



# Assessing productivity and carbon sequestration capacity of *Eucalyptus globulus* plantations using the process model Forest-DNDC: Calibration and validation

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## Abstract

The tree growth sub-module (PnET) of the mechanistic model Forest-DNDC was calibrated and validated for plantation grown *Eucalyptus globulus*. Forest-DNDC describes the biogeochemical cycles of C and N and can assist in estimating soil-borne greenhouse gas fluxes. For validation of the forest growth sub-module, data from commercial forest plantations in south-eastern Australia was used. Growth predictions agreed well with growth measurements taken at age 6 years from 28 permanent sample plots, with an average prediction error of  $-1.62 \text{ t C ha}^{-1}$  ( $-3.19\%$ ). Differences between predicted and measured aboveground C stocks ranged between  $-23.5$  and  $12.6 \text{ t C ha}^{-1}$ , which amounted to a relative root mean square error in prediction of 17.9%. Correlation between modelled and measured C in standing biomass was good ( $r^2 = 0.73$ ), with a Nash–Sutcliffe coefficient of model efficiency,  $ME = 0.65$ . The results obtained from the validation test reveal that Forest-DNDC can predict growth of *E. globulus* to a high level of precision across a broad range of climatic conditions and soil types. Forest-DNDC performed satisfactorily in comparison to other growth and yield models that have already been calibrated for *E. globulus* (e.g. BIOMASS, 3-PG, PROMOD or CABALA). In contrast to these growth and yield models, Forest-DNDC can additionally estimate total greenhouse gas budgets. The slightly lower precision of Forest-DNDC in comparison with specific management models, such as CABALA, are compensated for by the simple input requirements and application to regional situations.

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## 1. Introduction

There is general consensus that the increasing concentration of greenhouse gases (e.g.  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ ,  $\text{O}_3$ ) have led to changes in the earth's climate and

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a warming of the earth's surface. Furthermore, there is agreement that human activities such as fossil fuel combustion, land-use change and agricultural practices have contributed substantially to the rise in atmospheric greenhouse gas concentrations (IPCC, 1997). Forestry, and afforestation in particular, is regarded as an important contributor to the offset of greenhouse gas emissions. Projects that increase the area of plantations have been suggested for inclusion under the clean development mechanism (CDM) as defined in Article 12 of the Kyoto Protocol (Van Vliet et al., 2003). However, significant uncertainties in the reliability of carbon pool and flux measurements make it difficult to determine the (net) carbon benefits of afforestation or forestry management practices. As a result, further investment in, and development of, the plantation industry is threatened (Van Vliet et al., 2003).

There is a growing need for computer simulation models that can assist in the estimation of carbon budgets, net ecosystem exchange or trace gas emissions (Mosier, 1998; Landsberg, 2003; Van Vliet et al., 2003; Battaglia et al., 2004). Preferably, such models would require only basic and readily obtainable input parameters whilst producing reliable predictions across a wide range of climatic and edaphic conditions. There are a number of process-based, forest growth models described in the literature that have been validated for *Eucalyptus globulus*; the species investigated in this study. Amongst them are BIOMASS (Linder et al., 1985; Hingston and Galbraith, 1998; Hingston et al., 1998), 3-PG (Landsberg and Waring, 1997; Sands and Landsberg, 2002), PROMOD (Battaglia and Sands, 1997) and CABALA (Battaglia et al., 2004). These four forest productivity models could be used for carbon accounting purposes. CABALA (from CARbon BALance), a further development of PROMOD, and the most detailed of the four models, is particularly designed to model the carbon balance of even-aged, homogeneous stands. However, none of these growth and yield models is capable of modelling a total greenhouse gas budget, including soil borne emissions of NO, N<sub>2</sub>O or CH<sub>4</sub>. Carbon accounting is only one aspect of evaluating the net benefit of land use change.

The Forest-DNDC model (Li et al., 2000; Stange et al., 2000) is primarily designed for the prediction of forest production, soil carbon sequestration and trace gas emissions (NO, N<sub>2</sub>O, CH<sub>4</sub>, NH<sub>3</sub>) in upland and wetland forest ecosystems. Forest-DNDC uses the for-

est growth model PnET (Aber et al., 1996) as a sub-module. PnET has not been validated for *E. globulus*, but parameterisations for a variety of forest types exist (Aber and Federer, 1992; Aber et al., 1996).

The importance of *E. globulus* as a plantation tree species in Australia, Brazil, Portugal, Spain and China, has increased rapidly over the past decade (Reed and Tome, 1998; Wood et al., 2001; Xu et al., 2001; Parsons et al., 2004). Because of its fast growth, *E. globulus* has become important to the pulp and paper industries of many countries. In Australia, the hardwood resource increased by 354,500 ha between 1995 and 2000 with *E. globulus* comprising 62% (Wood et al., 2001). By the end of 2000, a total of 311,344 ha had been planted with *E. globulus*, mainly in Western Australia, South Australia and Victoria. The area of hardwood plantations continues to expand across southern Australia, and *E. globulus* is the dominant hardwood species planted (Wood et al., 2001; Parsons et al., 2004). In the state of Victoria, a total of 99,506 ha, or 83% of all hardwood plantations were planted with *E. globulus* by the end of 2000.

The aim of this study was the calibration and validation of the PnET tree growth sub-module of Forest-DNDC for plantation grown *Eucalyptus globulus*. The Forest-DNDC model was calibrated using measured biomass growth and relevant soil data from 20 permanent sample plots (PSPs) in commercial forest plantations in south-eastern Australia. The parameterisation was based almost entirely on published data or the results of direct measurements. Validation of model performance involved a comparison of simulated and measured data from a further 28 PSPs in 6-year-old plantations established in 1997 that were not used for calibration, and a rigorous statistical analysis of the simulation results.

## 2. Methods

### 2.1. Model description

The Forest-DNDC model is a process-based model for predicting forest growth and production, soil carbon and nitrogen dynamics, carbon sequestration and soil-borne trace gas emissions in upland and wetland forested ecosystems. It integrates photosynthesis and evapotranspiration-nitrification-denitrification and decomposition (PnET-N-DNDC), a forest biogeo-

chemical model (Li et al., 2000; Stange et al., 2000), with a matrix of approaches handling hydrological conditions.

The PnET-N-DNDC model consists of two components. The first component is driven by environmental controls, in particular climate, soil properties, vegetation type and anthropogenic activities. In this first component, sub-modules of soil climate, forest growth and decomposition predict biomass accumulation in roots, aboveground woody tissue and foliage as well as water content, temperature, pH, redox potential and substrate concentration profiles in the soil. The second component utilises the modelled soil environmental factors as inputs to drive nitrification, denitrification and fermentation sub-modules and predicts NO, N<sub>2</sub>O, CH<sub>4</sub> and NH<sub>3</sub> fluxes.

The simulation of forest growth has been adapted from the PnET model (Aber and Federer, 1992; Aber et al., 1995; Aber et al., 1996). In PnET, foliar N concentration is used to determine photosynthesis ( $A_{\max}$ ). Solar radiation, temperature and vapour pressure deficit, together with other mean daily climate variables, drive the calculation of realised  $A_{\max}$  at the top of the canopy. Radiation and specific leaf weight, and therefore also  $A_{\max}$ , decline with canopy depth. Leaf respiration is computed separately for day and night, based on temperature and photosynthesis. Nine forest types (pine, spruce, hemlock, fir, oak, hardwoods, birch, beech and rainforest) have already been calibrated for the PnET model (Aber and Federer, 1992; Aber et al., 1996). Besides the original PnET functions, shrub, sedge and moss were added in Forest-DNDC to enhance its capacity by covering the entire suite of the forest vegetations (Zhang et al., 2002).

Minimum input parameters required by the model are daily maximum and minimum air temperature, rainfall, ambient CO<sub>2</sub> concentration, N concentration in rainfall, humus layer type, litter layer depth, litter layer pH, bypass flow (surface efflux), mineral soil texture, mineral soil pH, stone content, organic carbon content, depth to groundwater level, latitude and management operations (e.g. planting, fertilisation, harvest, thinning, wetland restoration, etc.).

There is an agricultural version of the model called DNDC, with a crop growth sub-module instead of a tree growth sub-module (Li et al., 1992a). The Forest-DNDC and DNDC model have been successfully tested and applied in many countries and land use scenarios.

Further details on model development (Li et al., 1992a, 2000), validation (Smith et al., 1997, 2002; Stange et al., 2000) and regional and local scale applications (Li et al., 1992b, 1994; Butterbach-Bahl et al., 2001, 2004; Brown et al., 2002), are available from the cited publications.

## 2.2. Data

### 2.2.1. Soils, growth and silvicultural management

Soil information and plantation growth data, as well as information on relevant management operations (e.g. fertiliser applications), were collected to develop a climate and soil database for farm forestry research (Feikema et al., 2003b; Feikema et al., 2003a). The study involved a network of 302 permanent sample plots in 93 plantations across south-eastern Australia, predominantly in Victoria. The PSPs are located in plantations of *E. globulus* or *E. nitens* that were established between 1997 and 2001 on land previously used for grazing or agricultural production.

Soil profile descriptions were made to represent the range of soil types observed. Adjacent to each PSP, a soil pit was dug to a maximum depth of 4 m, or to the depth of an impeding layer, bedrock or the ground water level. Soil chemical and physical analysis was undertaken on samples from each layer for a subset of the PSPs (e.g. soil pH, soil texture, EC, exchangeable cations (Ca, Mg, K, Na), exchangeable Al and Ac, total N and organic C).

Growth information for each PSP consisted of standard inventory measurements (i.e. tree density, survival rate, mean tree height, mean dominant tree height, basal area, volume). Measurements of the 302 PSPs were taken at 2 year intervals at ages of 2, 4 and 6 years after planting. Growth measurements at age 2, 4 and 6 years of *E. globulus* were available for 33 PSPs established in 1997. Measurements at age 2 and 4 years were available for 132 PSPs established 1998 and 1999. For the remaining 137 PSPs growth measurements were only available at age 2 years.

Information about relevant silvicultural management operations was also available from the farm forestry database. All plantations were planted to produce pulpwood on a 10 year rotation cycle. Silvicultural practices were similar whether managed by farmers or timber companies. In general, the management consisted of:

- Site preparation and tree plantings during the winter of the year of establishment (mainly in July and August).
- Nitrogen fertiliser applications in the first few months after planting, at a rate of around 40 kg N ha<sup>-1</sup>, and in the second or third season at a rate of about 100 kg N ha<sup>-1</sup>.
- No pruning or thinning was carried out.

### 2.2.2. Climate:

All daily rainfall and air temperature data was taken from the interpolated climate surfaces of SILO Data Drill, supplied by the Queensland Government, Department of Natural Resources and Mines. The climate surfaces are created by interpolating daily historic climate observations (1 January 1957 until 20 June 2003) to a resolution of 0.05° (approximately 5 km<sup>2</sup> cell size) over all of mainland Australia and Tasmania. Interpolated daily rainfall, temperature, radiation, evaporation, relative humidity and vapour pressure data is available for each grid cell (Jeffrey et al., 2001).

### 2.2.3. Plant specific parameters:

A literature review was carried out to collect appropriate values for all required specific physiological input parameters for *E. globulus* in Forest-DNDC (Table 1).

## 2.3. Statistical evaluation of model performance

Simulations to estimate growth and carbon sequestration were performed for each PSP. Simulated growth was compared against measured field data based on total above ground biomass estimates (stems, branches and foliage) in t C ha<sup>-1</sup>. Above ground biomass was calculated from the inventory data using a linear relationship with basal area as suggested by the Australian Greenhouse Office for carbon accounting in eucalypt plantations (Snowdon et al., 2000):

$$y = ba \times 6.6 \text{ t dry weight } m^{-2} \quad (1)$$

where  $y$  is total above ground biomass (t dry weight m<sup>-2</sup>) and  $ba$  is the basal area over bark (m<sup>2</sup> ha<sup>-1</sup>). Biomass was converted to tonnes of carbon per hectare (t C ha<sup>-1</sup>) assuming an average tissue carbon concentration of 0.5 in *E. globulus* trees (Resh et al., 2003).

Statistical analysis of the simulation results consisted of calculating the mean error of prediction ( $\bar{e}$ , Eq. (2)), the relative mean error of prediction ( $\bar{e}\%$ , Eq. (3)), the mean and relative mean absolute error (MAE and MAE%, Eqs. (4) and (6)), the root mean and the relative root mean square error of prediction (RMSE and RMSE%, Eqs. (5) and (7)), the coefficient of determination ( $r^2$ , Eq. (8)) and the Nash–Sutcliffe index of model efficiency (ME, Eq. (9)) (Janssen and Heuberger, 1995; Legates and McCabe, 1999; Huang et al., 2003).

$\bar{e}$  and  $\bar{e}\%$  examine predictions and observations on an average level and investigate the bias of model predictions:

$$\bar{e} = \frac{\sum_{i=1}^n (O_i - P_i)}{n} = \bar{O}_i - \bar{P}_i \quad (2)$$

$$\bar{e}\% = 100 \frac{\bar{e}}{\bar{O}} \quad (3)$$

where  $O_i$  and  $P_i$  are the observed and predicted values,  $\bar{O}$  and  $\bar{P}$  are their averages and  $n$  is the number of cases.

MAE assesses the size of prediction errors on an individual level as it does not allow for compensation of positive and negative prediction errors (such as in  $\bar{e}$ ).

$$\text{MAE} = \frac{\sum_{i=1}^n |P_i - O_i|}{n} \quad (4)$$

Similar to MAE, RMSE measures absolute prediction errors, but in a quadratic sense, and is therefore more sensitive to outliers.

$$\text{RMSEP} = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \quad (5)$$

In the quadratic function of RMSE large errors have a greater effect compared to large errors in the linear function of MAE. Therefore, the greater the difference between MAE% and RMSE% the more significant prediction errors exist. For this comparison it is preferable to express MAE and RMSE not as absolute numbers, but as MAE% and RMSE%, a percentage relative to  $\bar{O}$ .

$$\text{MAE}\% = 100 \frac{\text{MAE}}{\bar{O}} \quad (6)$$

$$\text{RMSE}\% = 100 \frac{\text{RMSE}}{\bar{O}} \quad (7)$$

Table 1  
Value, description and source of input parameters used in calibration of the Forest-DNDC (PnET) model for *E. globules*

Parameter	Value	Unit	Description	Source
$A_{\max A}$	−46	–	Intercept of relationship between foliar N (%) and maximum photosynthetic rate ( $A_{\max}$ ; $\mu\text{mol CO}_2 \text{ g}^{-1} \text{ leaf s}^{-1}$ )	Aber et al. (1996)
$A_{\max B}$	71.9	–	Slope of relationship between foliar N (%) and $A_{\max}$ $\mu\text{mol CO}_2 \text{ g}^{-1} \text{ leaf s}^{-1}$ )	Aber et al. (1996)
$A_{\max \text{Frac}}$	0.76	–	Daily $A_{\max}$ as a fraction of early morning instantaneous rate	Aber et al. (1996)
AssimRootFraction/RootF	0.2	–	Fraction of assimilate allocated to roots	Pate and Arthur (2000)
BaseFolRespFrac	0.06	–	Respiration as a fraction of maximum photosynthesis	Adapted from Battaglia et al. (2004)
CoarseRootFraction	0.3	–	Fraction of stem wood in soil (coarse roots)	Keith et al. (2000)
DVPD1	0.05	–	Coefficients for photosynthesis reduction caused by vapor pressure deficit (DVPD) in $\text{DVPD} = \text{DVPD1} \times \text{VPDDVPD2}$ (VPD; kPa)	Aber et al. (1996)
DVPD2	2	–	Power factor in the function $\text{DVPD} = \text{DVPD1} \times \text{VPDDVPD2}$	Aber et al. (1996)
FolCNR	54	$\text{g g}^{-1}$	Carbon to Nitrogen ratio in foliage	Resh et al. (2003)
FolNCon	2	%	Foliage N concentration by weight	Resh et al. (2003)
FolNRetrans	0.5	–	Fraction of foliage N retranslocated before leaf falls down	Battaglia et al. (2004)
FolReten	2.25	yr	foliage retention	Sands and Landsberg (2002)
GDDFolEnd	1300	–	Growing degree days (GDD) at which foliar production ends	Li pers. Com., adapted from other evergreen trees in Forest-DNDC
GDDFolStart	400	–	GDD at which foliar production begins	Li pers. Com., adapted from other evergreen trees in Forest-DNDC
GrespFrac	0.25	–	Growth respiration, as a fraction of allocated carbon	Battaglia et al. (2004)
HalfSat	300	$\mu\text{mol s}^{-1}$	Light level where photosynthesis is $0.5A_{\max}$	Battaglia et al. (1996)
k	0.5	–	Canopy light extinction constant	Battaglia and Sands (1997)
LAIExpansionRate	0.1	–	LAI $_{\max}$ expansion rate of individual trees	Li pers. Com., adapted from other evergreen trees in Forest-DNDC
LAILimitRate	0.01	–	LAI $_{\max}$ limiting rate when LAI $_{\max}$ is over LastLAI	Li pers. Com., adapted from other evergreen trees in Forest-DNDC
LastLAI	5.5	$\text{m}^2 \text{ m}^{-2}$	LAI $_{\max}$ that can be maintained	Li pers. Com., adapted from other evergreen trees in Forest-DNDC
m_CfracB	0.5	–	Fraction of Carbon in biomass	Resh et al. (2003)
m_FolRelGrowMax	0.95	$\% \text{ yr}^{-1}$	Maximum relative growth rate for foliage	Li pers. com., estimated
m_GDDWoodEnd	1300	–	GDD at which wood production ends	Li pers. Com., adapted from other evergreen trees in Forest-DNDC
m_GDDWoodStart	400	–	GDD at which wood production begins	Li pers. Com., adapted from other evergreen trees in Forest-DNDC
m_MinWoodFolRatio	0.75	–	Minimum ratio of carbon allocation to wood and foliage	adapted from Pate and Arthur (2000)
m_PlantCReserveFrac	0.75	–	Fraction of plant carbon held in reserve after allocation to bud carbon	Aber et al. (1996)
m_SLWdel	0.2	$\text{g m}^{-2} \text{ g}^{-1}$	Change in specific leaf weight with canopy depth	Aber et al. (1996)

Table 1 (Continued)

Parameter	Value	Unit	Description	Source
m.WoodCNR	980	–	Carbon to Nitrogen ratio of woody biomass	Resh et al. (2003)
m.WUEConst	13.9	–	Coefficient in equation for water-use efficiency as a function of VPD	Li pers. Com., defaults for tropical or evergreen broad leaf trees
PeakLAI	6.5	m <sup>2</sup> leaf m <sup>-2</sup>	Potential maximum LAI	Battaglia and Sands (1997)
PsnTMax	45	°C	Maximum temperature for photosynthesis	based on Battaglia (1996)
PsnTMin	2	°C	Minimum temperature for photosynthesis	based on Battaglia (1996)
PsnTOpt	15	°C	Optimum temperature for photosynthesis	Battaglia et al. (1996)
RespQ10	1.3	–	Q <sub>10</sub> value for foliar respiration	Battaglia et al. (2004)
RootLF	2	yr <sup>-1</sup>	Fine root turn over	King (1996)
RootMRspFrc	1	–	Ratio of fine root maintenance respiration to fine root biomass production	Aber et al. (1996)
RootN	0.006	g g <sup>-1</sup>	Nitrogen in roots	Pate and Arthur (2000), Resh et al. (2003)
SLWmax	180	g m <sup>-2</sup>	Specific leaf weight at the top of canopy	adapted from Battaglia and Sands (1997) and Bennett et al. (1997)
WoodLF	0.03	yr <sup>-1</sup>	Turn over of woody tissue	based on King (1996) and Battaglia et al. (2004)
WoodMRFrc	0.06	g C m <sup>-3</sup> sapwood hr <sup>-1</sup>	Wood maintenance respiration as a fraction of gross photosynthesis	Pate and Arthur (2000)
WoodN	0.0006	g g <sup>-1</sup>	Nitrogen in woody tissue	Battaglia et al. (2004)

The coefficient of determination ( $r^2$ ) is reported as a measure of statistical correlation between model predictions and field observations.

$$r^2 = \left( \frac{\sum(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum(O_i - \bar{O})^2 \times \sum(P_i - \bar{P})^2}} \right)^2 \quad (8)$$

The Nash–Sutcliffe index of model efficiency (Eq. (9)) examines the agreement of individual predictions and observations as a quantitative measure of improvement in prediction in relation to the bench-mark situation  $\bar{O}$ . Any positive value for ME indicates that the model prediction is better than  $\bar{O}$ ; the closer to +1 the better (Nash and Sutcliffe, 1970; Janssen and Heuberger, 1995; Legates and McCabe, 1999; Huang et al., 2003).

$$ME = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (P_i - \bar{P}_i)^2} \quad (9)$$

The statistical assessments described above investigate different aspects, and provide a good overview, of model performance.  $\bar{e}$ ,  $\bar{e}\%$  and MAE% indicate

the accuracy and investigate the bias of predictions, whereas RMSE%, ME and  $r^2$  indicate the level of precision. The difference between RMSE% and MAE% is a measure for the existence of significant prediction errors. While ME reflects the goodness of fit based on a 1:1 line between predictions and observations,  $r^2$  provides a more common regression coefficient indicating the ability of the model to explain variations in the observed values (Janssen and Heuberger, 1995; Legates and McCabe, 1999).

#### 2.4. Calibration

The Forest-DNDC model was calibrated using measured biomass growth and relevant soil data from 20 PSPs. These 20 PSPs were selected to represent the range of productivity and fertility that was found amongst the available 302 PSPs. Five of these 20 PSPs were established in 1997 and provided growth data at age 6 years, while the other 15 were established in 1998 and provided measurements from 4-year-old trees. The 20 PSPs used for model calibration represent a variety of environmental conditions and soil types: Chromosols, Dermosols, Kurosols, Ferrosols,

Table 2

Range of climatic conditions experienced by the PSPs used in calibration

Average monthly maximum temperature (°C)	17.1–22.4
Average monthly minimum temperature (°C)	7.4–10.3
Lowest temperature (°C)	–5.0–2.5
Highest temperature (°C)	39.0–43.0
Precipitation (mm year <sup>-1</sup> )	563–1120
Raindays	131–272

Vertosols and Kandosols (Isbell, 1996). The range in climatic conditions amongst the 20 PSPs used in the calibration are presented in Table 2. The parameterisation of the model for *E. globulus* was almost exclusively obtained from published data or based on direct measurement (Table 1).

In Forest-DNDC, daily wood production is regulated by a factor, wood production efficiency (GDDWoodEff). GDDWoodEff is the fraction of the total forest C storage available for wood growth. It is determined by air temperature, wood growing duration and water stress. During calibration, the coefficient 2.2 in the equation was adjusted to 2.233 to optimise predictions.

$$\text{GDDWoodEff} = \frac{2.233 \times \text{air\_temp}}{(\text{GDDWoodEnd} - \text{GDDWoodStart}) \times \text{day\_water\_stress}^8} \quad (10)$$

$$\text{day\_WoodProdC} = \text{WoodC} \times \text{GDDWoodEff} \quad (11)$$

where air\_temp is air temperature, GDDWoodStart is accumulative temperature for wood growth to start, GDDWoodEnd is accumulative temperature for wood growth to cease, day\_water\_stress is the daily water stress factor, WoodC is forest C storage available for wood growth, and day\_WoodProdC is the daily wood production.

All parameters, including the GDDWoodEff and all ratios for biomass allocation (Table 1), were set to a constant value across all sites and age classes. They remained unchanged after calibration.

### 2.5. Validation

Evaluation of model performance involved a comparison of simulated and measured data from the remaining 28 PSPs in plantations established in

Table 3

Range of climatic conditions experienced by the PSPs used in validation.

Average monthly maximum temperature (°C)	17.6–22.4
Average monthly minimum temperature (°C)	7.4–8.5
Lowest temperature (°C)	–5.0–2.0
Highest temperature (°C)	39.0–43.0
Precipitation (mm year <sup>-1</sup> )	563–959
Raindays	133–184

1997 that were not used for calibration. The 28 PSPs were the oldest available *E. globulus* plantations. They were selected to reflect mid-rotation growth dynamics. As most *E. globulus* plantations in Victoria have only been established in the past decade, many are at, or approaching, mid-rotation. Comparisons of simulated and measured growth were made at age 6 years. The validation tests covered the plantations established on Kurosols, Sodosols, Dermosols, Chromosols and Tenosols according to Australian Soil Classification (Isbell, 1996). The ranges in climatic conditions within these 28 validation PSPs are listed in Table 3.

## 3. Results

A summary of results for the calibration and validation tests of the Forest-DNDC model for *E. globulus* plantations is shown in Table 4. In both cases, the calibration and the validation test,  $\bar{e}$  and  $e\%$  were small, with  $\bar{e} = 1.0 \text{ t C ha}^{-1}$  ( $e\% = 2.1\%$ ) for calibration and  $\bar{e} = -1.62 \text{ t C ha}^{-1}$  ( $e\% = -3.19\%$ ). The model predicted the calibration data set (Fig. 1) with a high level of precision (ME = 0.912,  $r^2 = 0.924$ ).

For the validation, MAE% was 14.60% (7.407 t C ha<sup>-1</sup>) and RMSE% was 17.88% (9.071 t C ha<sup>-1</sup>), amounting to a difference of 1.66 t C ha<sup>-1</sup> or 3.28% of  $\bar{O}$ . Model efficiency was ME = 0.645 and correlation between predicted and observed values was  $r^2 = 0.730$ . Plotting measured above ground biomass growth against predicted growth of the validation dataset (Fig. 2) allows for a qualitative visual evaluation of model performance. Details of the performance of the model for the validation PSPs are presented in Table 5.

Table 4  
Statistical analyses of results from the calibration and validation simulations of above-ground biomass growth of *E. globulus*.

Data set	<i>n</i>	$\bar{e}$ (t C ha <sup>-1</sup> )	$\bar{e}\%$	MAE (t C ha <sup>-1</sup> ) (and MAE%)	RMSE (t C ha <sup>-1</sup> ) (and RMSE%)	ME	<i>r</i> <sup>2</sup>
Calibration	20	1.006	2.09	3.139 (6.51%)	4.635 (9.62%)	0.912	0.924
Validation	28	-1.618	-3.19	7.407 (14.60%)	9.071 (17.88%)	0.645	0.730

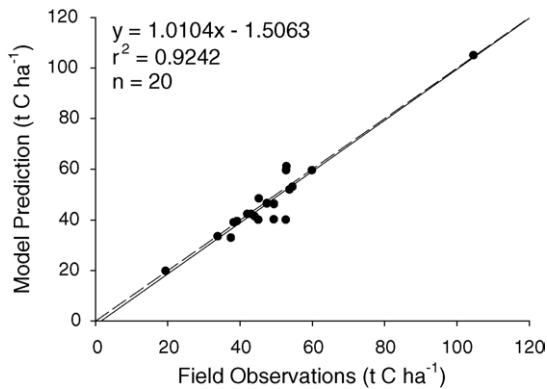


Fig. 1. Model predictions versus field observations of total above ground C (t C ha<sup>-1</sup>) for the calibration of Forest DNDC for predicting *E. globulus* biomass growth (*n* = 28, dashed line represents the 1:1 line, solid line represents the regression line).



Fig. 2. Model predictions versus field observations of total above ground C (t C ha<sup>-1</sup>) for the validation of Forest DNDC's capacity to predict *E. globulus* biomass growth (*n* = 28, dashed line represents the 1:1 line, solid line represents the regression line).

## 4. Discussion

### 4.1. Model performance

The statistical evaluation criteria  $\bar{e}$  and  $\bar{e}\%$  (Table 4) showed that the model is capable of predicting *E.*

*globulus* biomass growth with a good level of precision across a variety of environmental conditions and soil types without bias. Fig. 2 confirms that there was no systematic error. Within the available dataset there was no data for *E. globulus* plantations older than 6 years, as such, it was not possible to investigate the quality of growth predictions in older plantations reaching the end of their rotation cycle (9–11-year-old trees). A comparison of the total predicted aboveground biomass growth at age 4 years (1,052.5 t C ha<sup>-1</sup>) with the sum of all measurements taken in the same validation PSPs at age 4 years (981.5 t C ha<sup>-1</sup>) indicated that there might be a tendency to over predict the growth of younger stands (data not presented).  $\bar{e}$  was -7.23% for 4-year-old trees, but only -3.48% for 6-year-old trees (Table 5). A more negative prediction error means a stronger over prediction. This trend would suggest that the degree of over prediction decreases as the plantation ages. This may result in a slight under prediction of biomass growth in stands at harvest age. Nevertheless, the dataset of validation PSPs represented the upper age class of *E. globulus* plantations presently found in south-eastern Australia.

The difference between MAE% and RMSE% was only 3.28% or 1.66 t C ha<sup>-1</sup> (Table 4). That indicated that there were no cases with significant prediction errors (outliers). In combination, the individual prediction errors indicated a sufficient level of predictive precision for carbon accounting, with a ME of 0.645. However, model calibration and validation were carried out with interpolated climate data, which may have introduced further uncertainties to the performance test. Local site conditions such as exposure to wind or aspect differences are not captured in the SILO climate data. These conditions may greatly affect the precision of the model prediction. To overcome these uncertainties and distinguish between model error and climate data error the climate data would need to have been collected in the PSPs. Climate data at this scale is not available.

Table 5  
Measured and predicted above-ground biomass growth for *E. globulus* from 28 validation PSPs at age 6 years, with error in prediction

PSP	Plantation age (years)	Field measurement (t C ha <sup>-1</sup> )	Model prediction (t C ha <sup>-1</sup> )	Prediction error (t C ha <sup>-1</sup> )
1	6	41.184	44.154	-2.970
2	6	45.111	44.305	0.806
3	6	64.218	52.604	11.614
4	6	56.133	51.833	4.300
5	6	54.978	51.656	3.322
6	6	34.914	43.010	-8.096
7	6	48.081	43.008	5.073
8	6	41.679	49.573	-7.894
9	6	38.313	49.740	-11.427
10	6	43.659	49.741	-6.082
11	6	42.273	32.898	9.375
12	6	35.541	32.897	2.644
13	6	64.383	56.222	8.161
14	6	61.875	58.739	3.136
15	6	37.422	32.396	5.026
16	6	34.914	22.301	12.613
17	6	34.155	22.302	11.853
18	6	56.430	64.941	-8.511
19	6	42.603	66.097	-23.494
20	6	54.879	67.804	-12.925
21	6	50.523	47.394	3.129
22	6	47.025	48.611	-1.586
23	6	31.218	47.305	-16.087
24	6	71.379	76.839	-5.460
25	6	105.930	106.058	-0.128
26	6	61.281	66.659	-5.378
27	6	58.047	71.609	-13.562
28	6	62.040	64.786	-2.746
Sum		1420.188	1469.570	
Average		50.721	52.485	-1.764 (-3.48%)

#### 4.2. Comparison to other models

Most published process-based growth and yield models have been developed for tree species from the northern hemisphere. Models that focus on simulating the growth of *E. globulus* are BIOMASS, PROMOD, 3-PG and CABALA. These models have mainly been developed in Australia.

Hingston and Galbraith (1998) applied BIOMASS to five *E. globulus* plantations in Western Australia, but did not report any statistical indices of model performance. The authors reported that BIOMASS performed “reasonably well” in two plantations but had poorly predicted mean annual increment (MAI) in the other three plantations because factors affecting biomass allocation were not well understood. PROMOD (Battaglia and Sands, 1997) and 3-PG (Sands

and Landsberg, 2002) have been validated for the MAI of *E. globulus* at 19 sites, 15 in Northern Tasmania and 4 in Western Australia (Table 6). CABALA has been validated against the same 15 sites in Northern

Table 6  
Comparison of the capacity ( $r^2$ ) of four process-based models to predict biomass growth of *E. globulus* plantations in Australia

Model	Validated output variable	$r^2$	Source
CABALA	Standing volume	0.94	Battaglia et al. (2004)
PROMOD	Mean annual increment	0.81	Battaglia and Sands (1997)
Forest-DNDC	Above ground biomass	0.73	
3-PG	Mean annual increment	0.71	Sands and Landsberg (2002)

Tasmania, but for standing volume, rather than MAI (Battaglia et al., 2004). CABALA is based on PROMOD, but with additional process-based sub-modules (e.g. modules for frost damage, constraints on stomatal conductance and biomass allocation). A comparison of the predictive capacity of these models and Forest-DNDC used in this study is presented in Table 6.

A direct comparison of the predictive capacity of these 3 models with Forest-DNDC is difficult as different datasets were used for model validation. Nevertheless, Table 6 shows that CABALA ( $r^2 = 0.94$ ) and PROMOD ( $r^2 = 0.81$ ) can predict growth with a high level of precision. These two models have been developed to support silvicultural decisions and management in *E. globulus* plantations. Forest-DNDC ( $r^2 = 0.73$ ) predicted growth to a lesser level of precision, probably because of its more general representation of parameters that influence growth. A variety of parameters such as total available rooting depth, total plant available soil water, variable performance of different genetic strains of *E. globulus*, foliar frost damage and recovery or the influence of site preparations techniques are not taken into account by Forest-DNDC. The greater precision of CABALA and PROMOD is offset by the need for many more detailed input parameters making them less suitable for regional simulations, where certain parameters may not be readily available. However, PROMOD has been applied successfully to highlight suitable sites for plantation establishment across Tasmania (Mummery and Battaglia, 2001). The 3-PG model performed as well as Forest-DNDC, both models being less input demanding than CABALA and PROMOD. The input requirements of the Forest-DNDC model have been kept minimal so that it can operate from readily available spatial data sets to produce regional budgets of productivity, sequestration and atmospheric gas exchange. However, these low parameter requirements do not appear to have compromised the precision of Forest-DNDC's predictive capacity, such that it was able to satisfactorily predict *E. globulus* biomass growth across a variety of climatic and edaphic situations in Victoria.

## 5. Conclusion

The process-based biogeochemical model Forest-DNDC has been calibrated and validated successfully for growth of *E. globulus* for the first time.

Forest-DNDC was applied to a validation dataset of growth measurements taken in 28 PSPs in south-eastern Australia, from *E. globulus* trees aged 4 and 6 years. The model predicted above ground biomass growth with a mean error in prediction of  $-1.62 \text{ t C ha}^{-1}$  or  $-3.19\%$  (Table 4). The minor difference between the mean absolute error in prediction (MAE =  $7.407 \text{ t C ha}^{-1}$ ) and the root mean square error of prediction (RMSE =  $9.071 \text{ t C ha}^{-1}$ ) of  $1.664 \text{ t C ha}^{-1}$  or  $3.28\%$ , indicated that there were no cases with significant prediction errors. The Nash–Sutcliffe index of model efficiency (ME = 0.645) and the correlation between measured and predicted growth ( $r^2 = 0.730$ ) indicated that Forest-DNDC is capable of producing reliable growth predictions across a variety of environmental conditions. Forest-DNDC performed as well as other tree growth models (e.g. BIOMASS, CABALA, PROMOD, 3-PG) that have been applied to *E. globulus* in Australia. The advantage of Forest-DNDC is its capability to estimate total greenhouse gas budgets (NO, N<sub>2</sub>O and CH<sub>4</sub>) in addition to biomass growth (Stange et al., 2000). It can therefore assist in global change modelling and modelling the atmospheric impact of land use change scenarios.

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