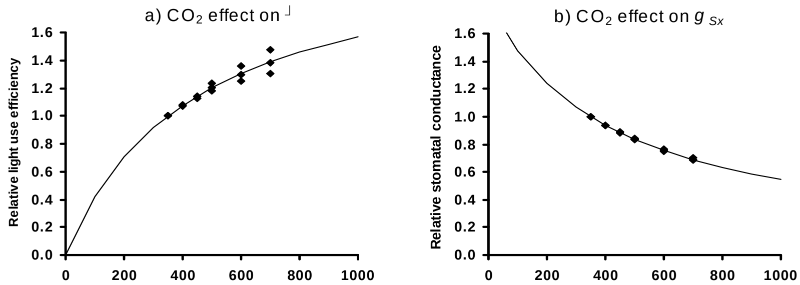

Figure 2. Effect of atmospheric CO_2 concentration on (a) light use efficiency α and (b) maximum stomatal conductance g_{Sx} at three distinct, contrasting sites. Points are output from the CABALA model for *Eucalyptus globulus*, scaled relative to values at $C_a = 350$ ppm for each site. Lines are fits of Eqn (1) to data from all sites, with 93% and > 99% variation explained in α and g_{Sx}, respectively.

4. INPUT LAYERS AND SIMULATIONS

The input surfaces required to run the 3-PG spatial model are:

Climate – monthly precipitation, average temperature, vapour pressure deficit and solar radiation.
Soils – texture, fertility, available soil water.
Detailed soils data were not available for the entire study area. Based on soils data from existing planted areas in the coastal region as described in Almeida et al. (2004a), we assume a standardised soil water holding capacity of 180 mm, and that the soil texture is clay loam. Fertility rating (FR) is an empirical ranking of soil fertility on a scale from optimum (1) to extremely infertile (0), and we adopted FR= 0.75. We recognise these assumptions can be a source of errors in the simulations due to their spatial variation.
The simulations used average monthly climate surfaces over a period of 7 years for temperature, VPD and precipitation for each of the historical, 2030 and 2050 scenarios. We also assumed the full area was planted at the same time.

The historical climate surfaces used 0.5 degree climate normals for 1971-2000. These climate data were calculated from the TS2.0 gridded time series data developed by the University of East Anglia Climate Research Unit (Mitchell et al., 2004). The time series data were first averaged by month for the 30-year period 1971-2000 for the variables of precipitation, mean temperature, and relative humidity. Monthly daylight vapour pressure deficit (VPD) where calculated according to Landsberg (1986). Gridded data were interpolated, converted into rasters and clipped to the study area using ArcInfo and ArcGeostatistical analysis softwares (ESRI). The resulting data is called the historical climate scenario.

Projections of future climate for 2030 and 2050 were based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenario (SRES) using the A1B scenario. We used the global climate model CSIRO Mark 3.0 (CSIRO, Australia) (Gordon et al., 2002) to produce the climate surfaces for 2030 and 2050. The resulting data are called the 2030 and 2050 scenarios. We recognise that disparity exists between model forecasts and SRES scenarios and use the current set as an example. In a more complete exploration, one should run a number of alternative models and scenarios to define the bounds of likely future behaviour.

The historical scenario has C_a = 350 ppm as of 2000, while the 2030 and 2050 scenarios correspond to 450 ppm and 520 ppm, respectively, according to IPCC predictions (IPCC, 2007). The spatial 3-PG was applied across the study area for all three scenarios.

5. RESULTS

5.1. Climate change and effects on productivity

Figure 3 shows seasonal variation of monthly rainfall and vapour pressure deficit for the historical, 2030 and 2050 scenarios. In 2030 and 2050, a slight reduction of annual precipitation (2% and 3%) occurs due to reductions during the dry season, despite an increase in February. Vapour pressure deficit increases in all months (8% and 15%) due to future increases in temperature. Despite these changes, forest productivity is predicted to increase in the study region, particularly in inland regions.

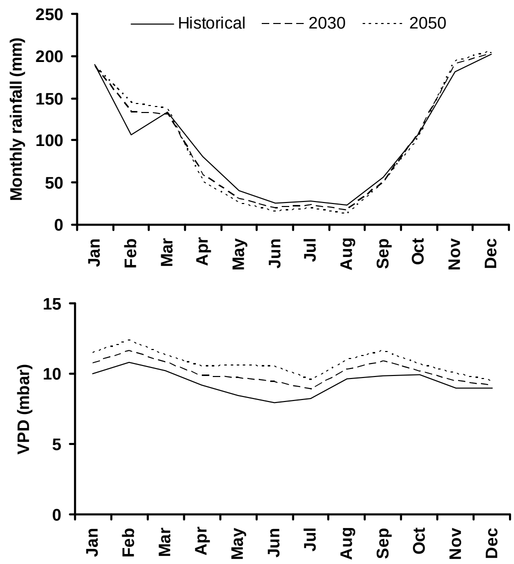

Figure 3. Comparison of seasonal variation of monthly rainfall and average daytime vapour pressure deficit (VPD) for the historic (——), 2030 (— — —) and 2050 (- - -) climatic scenarios.

Forest productivity is mapped across the study region in Fig. 4 in terms of mean annual increment (MAI) defined as volume of wood per ha per year after planting (m^3 ha^{-1} $year^{-1}$)and water use efficiency (WUE) at 7 years. Figure 4 shows the highest productivity areas are concentrated in the coastal region with potential MAI > 50 m^3 ha^{-1} $year^{-1}$. Other studies also show a gradient in forest productivity from the costal to inland regions in Brazil (Almeida et al., 2009). The 2030 and 2050 scenarios suggest significant increases in MAI, mainly in inland areas, with an average increment of the order of 6 m^3 ha^{-1} $year^{-1}$ by 2030 and 10 m^3 ha^{-1} $year^{-1}$ increment by 2050. WUE increases by an average of 1.0 g (DM) kg^{-1}(H_2O) in 2030 and 1.7 g (DM) kg^{-1} (H_2O) in 2050 compared with the historical scenario, showing that with increasing CO_2 the trees are more efficient in using water.

MAI was classified into 5 classes and WUE into 4 classes. Analysis of the changes in area distribution of each MAI and WUE class over the three periods suggests a large fraction of the region shifts to higher productivity. However, the fraction of the region with the highest productivity does not increase, despite a dramatic and sustained shift to high WUE of one class by 2030 and two classes by 2050 as shown by Fig. 5.

5.2. Sensitivity analyses

We performed a sensitivity analysis of predicted stem mass and WUE with respect to atmospheric CO_2, average monthly temperature, VPD and rainfall, all taken separately. These are shown in Fig 6. We also performed a sensitivity analysis with respect to the parameters $f_{C\alpha700}$ and f_{Cg700} that characterise the growth modifiers accounting for the effects of CO_2. The results are shown in Fig. 7. For all sensitivity analyses we used predictions based on the historical scenario as the reference.

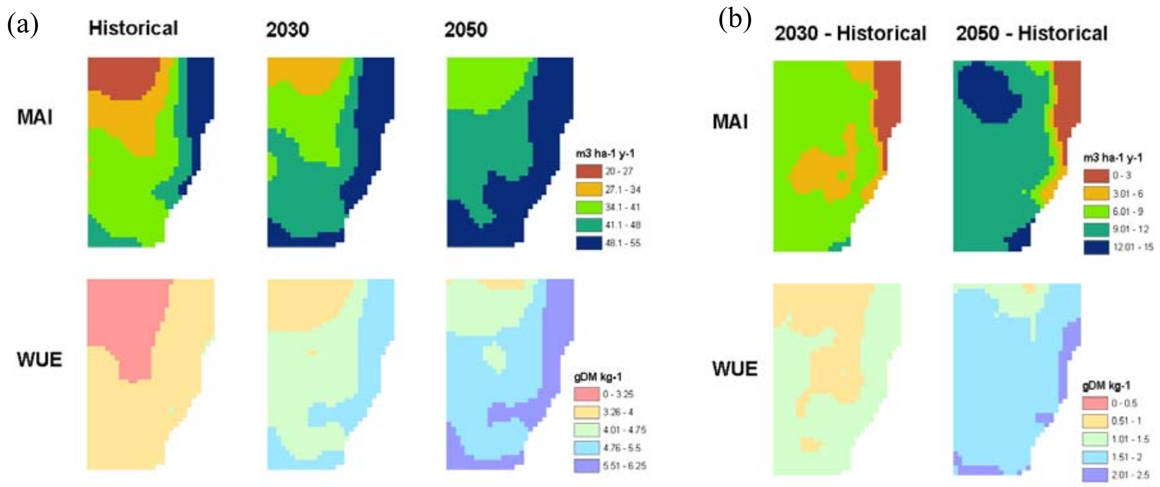

Figure 4. (a) Predicted mean annual increment, MAI ($m^3\ ha^{-1}\ year^{-1}$) and water use efficiency, WUE ($g(DM)\ kg^{-1}(H_2O)$) for historical, 2030 and 2050 climate scenarios and (b) change in predicted MAI and WUE for 2030 and 2050 climate scenarios as compared with the historical scenario.

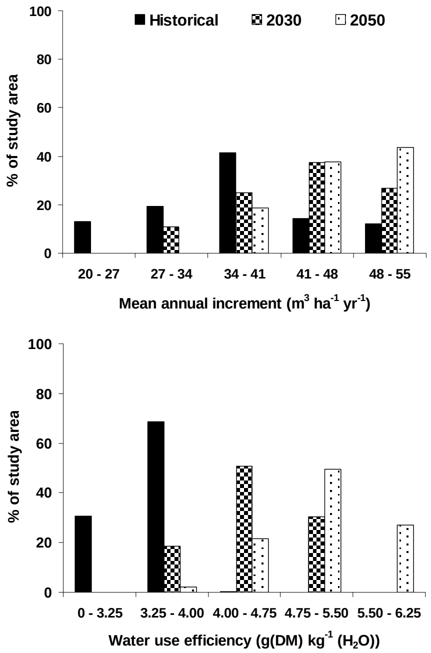

Figure 5. Comparisons of the areal distribution of mean annual increment and water use efficiency (WUE) across the study area for the historical, 2030 and 2050 climate scenarios.

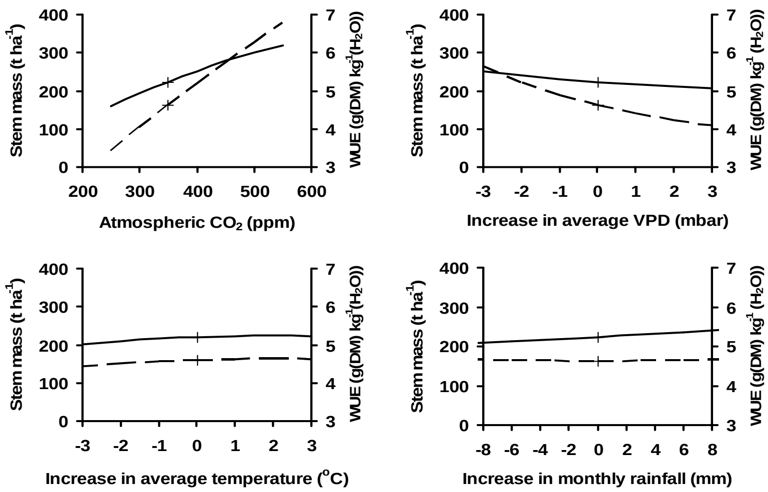

Figure 6. Sensitivity of stem mass (——) and WUE, (— —) as a function of changes in atmospheric CO_2, average temperature, and vapour pressure deficit (VPD) and monthly rainfall for an arbitrarily site in the study area. Reference conditions (shown +) are historic climate data with atmospheric CO_2 at 350 ppm.

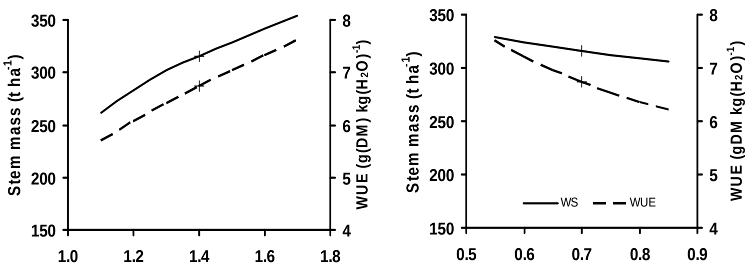

Figure 7. Sensitivity of predicted stem mass (——) and water use efficiency (WUE, — —) with respect to the parameters $f_{C\alpha700}$ and f_{Cg700} that character the CO_2 growth modifiers for light use efficiency and stomatal conductance, respectively. Reference conditions (shown +) are the 2050 climate scenario with atmospheric CO_2 at 520 ppm.

6. DISCUSSION

6.1. Validation of 3-PG for climate change studies

3-PG has been well tested across a wide range of conditions and species, and the parameter values used here were developed for the study area under current atmospheric CO_2 (Almeida et al., 2004a). However, 3-PG use to quantify the response of forest growth to changes in atmospheric CO_2 is not without concern. First, although we are confident the CO_2 growth modifiers $f_{C\alpha}$ and f_{Cg} capture the form of the dependence on C_a of the two key physiological variables in 3-PG (i.e., α and g_C), their parameterisation is based on outputs from CABALA; (Battaglia et al., 2004) process based model. Second, the modifiers do not take into account interactive effects. Fig. 2a suggests site and CO_2 effects do interact, and literature suggests both nutrition and water interact with CO_2 effects.

A quantitative validation of predicted CO_2 responses was made by comparing these with observations from FACE experiments. Ainsworth & Rogers (2007) and Buckley (2008) report that an increase of atmospheric CO_2 to around 550 ppm results in an increase in NPP of 24%-28% and a decrease in stomatal conductance of 16% to 24% across a range of species. Fig 2 shows that if C_a increases to 520 ppm, light use efficiency increases by 25% and conductance decreases by 20%, which is approximately consistent with the FACE observations (Norby et al., 2005). Application of 3-PG for C_a = 520 ppm at random sites in the study area showed significant seasonal variation in climatic effects, e.g. NPP increased by up to 80% in some months.

6.2. Sensitivity analyses

In 3-PG biomass production is determined by atmospheric CO_2, air temperatures, VPD, and rainfall (through available soil water). These factors are affected differently by climate change, and we have seen (Fig. 4) that climate change induces a potential significant increase in productivity. Fig. 6 shows the predicted changes in production and WUE induced by changes in each of these climate factors separately. Production is clearly only weakly sensitive to average temperature because temperatures in a substantial proportion of the study area are close to the optimum for this species. Biomass production is strongly affected by atmospheric CO_2 alone. Stem production is sensitive to VPD and rainfall, and the changes induced in these climatic factors by climate change actually reduce growth (Fig. 6). However, the dramatic effect due to the increase in CO_2 itself yields a significant net increase in production.

The parameter sensitivity analysis in Fig. 7 shows that stem mass is sensitive to $f_{C\alpha700}$, and hence to the effect of CO_2 on light use efficiency, but less so to f_{Cg700}, and hence to the effect of CO_2 on conductance. WUE is also sensitive to these parameters. Accordingly, it is important to accurately determine $f_{C\alpha700}$ and f_{Cg700}.

6.3. Effects of climate change on forest production

Analysis of Fig. 4a suggests a significant change in forest productivity from historical to 2030 and 2050 periods, extending the area with MAI in the range of 41 to 48 m^3 ha^{-1} $year^{-1}$ into the west region. In fact the biggest increments are concentrated in the west with increments of the order of 6 m^3 ha^{-1} $year^{-1}$. Our results suggest an increase of 17% and 26% in mean annual increment as atmospheric CO_2 increases from 350 ppm to 450 ppm in 2030 and to 520 pm in 2050, respectively. This increment is due to the direct effects of atmospheric CO_2 in increasing both light and water use efficiency, despite a decrease of 2% and 3% of rainfall and increase of 8% and 15% of VPD in 2030 and 2050. Since these changes in rainfall and VPD by themselves would reduce growth (Fig. 6), climatic induced changes in these variables act to reduce forest growth when compared to the historical period with atmospheric CO_2 at 350 ppm. In fact, if the change in C_a to 520 ppm by 2050 is ignored, and only changes in temperature, VPD and rainfall are taken into account, production at three random sites fell 12% to 17%, and water use efficiency fell by 8% to 13%.

The results of the simulations indicate a substantial change in water use efficiency from the historical to 2030 and 2050 periods. The plantations use similar amount of water producing more biomass. The increments in WUE average 1.0 gDM kg^{-1} in 2030 to 1.7 gDM kg^{-1} in 2050, and represent changes of 29% and 51% in WUE for 2030 and 2050 when compared with historical period. The climate induced changes of MAI and WUE vary across the study area (Fig. 4). The average temperature increases from historical (23.2 ºC) to 2030 (24.1ºC) and 2050 (24.7 ºC) periods with a more pronounced increase in the inland regions making the temperatures closer to the considered optimum (25 ºC).

If these changes do occur it will increase the amount of land with high productivity for *Eucalyptus* plantations in this region. From the total area of 32 million hectares (Mha), 8.5 Mha currently have potential productivity above 40 m^3 ha^{-1} $year^{-1}$. With increasing CO_2 this area increases to 20.5 Mha in 2030 and 26 Mha in 2050.

A more detailed study including the spatial variability of soil attributes is necessary to more fully map the potential limitations of forest production within the region. Also, local experiments including CO_2 enrichment will be necessary to fully evaluate *Eucalyptus* responses. However, this study provides an indication of the potential expansion of the forest lands in this region. It is worth noting that although part of the growth increases predicted are due to improved WUE, much is due to the direct effects of elevated CO_2 on light use efficiency. It is also assumed that under elevated CO_2 the partitioning of biomass within trees remain largely unchanged. Evidence to support these assumptions from FACE experiments are mixed, and have been shown to be both species and even genotype dependent.

7. CONCLUSIONS

The importance of including the effects of elevated CO_2 when forecasting growth under climate change has been indicated in this study. Even though important environmental drivers of production become less favourable in 2030 and 2050, our modelling suggests that these effects may be offset by the beneficial effect of elevated CO_2 on biomass production. In this work we did not consider the inter-relationship between soil fertility and the ability of stands to utilise elevated CO_2, a known area of complexity. It is clear that exploring future production will require process-based models such as 3-PG to explore the complex interactions in space and time that will affect future production. However, as also indicated here, predictions are dependent upon assumptions about the nature of plant responses to elevated CO_2, both in terms of photosynthetic response and biomass partitioning response. Until these physiological responses are better defined, models can at best be used to bound future responses and indicate spatial areas where tree response will be highly dependent on model constructs.

ACKWONLEDGMENT

Thanks to Dr. Philip Smethurst for his comments on the manuscript.

REFERENCES

Ainsworth, E.A., Rogers, A., (2007), The response of photosynthesis and stomatal conductance to rising [CO_2]: mechanisms and environmental interactions. *Plant, Cell and Environment,* 30, 258-270.

Almeida AC, Siggins, A., Batista, T.R., Fonseca, S., Loos, R., (2009), Mapping the effect of spatial and temporal variation in climate and soils on *Eucalyptus* plantation production with 3-PG, a process-based growth model. *Forest Ecology and Management*, submitted.

Almeida, A.C., Soares, J.V., Landsberg, J.J., Rezende, G.D., (2007), Growth and water balance of *Eucalyptus grandis* hybrid plantations in Brazil during a rotation for pulp production. *Forest Ecology and Management*, 251, 10-21.

Almeida, A.C., Landsberg,J.J., Sands,P.J., (2004a), Parameterisation of 3-PG model for fast-growing *Eucalyptus grandis* plantations. *Forest Ecology and Management*, 193, 179-195.

Almeida, A.C., Landsberg, J.J., Sands, P.J., Ambrogi, M.S., Fonseca, S., Barddal, S.M., Bertolucci, F.L., (2004b), Needs and opportunities for using a process-based productivity model as a practical tool in *Eucalyptus* plantations. *Forest Ecology and Management*, 193, 167-177.

Battaglia, M., Sands, P., White, D., Mummery, D., (2004), CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. *Forest Ecology and Management,* 193, 251-282.

Buckley, T.N. 2008. The role of stomatal acclimation in modelling tree adaptation to high CO_2. *Journal of Experimental Botany,* 59, 1951-1961.

Constable, J.V.H., Friend,A.L., (2000), Suitability of process-based tree growth models for addressing tree response to climate changes. *Environmental Pollution*, 110, 47-59.

Iglesias, G., Wiltermann, D., (2008). *Eucalyptus* universalis: Global cultivated eucalypt forests map. Version 1.0. In Eucalyptologics information resources on eucalypt cultivation worldwide. www.git-forestry.com.

IPCC, (2007): Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Landsberg, J.J., (1986). Physiological ecology of forest production. Academic Press, London. 198 pp.

Landsberg, J.J., Waring, R.H., (1997), A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology and. Management*. 95, 209-228.

Landsberg, J.J., (2003), Modelling forest ecosystems: state-of-the-art, challenges and future directions. *Canadian Journal of Forest Research*. 33, 385-397.

Mitchell, T.D., Carter, T. R., Jones, P. D., Hulme, M., New, M., (2004), A comprehensive set of climate scenarios for Europe and the globe: the observed record (1900-2000) and 16 scenarios (2000-2100). *University of East Anglia*

Norby, R.J., DeLucia, E.H., Gielen, B., and 16 others (2005), Forest response to elevated CO_2 is conserved across a broad range of productivity. *Proceedings of the National Academy of Sciences of the United States of America*, 102, 18052-18056.

Sands, P.J., Landsberg,J.J., (2002), Parameterisation of 3-PG for plantation grown *Eucalyptus globulus*. *Forest Ecology and Management*. 163, 273-292.