Modeling productivity and transpiration of *Pinus radiata*: climatic effects

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Summary  Climatic effects on annual net carbon gain, stem biomass and annual transpiration were simulated for *Pinus radiata* D. Don at Canberra and Mt. Gambier. Simulations were conducted with an existing process-based forest growth model (BIOMASS, Model 1) and with a modified version of the BIOMASS model (Model 2) in which response functions for carbon assimilation and leaf conductance were replaced with those derived from field gas exchange data collected at Mt. Gambier.

Simulated carbon gain was compared with a published report stating that mean annual stem volume increment (MAI) at Mt. Gambier was 1.8 times greater than at Canberra and that the difference could be the result solely of differences in climate. Regional differences in climate resulted in a 20% greater simulated annual transpiration at Canberra than at Mt. Gambier but only small differences in simulated productivity, indicating that climatic differences did not account for the reported differences in productivity. With Model 1, simulated annual net carbon gain and annual increase in stem biomass were greater at Canberra than at Mt. Gambier, whereas Model 2 indicated a similar annual net carbon gain and annual stem biomass increase in both regions.

Keywords: carbon gain, simulation model, stem growth.

Introduction

Primary productivity and biomass gain of a plant or an ecosystem vary with the availability of resources and the characteristics of the environment (e.g., Smith and Hinckley 1995a, 1995b). Changes in climate can cause changes in productivity, and sometimes alter the geographic range over which a species can grow (e.g., Barlow and Conroy 1988, Booth and McMurtrie 1988).

The productivity of *Pinus radiata* D. Don can be manipulated silviculturally by operations that alter resource availability (e.g., Sheriff 1995a). However, the responses of primary productivity and biomass gain to silvicultural manipulation depend on constraints imposed by the environment. Thus, to predict these responses in different environments requires detailed information on the effects of environmental variables on the underlying processes that govern productivity.

Nambari (1995) reported that stem volume growth of *P. radiata* increases 1.8 times as fast in trees located near Mt. Gambier (southeastern South Australia) than in trees located in other parts of southern Australia receiving similar amounts of rainfall, and hypothesized that the difference results from access to aquifer water at Mt. Gambier (see Teskey and Sheriff 1996). An alternative hypothesis is that the difference is a result of differences in humidity and temperature of the two regions (Sheriff and Mattay 1995). To distinguish between these hypotheses, we estimated net carbon assimilation ($A_{\text{CO}_2}$) and transpiration ($E$) for the two regions with the BIOMASS model (McMurtrie et al. 1990a, McMurtrie and Landsberg 1992), and with a modified version of the BIOMASS model in which the functions for the responses of $A_{\text{CO}_2}$ and leaf conductance ($g_l$) to humidity and temperature were replaced with those derived by Sheriff (1995).

Materials and methods

BIOMASS—Model 1

The BIOMASS model predicts crop yield through a dynamic, process-based simulation of net canopy carbon assimilation and transpiration (McMurtrie et al. 1990b, 1992). Rates of carbon assimilation and transpiration were calculated on a daily basis using meteorological variables, soil water characteristics and stand conditions at the beginning of the simulation period as model inputs.

BIOMASS—Model 2

In Model 1, $A_{\text{CO}_2}$ and $g_l$ decline linearly as the leaf to air vapor pressure gradient, considered here to be the same as atmospheric vapor pressure deficit (vpd), increases beyond a threshold value. In addition, both $A_{\text{CO}_2}$ and $g_l$ are quadratic functions of temperature when other variables are constant, and are reduced by overnight subzero temperatures. However, partial regression coefficients of a multiple nonlinear analysis of field gas exchange data (Sheriff 1995) indicate that net $A_{\text{CO}_2}$ and $g_l$ of *P. radiata* decline exponentially with increasing vpd and that their variation with temperature follows quadratic relationships but with different parameters to those used in Model 1. The forms of these relationships for responses to vpd
are:

\[ A_{\text{CO}_2} = k_1 e^{-k_2 D}, \]  

\[ g_l = k_3 k_d (k_d + D). \]

The forms of these relationships for responses to temperature are:

\[ A_{\text{CO}_2} = k_3 (1 - k_4 (T_l - T_m)^2), \]

\[ g_l = k_4 (1 - k_5 (T_l - T_m)^2). \]

where \( k_1, k_2, k_3 \) and \( k_4 \) are multipliers whose values depend on effects of other variables on \( A_{\text{CO}_2} \) or \( g_l \); \( k_1, k_2, k_3 \) and \( k_4 \) are parameters, \( D \) is ambient vpd, \( T_l \) is leaf temperature, and \( T_m \) and \( T_l \) are statistically derived temperature “optima” for \( A_{\text{CO}_2} \) and \( g_l \). Responses to temperature are such that \( g_l \) increases with temperature to a maximum at about 32 °C and then declines, whereas at ambient temperatures, net \( A_{\text{CO}_2} \) increases almost linearly with temperature.

\section*{Simulations}

Weather data used for the simulations were collected by the Australian Bureau of Meteorology stations at Canberra and Mt. Gambier during the 10 years from January 1, 1984, until December 31, 1993 (Table 1). For each simulation it was assumed that soil characteristics and foliar nutrition in the two regions were the same and that stand conditions were the same at the beginning of the simulation. Leaf area index (LAI) was specified as an input to the model; projected LAI increased from 3 to 4.5 at both sites during the simulations.

\section*{Regional effects}

To examine the relative effects of incident light, temperature, vpd and rainfall on net \( A_{\text{CO}_2} \) and \( E \) at the two locations, model estimates were recalculated when each weather variable was swapped, in turn, between regions. Because vapor pressure deficit depends on the absolute humidity of the air and on its temperature, the vpd and temperature variables were swapped together.

\section*{Results and discussion}

\subsection*{Simulations}

Both versions of the BIOMASS model indicated considerable year to year variation in carbon gain (Figures 1a and 2a). Variations were caused by changes in all weather variables, with different variables contributing differently in different years. The generally greater carbon gain predicted by the modified Model 2 than by the unmodified Model 1 probably resulted from its greater sensitivity to adverse environmental conditions, especially dry air. Transpiration also varied between years (Figures 1b and 2b), but there was less difference between years than for carbon assimilation. Altering model response had little effect on transpiration, partly because both models are water-limited, and most water input to the soil is lost by evapotranspiration during the same year. There were only small differences between the two versions of the model in patterns of carbon gain or stem biomass increase (Table 2).

\subsection*{Regional effects}

The most obvious differences between simulated values for the two regions were the relatively small variations in yearly values for transpiration and greater assimilatory transpiration

\begin{table}[h]
\caption{Ten-year means of weather values used for simulations.}
\begin{tabular}{lcccccc}
\hline
Site & Daily radiation (MJ m$^{-2}$ day$^{-1}$) & Daily temperature (°C) & Daily relative humidity (%) & Annual rainfall (mm year$^{-1}$) \\
& & Maximum & Minimum & Average & Maximum & Minimum \\
Canberra & 17.2 & 18.6 & 7.2 & 84.9 & 95.7 & 71.3 & 669.4 \\
Mt. Gambier & 15.5 & 18.0 & 8.8 & 88.3 & 97.1 & 76.9 & 708.2 \\
\hline
\end{tabular}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Simulated (a) annual net carbon assimilation and (b) transpiration for Canberra (shaded) and Mt. Gambier (unshaded) by Model 1.}
\end{figure}
efficiency (ATE = assimilation/transpiration) at Mt. Gambier. This site had an ATE about 18% greater for the data as a whole and about 20–26% greater for annual transpiration rates at Mt. Gambier. The higher water use efficiency at Mt. Gambier than at Canberra is largely a result of lower vpds, and to some extent lower average radiation, both of which lessen evaporative demand.

Site differences were greater for Model 2 simulations than for Model 1 simulations. (cf. Figures 1 and 2). Averaged over 10 years, output from the unmodified Model 1 predicted slightly greater net carbon assimilation and stem biomass increase at Canberra than at Mt. Gambier (Table 2). The modified Model 2 also indicated only small differences in net carbon assimilation and stem biomass increase, but it showed a slightly greater net carbon assimilation at Mt. Gambier than at Canberra. Both models predicted about 20% greater transpiration at Canberra than at Mt. Gambier as a result of differences in interception loss, reflecting fewer periods of heavy rain at Canberra compared with Mt. Gambier.

Swapping weather variables

Simulations run with weather variables swapped between Canberra and Mt. Gambier indicated that regional differences in climate can result in different simulated values for productivity and transpiration. The unmodified BIOMASS model predicted larger effects of swapping weather variables between the two regions on net carbon assimilation, stem biomass and transpiration than the modified BIOMASS model (Table 3). Output from the unmodified BIOMASS model indicated that both radiation and rainfall at Canberra contributed to the greater carbon gain and stem biomass increment in simulations for that region. However, these effects were offset by the effects of temperature and relative humidity at Canberra which were less favorable for carbon gain than at Mt. Gambier (Table 3). All of the Canberra weather variables contributed to the high transpiration rates simulated at Canberra. The modified BIOMASS model produced a similar result, but the Mt. Gambier radiation values were, on average, more favorable for net carbon assimilation.

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Table 2. Estimated annual net carbon assimilation (Mg C ha⁻¹ year⁻¹), stem biomass increase (Mg C ha⁻¹ year⁻¹) and transpiration (mm year⁻¹) in the Canberra and Mt. Gambier regions. Values are means± SE calculated over 10-year periods with Models 1 and 2.

<table>
<thead>
<tr>
<th>Model</th>
<th>Carbon assimilation</th>
<th>Stem biomass</th>
<th>Transpiration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Mg C ha⁻¹ year⁻¹)</td>
<td>(Mg C ha⁻¹ year⁻¹)</td>
<td>(mm year⁻¹)</td>
</tr>
<tr>
<td><strong>Canberra</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 1</td>
<td>18.3 ± 1.2</td>
<td>14.2 ± 1.0</td>
<td>606 ± 22</td>
</tr>
<tr>
<td>Model 2</td>
<td>25.6 ± 1.7</td>
<td>19.8 ± 1.4</td>
<td>612 ± 22</td>
</tr>
<tr>
<td><strong>Mt. Gambier</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 1</td>
<td>17.0 ± 0.6</td>
<td>12.6 ± 0.5</td>
<td>500 ± 7</td>
</tr>
<tr>
<td>Model 2</td>
<td>26.3 ± 1.1</td>
<td>19.7 ± 0.9</td>
<td>517 ± 10</td>
</tr>
</tbody>
</table>

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Table 3. Effects on simulated annual net carbon assimilation, stem biomass increase and rainfall of swapping radiation, rainfall or temperature and humidity values between the weather data files for Canberra and Mt. Gambier. The effects are shown as the percentage change in the value of the simulated variable after the weather variable was swapped.

<table>
<thead>
<tr>
<th></th>
<th>Canberra</th>
<th>Mt. Gambier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radiation</td>
<td>Rainfall</td>
</tr>
<tr>
<td><strong>Model 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon assimilation</td>
<td>−3.9</td>
<td>−10.3</td>
</tr>
<tr>
<td>Stem biomass</td>
<td>−4.6</td>
<td>−12.5</td>
</tr>
<tr>
<td>Transpiration</td>
<td>−0.9</td>
<td>−11.1</td>
</tr>
<tr>
<td><strong>Model 2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon assimilation</td>
<td>7.6</td>
<td>−3.9</td>
</tr>
<tr>
<td>Stem biomass</td>
<td>6.2</td>
<td>−6.0</td>
</tr>
<tr>
<td>Transpiration</td>
<td>−3.0</td>
<td>−10.3</td>
</tr>
</tbody>
</table>
lation and stem biomass increase than the Canberra radiation values.

Conclusions

The simulated results were not consistent with the finding of Nambiar (1995) that *P. radiata* is more productive at Mt. Gambier than at Canberra, or with the hypothesis of Sheriff and Mattay (1995) that differences in climate between Mt. Gambier and Canberra would be expected to cause an 8% higher annual net carbon assimilation at Mt. Gambier. Simulated carbon gain values averaged about 1.4% more at Canberra than at Mt. Gambier; however, a simulated 20% higher annual transpiration at Canberra is consistent with Sheriff and Mattay’s (1995) estimate of 19% greater annual transpiration at Canberra.

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References


