

Estimating NPP and impacts of climate change on sandy soils in Australia using a soil carbon model calibrated to measurements of soil carbon, nitrogen and carbon isotopes

John Carter^{1,2}, Jonathan Wynn^{3,2} and Michael Bird^{3,2}

¹Natural Resource Sciences Centre, Department of Natural Resources, Mines and Energy, Indooroopilly, Qld4068, Australia.

Email: john.carter@nrm.qld.gov.au

²CRC Greenhouse Accounting, Australia.

³Research School of Earth Sciences, Australian National University, Canberra, ACT, 0200, Australia; current address: School of Geography and Geosciences, University of St. Andrews, St. Andrews, KY16 9AL, United Kingdom; jonathan.wynn@st-andrews.ac.uk, michael.bird@st-andrews.ac.uk

Abstract

The CENTURY model was modified and calibrated to a robust data set from 31 regions of sandy soils using landscape average measurements of soil carbon, nitrogen and $\delta^{13}\text{C}$, $\delta^{14}\text{C}$ and some remotely sensed data. The 31 regions covered the full range of climate experienced in Australia including temperature extremes from Katherine in the Northern Territory to Cape Grim in Tasmania, and rainfall extremes from desert sand hills in the interior to tropical rainforests of the east coast of Queensland. A genetic algorithm was used to calibrate generic parameters describing ecosystem attributes such as N inputs, N loss after fire, and plant growth sensitivity to temperature. In addition one or two site specific parameters relating to fire frequency were calibrated for each individual site. The model was spun up for a period of at least 5000 years to equilibrate isotope pools. Atmospheric $\delta^{13}\text{C}$ and $\delta^{14}\text{C}$ concentrations were varied annually to incorporate the Suess effect and bomb pulse C. The modified model was able to describe the variation across sites in terms of C, N, $\delta^{13}\text{C}$ and $\delta^{14}\text{C}$ reasonably well but with some exceptions. Simulated NPP was close to estimates obtained independently from remotely sensed data. Following model calibration, climate change scenarios were run for 70 years in the future to assess the sensitivity of the tree-grass-soil system to future climate and increasing atmospheric CO_2 .

Key Words

Isotope, atmosphere, NDVI, transpiration

Introduction

Sandy soils with less than about 10% clay content cover approximately one third of Australia and a further one third of Australia has soils with less than 20% clay in the surface. Many of these soils occur in arid and semi-arid regions although smaller areas occur in more mesic locations. Sandy soils are not widely used for agriculture and light grazing is the predominant land use. The vegetation on these soils ranges from tropical rainforest with no grassy understorey to arid spinifex (*Triodia Spp.*) pastures with few trees. Fire regimes range from nearly annual to almost total absence of fire. Understorey species range from almost pure C_4 in hot arid regions to pure C_3 in cold wet environments. Net primary production (NPP) is estimated to range from about 50 to 1000 $\text{gC/m}^2/\text{year}$ and soil carbon stocks range from 500 to 10000 gC/m^2 to a depth of 30 cm. These carbon stocks both above and below ground are potentially vulnerable to management and climate change because of low nutrient status and low protection of organic matter by clay minerals. Modification of fire regimes may allow N limited systems to gradually accrete or lose carbon in above and below ground pools and change the tree grass balance. The amount of grass or trees in any region is a function of disturbance (frequency and intensity) and the relative competitiveness of trees and grasses at any level of potential growth as determined by water availability and fertility. The balance of trees and grasses is critical when investigating C stocks under global change. Increasing or decreasing tree density in savanna systems can make large changes in above ground carbon stocks in these systems. Our aim is to simulate carbon, carbon isotope and nitrogen stocks and NPP (following the example of Jenkinson *et al.* 1999) over a range of environments and to develop as far as possible a generalised set of parameters that has applicability over the sandy soils of Australia.

Methods

Field Sampling Methodology

Thirty-one regions of sandy soil (Figure 1) were sampled using a stratified methodology which estimates carbon inventories across the distribution of trees and grass using a set of samples taken near trees and

away from trees ("tree" and "grass" samples). The average percentage canopy cover, measured at each sampling location, was used to apportion the representation of tree and grass samples. At each of the 31 regions, a total of 200 soil cores were collected according to the following protocol. Five transects were established at least 1 kilometre apart within a region of a given soil type and narrow climatic variability. Along each of the 5 transects, a total of 5 locations were sampled, each at least 100 m apart. At each of these locations, a total of 8 soil cores were taken at two depth intervals (5 and 30 cm) from 4 types of sampling position. One 30 cm deep core was taken from both a tree and a grass position and 5 cm deep cores were also taken from three tree and grass positions. Each group of three cores was bulked to make two 0–5 cm samples. This sampling regime produces two 0–30 cm and two 0–5 cm samples from each location, totalling 20 samples from each transect and 125 samples from each region. Sand content (<63 μm) in the samples ranged from 80% to 99%. Rainfall across these regions ranged from 133 to 1850 mm/year and annual average temperature from 12.2 to 27.9 °C. While the data set covers a range of climates it is biased towards wetter locations. The average annual rainfall for the set is 876 mm while the continental average is about 450 mm. As sites were not representative of the average for sandy soils a weighting value was determined for each site based on its representativeness of sandy soils in rainfall and temperature space.

Sample Preparation and Analytical Methodology

A series of 24 bulked samples from each region was used in the analyses. Four "bulk-bulk" (-BB) samples were prepared for each sample type: 0–5 cm tree (5T), 0–5 cm grass (5G), 0–30 cm tree (30T) and 0–30 cm grass (30G). Each of these samples contains 1/25th of the specified sample type from the 25 locations of that type within the region. Twenty "single-bulk" (-B) samples represent the averages of the four sample types (5T-B, 5G-B, 30T-B, 30G-B) over 5 transects, each containing 1/5th of the sample from the 5 locations within each transect. Measurements of any soil property in the -BB samples were considered to represent the mean value for the region, while an estimate of the spatial variability of the property can be determined from the variability evident in the 5 -B samples from each transect. Mass concentration of solids (or "dry bulk density") for each of the 4 -BB samples, and 20 -B samples from each region was determined based on the average of all individual samples of that type. Organic carbon concentration of the -BB samples was measured manometrically after combustion to CO₂ and cryogenic purification. The stable carbon isotope ratio of CO₂ produced by combustion was measured by dual-inlet mass spectrometry. All stable isotope measurements are reported in standard δ -notation with respect to the VPDB scale. Carbon concentrations and stable carbon isotope ratios of -B samples were measured using elemental analysis-continuous flow mass spectrometry at the Australian National University. For each of the 31 sand soil regions, -BB samples of tree and grass samples from the 0–30 cm depth interval were mixed in proportion to the canopy cover (a "bulk-bulk-bulk" -BBB sample) and analysed for C-14 activity by conventional radiocarbon methods. Radiocarbon measurements are reported in δ -notation with respect to Oxalic Acid standard.

Carbon model and Optimisation

A version of Century version 4.0 (Parton *et al.* 1992), was customised in the following ways: vegetation $\delta^{13}\text{C}$ and $\delta^{14}\text{C}$ was modified by changes in atmospheric concentrations; radioactive ^{14}C decay was added to the model, charcoal from grass and litter burning was moved directly into the slow pool; isotopic fractionation of charcoal from C₄ grasses was simulated (Krull *et al.* 2003); N mineralisation was modified to make it sensitive to soil moisture and temperature; and decomposition rates were made sensitive to low pH values. The model was run in savanna mode regardless of the vegetation that existed at each site and the tree/grass balance was allowed to be determined by the model. Parameters defining decay rates were set to values appropriate for a 30 cm depth. A framework was coded to allow automatic parameterisation across all sites by running the model in inverse mode. Optimisation was carried out using a genetic algorithm (GA) (Carroll 1996). This code initialises a random sample of individuals with different parameters to be optimised using the genetic algorithm approach, i.e. evolution via survival of the fittest. The selection scheme used was tournament selection with a shuffling technique for choosing random pairs for mating. The routine included binary coding for the individuals, jump mutation, creep mutation, and the option for single-point or uniform crossover, and a micro-GA. The micro-GA facility generated a new population of fittest individual and random other members when the variability in the population was less than 1%. The concept of multiple constraints was used to limit the possibility of non-unique parameter sets, and upper and lower bounds for parameters based on *a-priori* estimates of plausible values were used to limit search space.

$\delta^{13}\text{C}$ of woody vegetation was estimated from the relationship demonstrated by Miller *et al.* (2001) but constrained at high rainfall to a minimum value of -29.0 . The isotope ratio for the ground layer was based on the measured $\delta^{13}\text{C}$ ratios with the proportion of C_4 contributing to the $\delta^{13}\text{C}$ ratio based on modifications of the relationships devised by Hattersley (1983) and from other published sources e.g. Bowman & Cook (2002). Atmospheric CO_2 was set to 280 ppm before 1890 and transitioned in a linear manner to 370 ppm in 2004, or 586 ppm in 2070 SRES92a (IPCC 1996). Atmospheric $\delta^{13}\text{C}$ concentration was estimated from an equation fitted to data from Cape Grim (Francey & Allison 1998) and the Siple ice core (Neftel *et al.* 1994). Annual atmospheric $\delta^{14}\text{C}$ data for the southern hemisphere was taken from the INTCAL98 radiocarbon age calibration data set (Stuiver *et al.* 1998) and the high-precision radiocarbon age calibration for terrestrial and marine samples data set (Stuiver *et al.* 1998).

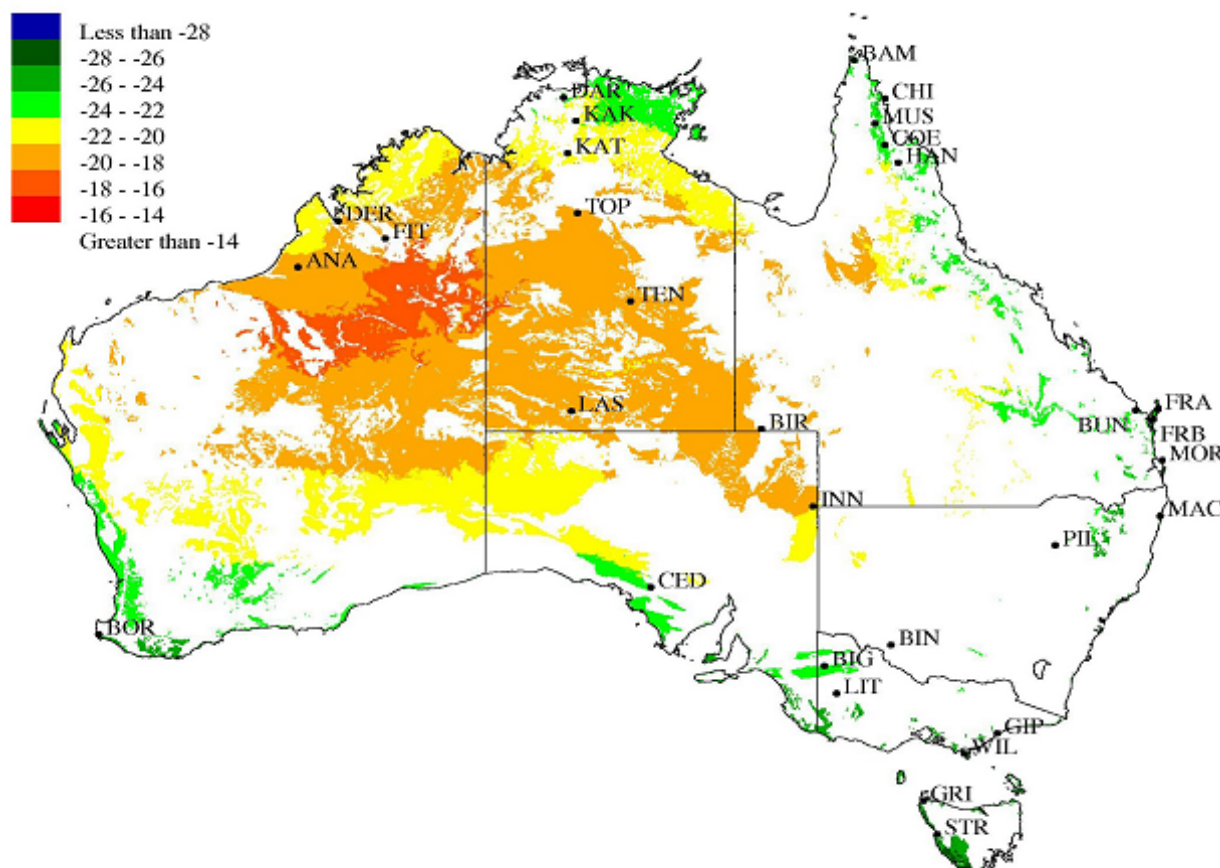


Figure 1: Sampling site locations and map of sandy soils showing estimated $\delta^{13}\text{C}$ interpolated as a function of average vapour pressure deficit (VPD).

National Oceanographic and Atmospheric Administration (NOAA) Normalised Difference Vegetation Index (NDVI) satellite data were taken from single pixel data from the Pathfinder dataset (Agbu & James, 1994). The ten-day data composites were further composited to monthly means, and long-term means. Some data was eliminated due to obvious cloud masking / cloud shadow omissions. Fire frequency was estimated during model optimisation and simulated fire frequency of most sites was constrained within the published low and high fire return intervals (Walker *et al.* 1981). Due to the broad scale nature of fire mapping a number of rainforest and island sites were given longer fire return constraint intervals than from Walker's estimates, while several sites were assigned shorter intervals. Charcoal carbon input from fire was constrained to a minimum of 0.9% of standing fine fuel (Carter, unpublished data) and to between 2 and 7% for grass and tree litter biomass (Graetz & Skjemstad, 2003). N input was set as a function of annual precipitation, and additional inputs from non-symbiotic fixation and other sources were included in this source to simplify optimisation. Carbon nitrogen ratios for the various vegetation types were set from literature values. Maximum tree leaf area index (LAI) was constrained to a function of mean NDVI based on data developed by McVicar (1996) for Australian plant communities, $\text{LAI} = -0.57239 + 1.48146\text{e-}6 * \text{NDVI}^3$ (NDVI scale 0-255).

For three sites (LAS, INN and BIR) it was necessary to include an estimate of wind erosion, and drainage was constrained in several sites (GRI, GIP, DAR) as no sensible combination of parameters could reproduce carbon stocks at these sites. Field notes and photographs supported the assumptions made. Accurate estimates of parameters, such as degree of saturation, could conceivably be obtained from remote sensing but are not yet available at the continental scale. As a result model estimates are somewhat better than could be expected from a simulation for areas without detailed site descriptions.

The weighting values, determined by representativeness in temperature-rainfall space, were used in climate change studies to estimate average changes over all sandy soils in Australia. Daily rainfall climate from SILO (Jeffrey *et al.* 2001) was used to construct monthly climate data sets and calculate statistics for the generation of stochastic rainfall for use in the spin up period. Climate change scenarios (CSIRO, 2001) were generated for the period 2004–2070 using high and low estimates of rainfall and temperature for each region. The changes in temperature and rainfall were applied in a linearly increasing manner to a rolling sequence of measured 1970–2003 climate variables for each site for rainfall (Figure 2) and temperature (Figure 3). Temperature changes were assumed to increase minimum temperatures more than maximum temperature (66% and 34% of increase respectively).

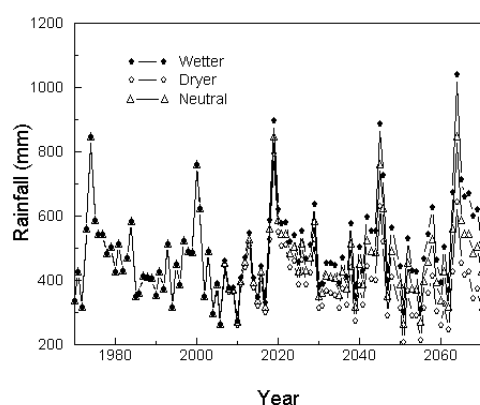


Figure 2: Average rainfall trends for climate change scenarios.

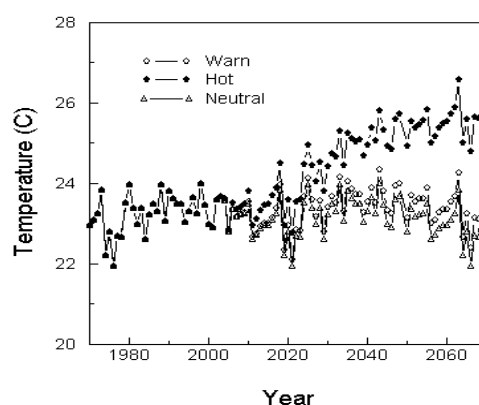


Figure 3: Average temperature trends for climate change scenarios.

Parameter optimisation

Total C, N, C:N ratio, NPP, $\delta^{13}\text{C}$ and $\delta^{14}\text{C}$ were estimated for each model run for each site and absolute errors were accumulated into a fitness score. Specific evaluations were made of the correlation of NPP to estimated annual average transpiration and long term mean NDVI. Multiple linear correlations were run for each site between leaf mass (grass and tree) and time series NDVI data from the Pathfinder series were added to the objective function. For C, N, $\delta^{13}\text{C}$ and $\delta^{14}\text{C}$ in global parameterisation, errors were weighted by the variance in the observed data where available. Because the dynamic range of errors was greater than 3 orders of magnitude (e.g. C vs. $\delta^{13}\text{C}$ errors), scores were treated such as to give them approximately equal weighting to avoid undue weight being placed on parameters controlling estimation of total soil carbon stocks. Cross validation approaches are yet to be evaluated.

In total there were 124 soil chemistry observations, 31 estimates of tree canopy cover and 31 time-series of NDVI (of varying length due to cloud cover) used to automatically estimate 45 parameters, 14 of which are global (i.e. apply to all sites) and 31 of which apply a fire frequency at each site. Parameters optimised (identified by sensitivity analysis) included: maximum decay rate and maximum C:N ratio for material entering the passive pool; slope and intercept for N input as a function of rainfall; slope and intercept for optimum growth temperature for trees and grasses; tree temperature response when temperature was less than optimum; slope and intercept for site potential for grass production as a function of VPD; ratio of rain/potential evaporation below which there is maximum negative impact of soil anaerobic conditions on decomposition; the minimum ratio of available water to potential evaporation which would completely limit production; minimum C/E ratio for surface microbial pool; proportion of charcoal and N returning from burnt material, proportion of live trees killed by fire; and maximum gross monthly production.

Some parameters were not solved directly as model inputs but were estimated indirectly from external variables that were available spatially. Temperatures for optimum growth for trees and grasses were determined from regressions on temperature of the wettest quarter where slopes and intercepts were determined by optimisation. In addition to the automatically optimised parameters, a range of about 20 other parameters were manually adjusted. These parameters were associated with soil erosion, drainage and plant partitioning. Additionally model NPP was compared to NPP estimates derived from an empirical function of NDVI (Prince 1991).

Results

Model Calibration

The model calibration results show that the global set of parameters could be found which explained a high proportion of the variation between sites in soil carbon (Figure 4), N, $\delta^{13}\text{C}$, estimated NPP and to a lesser extent C:N ratio and $\delta^{14}\text{C}$.

Carbon 13 isotope and tree-grass competition.

The model simulates $\delta^{13}\text{C}$ adequately (Figure 5) at most sites indicating that the ratio of inputs from trees and grasses for northern Australia is correct. Several sites (KAK, COE) are apparently less grassy (with C_4 species) than indicated by the model and it is difficult to obtain a set of parameters to explain these data. In these cases trees may be accessing significant deep soil water that is not available to the grasses.

Nitrogen stocks and C:N ratios

Nitrogen is moderately well simulated. The modelled mean for all sites is close to the simulated mean and overall there is a 1:1 relationship between observed and predicted values (Figure 6). However there are considerable discrepancies at individual sites. Inputs from legumes, pH, and losses from leaching and fire may account for some of these anomalies. The sand islands (FRA, MOR) on the coast of Queensland showed the highest C:N ratios (~45) and desert sand dunes (BIR, INN) showed the lowest C:N ratios (~6). The sites WIL and STR have lower simulated N than measured N for reasons that are not readily apparent. The range of C:N values (Figure 7) matches the observed range. However, in general C:N ratios are poorly simulated. Input of N from atmospheric sources (wet and dry deposition) is a key model input and control on NPP. Using optimised parameters and Australian average rainfall the mean continental atmospheric N input is estimated at 3 kg/ha/year.

Carbon 14 Bomb Pulse

The model significantly underestimated ^{14}C at a number of sites with GRI and GIP being the worst outliers (Figure 8). At these sites there is almost no incorporation of bomb pulse carbon into the top 30 cm of the soil profile. To account for this both C input and decay rates of biomass would need to be much lower than suggested by the model, or alternatively, the proportion of vegetation decaying directly to CO_2 rather than passing through the soil needs to be much higher.

NPP Estimates

NPP estimates for the sites range from 1 T/ha/year to 20 T/ha/year. These values seem plausible and match estimates made directly from remote sensing (Figure 9). Estimates of above ground NPP derived from accumulated NDVI days as parameterised for the Sahel in Africa by Prince (1991) shows that the correlation between the model and empirical NDVI based approaches appears robust with small deviation at higher values of NDVI. NPP / AET (evapotranspiration) estimates calculated by the model were consistent with those from global studies (Schimel *et al* 1996). Fully wooded low VPD sites had higher water use efficiency than grasslands. Across all sites transpiration use efficiency (not adjusted for VPD) was 11.9kg biomass/ha/mm.

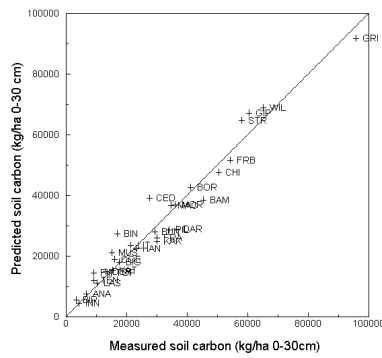


Figure 4. Soil carbon with 1:1 line,
 $y = 2126 + 0.95 * x$, $r^2 = 0.95$

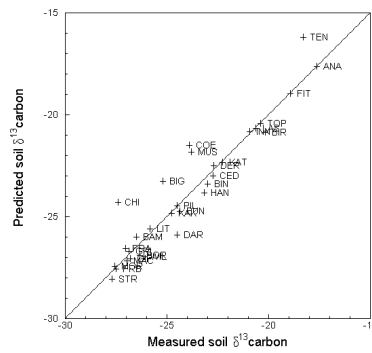


Figure 5. Soil $\delta^{13}\text{C}$ with 1:1 line,
 $Y = 0.78 + 0.99 * x$, $r^2 = 0.89$

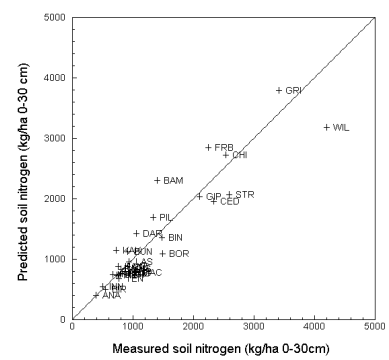


Figure 6. Soil nitrogen with 1:1 line.
 $y = 152 + 0.87 * x$, $r^2 = 0.85$

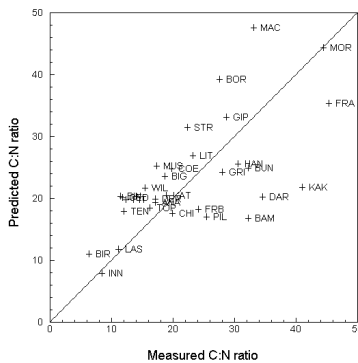


Figure 7. C:N ratio with 1:1 line
 $= 10.4 + 0.57 * x$, $r^2 = 0.42$

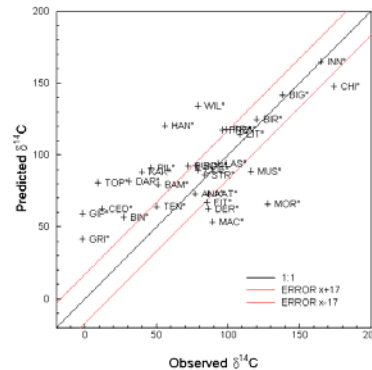


Figure 8. $\delta^{14}\text{C}$, with 1:1 lines
parallel to 1:1 line represent
average measurement error.
 $Y = 55.4 + 0.46 * x$, $r^2 = 0.46$

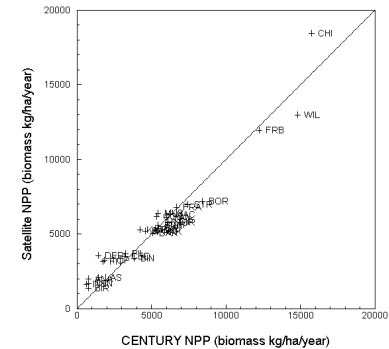


Figure 9. Net primary production
from CENTURY and from
average NDVI
 $Y = 772 + 0.91 * x$, $r^2 = 0.94$

Discussion

Demonstrating that a model can be calibrated to a number of different variables simultaneously with a largely generic parameter set is a strong test of model functionality. Stable parameter sets were usually obtained in 300-500 model iterations. However one set of stable parameters does not preclude other sets of parameters (or model formulations) that are nearly as effective in reducing error but that are more realistic. C and N at all sites are not likely to be easily explained without a priori knowledge of local conditions and other nutritional limitations. Sites on sand islands off the coast of Queensland are an example (FRA, FRB, and MOR). C stocks are likely to be determined by age and leaching of nutrients such as P. While the CENTURY model caters for both leaching and phosphorus it is not easy to calibrate the model and invoke model runs of several hundred thousand years. Instead parameters such as fire regime are modified by the optimisation procedure to explain the properties of these locations.

Initial testing of the model using only predictions of carbon to calibrate the model gave better predictions of soil carbon than in the final simulation (Figure 4). When the number of predicted variables was increased, the fit statistics for any one variable declined, indicating that elements of model functionality or parameterisation were inadequate. Total soil C was generally well simulated over a wide range of values with most simulated values being within one standard error of the measured data. At two sites (CED, BIN) the model consistently overestimated the amount of soil carbon and simulated $\delta^{14}\text{C}$ values were younger than measured. It is possible that soil erosion has removed surface materials at these sites. C stocks at two sites were consistently underestimated (DAR and KAK). At these sites $\delta^{14}\text{C}$ age was underestimated as was the C:N ratio. This is suggestive of too little charcoal being simulated and the need to have a separate pool for charcoal with a slower rate of decay than for the passive pool in general. It is possible that at these sites additional charcoal may have been deposited by water.

Fire Frequency

The mean pre-European fire interval for our sites (with the exception of rainforest sites CHI and FRB) was 9.9 years between fires compared to a mean fire interval of 8.4 years estimated by Walker *et al.* (1981) for the same locations. There is accumulating evidence that in many parts of Australia fire frequency is declining due to fragmentation of fuel resulting from land development, and a reduction of fuel due to grazing.

Climate change impacts

The change in carbon stocks (derived from the weighted change from each individual site) from the present day to 2070 over a range of climate scenarios (Table 1) suggests small increases in soil C stocks (~4%) and small losses in woody biomass carbon under drier conditions but accretion under wetter or neutral conditions with the assumption of no change in fire frequency or severity. It is possible that CO₂ fertilisation is providing some gains in vegetation and soil carbon as the model predicts increases in C stocks of about 5% with no climate change (neutral) conditions. Nitrogen availability may well be limiting response to increased CO₂. While the changes are small, the areas are large (one third of the continent) and a 1 tonne per hectare change in carbon stocks on sandy soils translates roughly to a change of 250 Mt in C stocks over the next 67 years. Simulations of $\delta^{14}\text{C}$ values suggest that C stocks have longer turnover times and are probably more stable than model simulations of $\delta^{14}\text{C}$ values would suggest.

Table (2) Projected changes in woody biomass carbon and soil carbon in Australian sandy soils (0-30cm) under a range of climate change scenarios and CO₂ fertilisation.

Rainfall Scenario	Temperature Scenario	Tree carbon (t/ha)	Soil Carbon (t/ha/30cm)	% of current woody biomass C	% of current soil C
Current (2004)	Current (2004)	28.66	16.49	100	100
Dryer	Neutral	27.46	17.05	95.8	103.4
Dryer	Warm	27.49	17.01	95.9	103.1
Dryer	Hot	27.52	16.79	96.0	101.8
Neutral	Neutral	30.23	17.22	105.5	104.4
Neutral	Warm	30.31	17.18	105.8	104.2
Neutral	Hot	30.52	16.93	106.5	102.7
Wetter	Neutral	31.62	17.35	110.3	105.2
Wetter	Warm	31.74	17.31	110.7	105.0
Wetter	Hot	32.07	17.04	111.9	103.3

Conclusion

The great diversity of sandy soils, vegetation and climate is a significant modelling challenge. Parameterisation under multiple constraints increases the likelihood that parameters on average are correct and the model is robust over a diverse range of conditions. Simulations of climate change scenarios and the impact of CO₂ suggest that soil C stocks in sandy soils are relatively stable but there is a risk of loss of vegetation carbon under drying scenarios.

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