A continental biomass stock and stock change estimation approach for Australia

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Revised manuscript received 27 September 2004

Summary

To implement Australia's National Carbon Accounting System it is necessary to estimate biomass stock, continentally, and change in stock, at a sub-hectare spatial resolution. The approach developed to meet this requirement is a hybrid between GIS-based process modelling and empiricism.

Multi-temporal mapping of productivity was carried out using a variant of the 3PG (physiological principles predicting growth) model. Relationships were found between mapped productivity indices and measurements of biomass at maturity (i.e. long-term-undisturbed stands). This information was then used to interpolate maps of biomass potential.

Simple growth formulae were used to plot biomass accumulation, with the 'rate of approach to mature biomass' set by the age at which maximum current annual increment occurs and the predicted site plant productivity over time. The age of the forest stand was determined from disturbance events detected by twelve national coverages of Landsat MSS, TM and ETM+ remotely-sensed data collected between 1972 and 2002. Responses to thinning of existing forests are calculated using an adjustment of stand age concurrent with the intensity of the thinning event.

Keywords: carbon; carbon sequestration; models; accounting; inventories; area; remote sensing; forest management; productivity; growth rate; increment; thinning; Australia

Introduction

Australia's National Carbon Accounting System (NCAS) will provide a comprehensive carbon accounting capability for Australia to report on related international obligations, to support domestic policy development, and to monitor carbon stock change at fine resolution in support of project-level carbon accounting. Australia's international carbon accounting commitments include the United Nations Framework Convention on Climate Change and its Kyoto Protocol, and the Montreal Process.

To achieve this capability, the Commonwealth Government committed $12.5 million over five years (1998/99–2002/03) for development of the NCAS. The NCAS considers all forms of greenhouse gases and activities in both the agricultural and forestry sectors.

The decision to implement a comprehensive and integrated NCAS was based on the development of a critical mass of resource information and significant core capabilities that have broad applications. The most significant of these is coverage of Australia by twelve Landsat MSS (1972–1988) and TM/ETM+ (1988–2002) data sets. The pixel resolution of the data is 50 m for MSS and 25 m for TM/ETM+ (Furby 2001). Another core product was interpolated monthly climate maps of Australia for rainfall; evaporation; minimum, maximum and average temperature; and number of frost days per month. Slope and aspect-corrected 250 m resolution solar radiation measurements, direct and diffuse, were also developed (Landsberg and Kesteven 2001). Together these products provided the time-variable process-based inputs to the modelling activities of the NCAS.

A major objective of the NCAS is the measurement of change in carbon stocks: uptake and loss of carbon by biomass, litter and soil. In both agricultural and forestry land systems this requires estimation of tree biomass, including changes due to growth and loss from land clearing and forest harvest.

The specific issue addressed in this paper is the development of a model to estimate biomass stock and growth. The methods used in the FullCAM model to estimate continental carbon stocks and change for the NCAS are described. Richards (2001b) provides a broader account of the development of NCAS.

This paper is the second of a series of three in this issue of *Australian Forestry*. The other two papers in the series:

(i) describe the development of the integrated carbon accounting model FullCAM, and
(ii) apply the model to account for carbon in the post-1990 national plantation estate, using inventory approaches based on stem volume.

Methods

Method selection

Several possible methods were available to implement a national program to estimate biomass for the NCAS. These included direct estimation via a range of remote sensing techniques such as radar and lidar, field sampling such as stratified random or plot sampling (inventory approaches), and process modelling.

The main determinants of the choice of method were that:

1. measurement should be dynamic through time, and include estimates as far back as the early 1970s;
2. all forests (some 160 million ha of managed and unmanaged forests) should be included;
3. measurements should have a spatial resolution of less than one hectare and take account of biomass stock, disturbance history and growth at a corresponding scale; and
4. the land-based accounting should conform with the Kyoto Protocol requirement that qualifying land units are reported upon (i.e. the accounting of carbon stock changes and emissions relevant to each relevant land unit through time).

These criteria require a dynamic approach at a fine temporal and spatial scale. Conventional measurement (inventory) of Australia's forests at such a fine scale is, however, not feasible. There are also insufficient data to construct historic inventories. This means that measured (inventory) approaches alone are not a practical means of implementing the requirements of the United Nations Framework Convention on Climate Change and the Kyoto Protocol in Australia's circumstance.

The historic requirement (i.e. estimates back to the early 1970s) for forest disturbance data (land clearing, harvest, reforestation) meant that contemporary remote sensing techniques such as radar and lidar, which were not generally available until the early 1990s, could not be used. However, the optical instrument Landsat was available over this period, and could be used to identify canopy disturbance at a fine resolution, therefore providing the ability to determine forest age.

Under the circumstances, the available approaches were limited to the use of process or empirical growth modelling, supported by the identification of forest disturbance using Landsat data. Unfortunately the paucity of mensurational data for many non-commercial forest types (and supporting models to estimate total biomass from measured stem volume or basal area) meant that empirical growth modelling was not a feasible approach. The applicability of process-based growth models was also limited as none of the models was widely calibrated for the range of forest systems under consideration.

Continental biomass inventory

The available options for the design and implementation of a continental biomass inventory, given the available information, were developed via an expert workshop (CSIRO 2001a,b). The recommendation was to develop a hybrid approach using remote sensing (Landsat), and empirical and process models (see Richards 2001a,b).

CSIRO Forestry and Forest Products was engaged to compile a data-base of biomass measurement from published and unpublished studies, providing each had adequately reported methods, as needed to establish confidence in the robustness of the data. The data are representative of Australia's major forest types, ranging from savannahs to rainforest. The spatial distribution also covered most of Australia. The data compilation is available from the authors on request.

A key element of this approach is the use of Landsat data to provide fine-resolution data on disturbance history over a 30-y period, which in turn can be used to estimate stand age. The forest type disturbed is extracted by merging the disturbance history mapping and the vegetation mapping of the National Vegetation Information System prepared by the National Land and Water Resources Audit.

Index of biomass productivity

The hybridisation of empirical and process modelling to determine an index of productivity was achieved by using the monthly climate surfaces developed for the NCAS (Kesteven *et al.* 2004) in conjunction with CSIRO's national soil moisture holding capacity and fertility mapping (McKenzie *et al.* 2000), the nine second (250 m) Digital Elevation Mapping Version 2.0 (AUSLIG 2001), and Normalised Difference Vegetation Index (NDVI) data of the Environmental Resources Information Network (ERIN), to produce a relative index of productivity, both spatially and temporally. The monthly climate surfaces (Kesteven *et al.* 2004) were derived using the ANUCLIM software (McMahon *et al.* 1995) and Bureau of Meterology weather station data. The model used to develop the productivity mapping was a modified version of the 3PG model (Landsberg and Waring 1997; Coops *et al.* 1998; Coops and Waring 2001; Landsberg *et al.* 2001). The development of the productivity index mapping (Fig. 1) is reported in Landsberg and Kesteven (2001).

Results

Correlating biomass and productivity

The empiricism was introduced in relationships derived between productivity maps and available above-ground biomass measurements. The spatially-referenced data for sites with no reported recent disturbance were then plotted against calculated long-term average productivity. This regression considered biomass accumulated (with no known disturbance history) against the long-term average productivity of the site. The relationship between mass and productivity was then used to derive a map of potential site biomass at maturity (i.e. for long-term undisturbed stands).

A linear regression found a significant correlation ($P < 0.01$, $r^2 = 0.68$) between long-term above-ground stand biomass (M) and long-term average productivity (P_{avg}). A square root transformation of both dependent and independent variables was required to meet assumptions of normality and homogeneity (Fig. 2):

$$M = (6.011 \times P^{1/2} - 5.291)^2 \qquad (1)$$

where P is the long-term average productivity index and M is the above-ground biomass in t dry matter ha^{-1}.

Other linear and non-linear regression models were tested to explore the relationship between mass and productivity, but none of these alternatives showed any marked improvement over (1) in error distribution or in root mean square error. The higher-order polynomial equations and logarithmic transformation also resulted in models that could not reasonably be extrapolated.

The regression approach has an advantage over a purely process-driven model which has been shown to generally over-predict site biomass since factors such as insect attack are not taken into account (Kurz *et al.* 1998). The potential (site) biomass estimate represents the biomass which growth will generally approach.

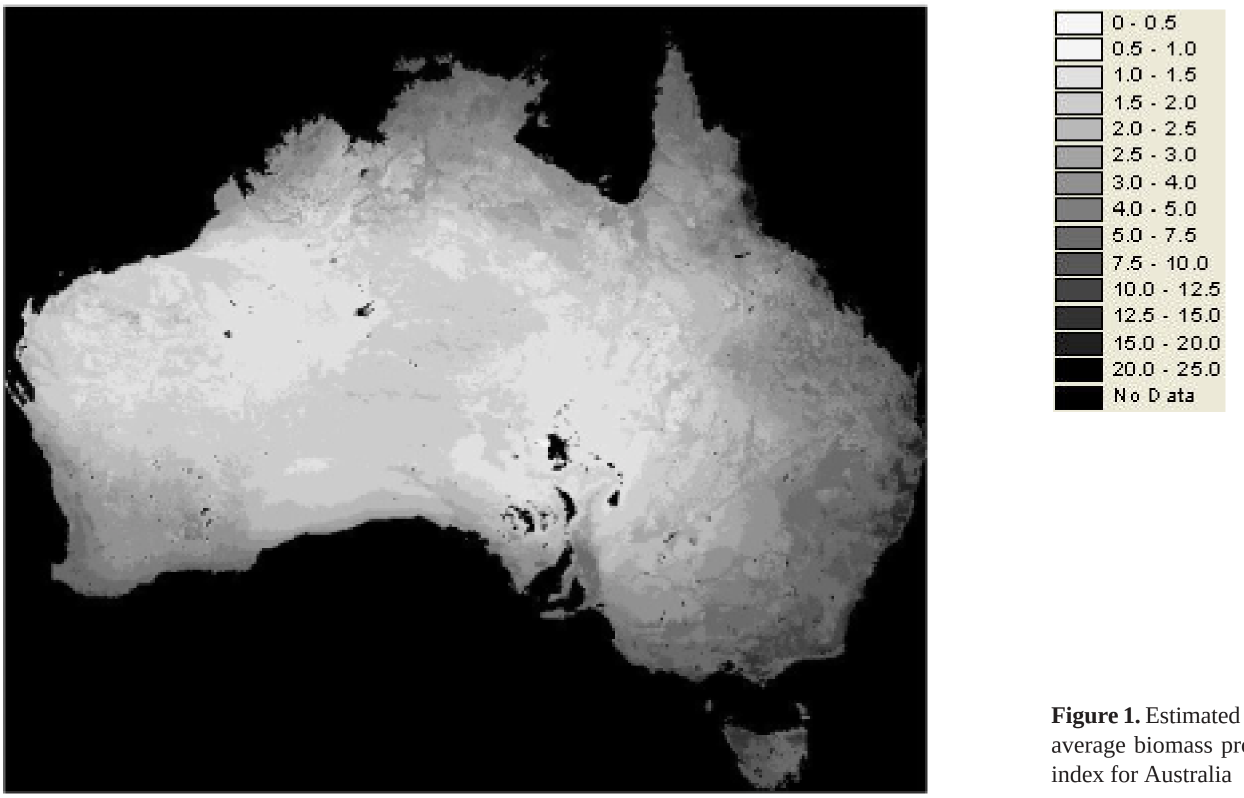

Figure 1. Estimated long-term average biomass productivity index for Australia

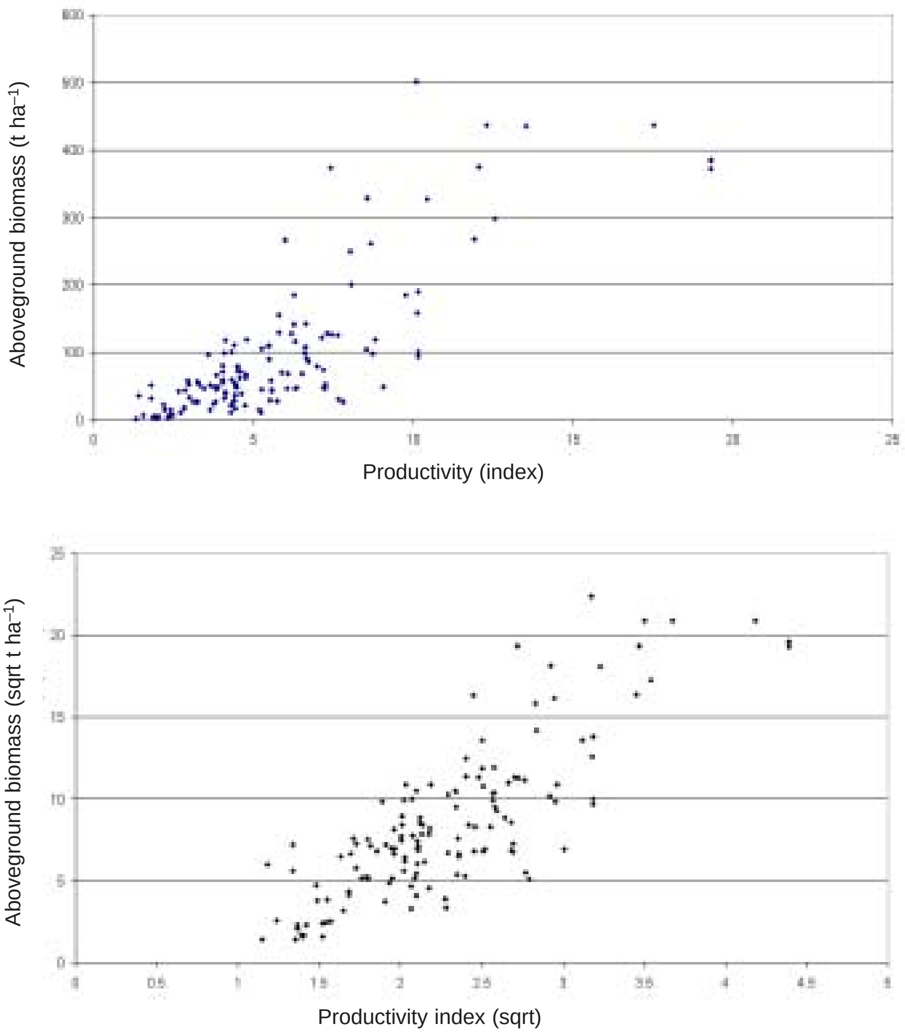

Figure 2. Plot of (a) raw biomass and productivity data and (b) square-root-transformed data

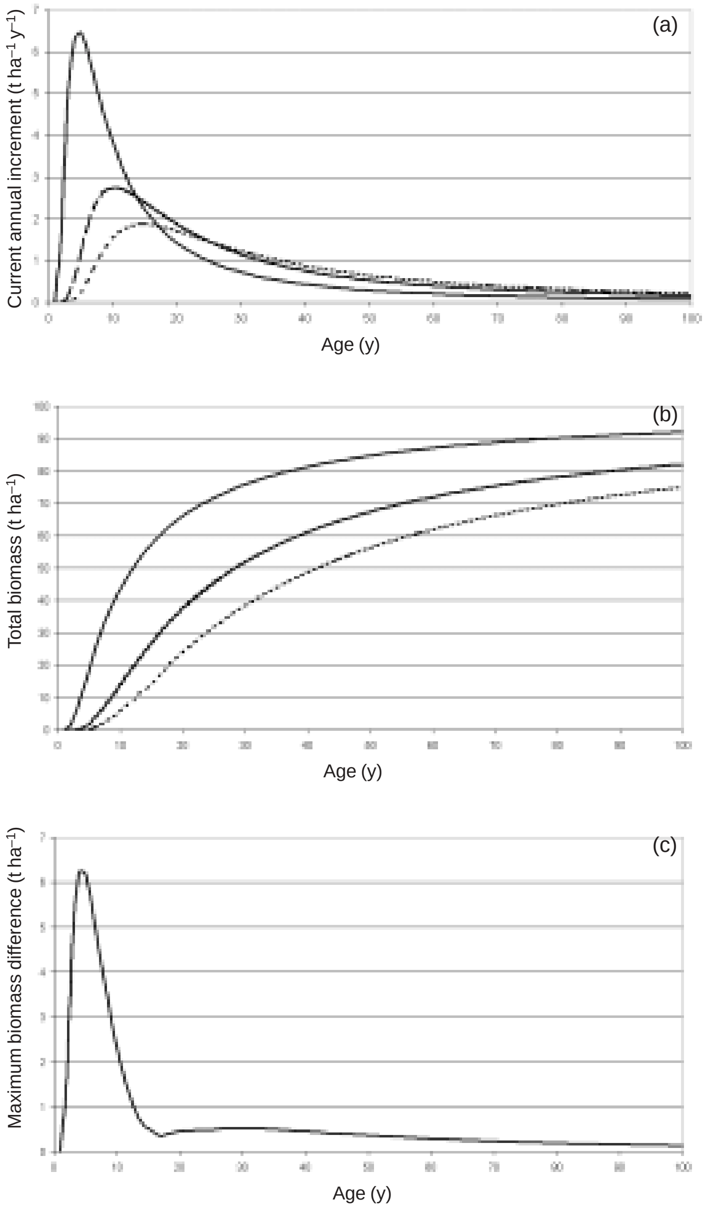

Figure 3. (a) Current annual increment (CAI), and (b) total biomass for varying k values and M = 100 t ha^{-1} (— max @ 5 y; - - - max @ 10 y; . . . max @ 15 y); and (c) difference in current annual growth (CAI) with age, for k set to maximise CAI at 5 and 15 y

Therefore, a mathematical model was developed to enable calculation of biomass and age and the rate at which the maximum biomass is approached.

Age-based stand growth can be expressed by equation (2),

$$M_A = M e^{-k/A}\,, \qquad (2)$$

where M_A is the predicted aboveground tree biomass (t ha^{-1}) at age A (y), M is the maximum long-term above-ground tree stand biomass; and k is an estimated constant that determines the rate of approach towards M.

Available data, such as those reported by West and Mattay (1993), suggest the age of maximum current annual increment (CAI) is approximately constant for many eucalypt species and independent of site productivity. The constant k is set to reflect this age of maximum CAI.

Given (1) and (2), the long-term average annual increment between A and $A + 1$ years (I_A) for a stand can be estimated from the long-term average productivity (P):

$$I_A = (6.011 \times P^{1/2} - 5.291)^2 \times (e^{-k/A} - e^{-k/(A+1)}). \qquad (3)$$

However, as productivity in any given year (P_A) may vary around the average productivity (P) due to non-average weather or other factors, the average annual growth increment may be adjusted for the productivity in that year (P_A) as a ratio with the average productivity (P):

$$\bar{I}_A = I_A \times (P_A / P). \qquad (4)$$

Discussion

Fundamental to the implementation of the method is the existence of a robust relationship between biomass and site productivity. However, it was recognised that the use of a range of methods by independent researchers taking the site measures (many of whom applied models of allometry to independent variables such as basal area and tree height) would possibly result in a researcher-driven variability in the field measurements. This would inevitably weaken the relationship between biomass and productivity.

While there was little doubt that the relationship between site biomass and site productivity would exist, the robustness of the relationship in terms of the quality of fit and error distribution was considered to be good, given the variability likely to be embedded in the site estimates from the various research studies. Further site study should target the areas where productivity is high (Productivity Index greater than 15), to clarify the relationship at this extreme. It can be seen from Figure 1 that only a very small fraction of forests are of this high productivity class.

The derivation of a maximum potential (undisturbed) biomass is a straightforward application of (1) to the 250 m slope-and-aspect-corrected productivity index (Fig. 1). Monthly productivity maps at a 1 km resolution were also created for the period between 1970 and 2000. The monthly maps were summed to years and then averaged over the 30-y period to re-estimate the annual average biomass potential P in (1). This re-estimated long-term site potential (P_{avg}) is used in (4), instead of P, to maintain an average correction of 1 in the calculation of growth in particular years.

Age-related biomass and productivity

Varying the value of k for a given M in (2) so that the maximum CAI occurs from 5 to 15 y (Fig. 3a) shows how the CAIs become very similar after about age 20 y despite this wide range of k values (Fig. 3b). The maximum difference in annual growth appears to occur between ages 2 and 15 y (Fig. 3c). After about age 15 y, the maximum difference in annual growth is less than about 0.5 units y^{-1}, i.e. it is relatively insensitive to the value of k.

The application of this method to plantation systems would require the recalculation of M and k to reflect lowering the age of maximum CAI and increasing the potential maximum growth due to improved establishment techniques and genetic improvement of plant stock. This would entail reviewing and analysing annual growth data for various plantation types.

This modelled approach predicts the total above-ground biomass, but, by applying general or species-specific allometry, estimates of gross or even net volume would be possible. Field inventory for verifying or correcting these estimates would be much less demanding than the equivalent complete measurement of biomass or volume.

Conclusion

The use of a hybrid approach — both process-driven and empirical — has enabled development of a robust generalised method for determining forest biomass stocks and rates of forest growth for Australia. The generalised model performs well when compared to available data, although these are sparse for many forest types. The absence of any significant bias or pattern within the error distribution for forest type or parts of the biomass range indicates that the general model will provide satisfactory performance across the whole continent. The r^2 value of 0.68 for the linear regression between site productivity and above-ground biomass also suggests good performance, particularly given that the 'measured' data for above-ground biomass are derived from many sources and methods of data capture.

Within the NCAS FullCAM model the biomass productivity of a site (nationally at a 250 m grid resolution) is used to determine the site biomass potential. This potential is presumed to have been reached in undisturbed forest systems. In disturbed systems, as identified through the NCAS multi-temporal remote sensing program, the biomass potential sets the site's maximum stock that successive modelled growth increments will approach according to growth equation (2). Subsequent removal of all trees resets forest age to 0, while a thinning resets only the fraction thinned to age 0. Alternatively, the effects of release from competition and stimulation of growth in a stand after thinning can be simulated by reducing the average age of the stand.

Review of the residuals from lines of best fit that define the pivotal relationship of biomass to productivity indicate that more data are needed in the high-biomass forest types. The other priority is the determination of growth patterns of lower-productivity (generally non-commercial) forest types so that the age of maximum CAI can be determined more accurately. Few yield tables are available for these types of forests.

The method as applied has provided a biomass account with a high degree of spatial and temporal specificity. It takes account of key environmental and physiological factors, as well as long-term physical disturbance, in determining standing biomass. There is potential to test further applications of this modelled approach to plantation systems and to the estimation of wood product.

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