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Growth and carbon stock change in eucalypt woodlands in northeast Australia: ecological and greenhouse sink implications

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Abstract

Data from 57 permanent monitoring sites are used to document the growth in woody vegetation and estimate the carbon sink in 27 M ha of eucalypt woodlands (savannas), contained within *c.* 60 M ha of grazed woodlands in Queensland (northeast Australia). The study sites are shown to be representative of the environment and structure of the eucalypt woodlands in the defined study area. Mean basal area increment for all live woody plants in 30 long-term sites, with an average initial basal area of 11.86 ± 1.38 (SE) $m^2 ha^{-1}$, was 1.06 $m^2 ha^{-1}$ over a mean 14 years timeframe. The majority of the measurement period, commencing between 1982 and 1988, was characterized by below-average rainfall. The increase in live tree basal area was due primarily to growth of existing trees (3.12 $m^2 ha^{-1}$) rather than establishment of new plants (0.25 $m^2 ha^{-1}$) and was partly offset by death (2.31 $m^2 ha^{-1}$). A simple but robust relationship between stand basal area and stand biomass of all woody species was developed for the eucalypt dominant woodlands. Analysis of above-ground carbon stocks in live and standing dead woody plants gave a mean net above-ground annual carbon increment for all 57 sites of 0.53 $t C ha^{-1} y^{-1}$, similar to values estimated elsewhere in world savannas. Published root : shoot ratios were used to infer C flux in woody root systems on these sites. This results in an estimated sink in above- and below-ground biomass of 18 $Mt C y^{-1}$ over the eucalypt woodlands studied, and potentially up to 35 $Mt C y^{-1}$ if extended to all grazed woodlands in Queensland. It is suggested that introduction of livestock grazing and altered fire regimes have triggered the change in tree-grass dominance in these woodlands. Thus, change in carbon stocks in the grazed woodlands of Queensland is identified as an important component of human-induced greenhouse gas flux in Australia, equivalent in magnitude to *c.* 25% of the most recently published (1999) total estimated national net emissions. The latter inventory takes into account emissions from land clearing, but does not include the sink identified in the present study. This sequestration also represents a small but significant contribution to the global terrestrial carbon sink.

Keywords: eucalyptus, Australia, carbon stock change, carbon, greenhouse sink, savanna, woodland

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Introduction

Savanna (woodland) and grassland ecosystems cover about 11% of the global land surface (Scholes & Hall, 1996) and account for around 30% of terrestrial net primary production (Field *et al.*, 1998). Historical accounts,

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photographic records and quantitative monitoring have documented increases in woody plant density or cover in savannas and invasion of grasslands by woody shrubs and trees over the past 100–200 years (see reviews by Archer, 1995; Idso, 1995; Archer *et al.*, 2001). The increase in woody plant cover in these systems has been called woody plant proliferation, vegetation thickening, bush encroachment, shrub encroachment, woody weed invasion or woody regrowth, and is widespread in arid or semiarid savannas and grasslands in North and South America, Africa, South-east Asia and Australia (Houghton *et al.*, 2000; van Auken, 2000; Archer *et al.*, 2001; Pacala *et al.*, 2001). These increases in woody plants are examples of the more general phenomena of vegetation recovery and succession that either follow episodic ecosystem disturbance events, or are associated with certain protracted disturbances in many woody ecosystems (Gifford & Howden, 2001).

Change in the tree-grass balance in savanna and grassland ecosystems has been identified as having the potential to significantly impact on the global carbon budget (Scholes & van der Merwe, 1996), but quantification of the carbon stocks and fluxes in these ecosystems has been limited (Pacala *et al.*, 2001). Most attention has focused on the possible contribution of increasing biomass in forests (e.g. Dixon *et al.*, 1994; Valentini *et al.*, 2000) to offsetting greenhouse emissions from human activities, particularly fossil fuel burning. For example, Sohngen & Haynes (1997) identified the potential for increased carbon storage in unreserved timberlands in the United States and Phillips *et al.* (1998) have reported a widespread increase in the biomass of surviving neotropical forest in Central and South America over recent decades. However, the absence of sufficient, reliable inventory data is a significant factor in limiting biomass estimates for tropical forests (Brown & Gaston, 1995) and is an even greater problem for savanna and grassland ecosystems. Thus, while there is widespread evidence to support the potential for substantial increase in biomass carbon stocks in savannas, available inventory data are generally restricted to (commercially harvested) forests (Houghton, 1995).

Inclusion of the sink that results from proliferation of woody vegetation in savannas in greenhouse gas inventories has been limited, not only by lack of reliable data on the change in carbon stocks, but also by incomplete understanding of the complex interaction between natural and anthropogenic factors contributing to this structural change. Accounting for anthropogenic emissions in the Land Use Change and Forestry (LUCF) Sector of National Greenhouse Gas Inventories prepared for the United Nations Framework Convention on Climate Change (UNFCCC), is intended to include all carbon fluxes in forests and other woody biomass stocks subject to 'ongoing human activity' (IPCC, 1997), but attribution of the fluxes in some communities to natural or human-induced factors is not straightforward. Future international accounting rules under the 1997 Kyoto Protocol to the UNFCCC (or alternative future international agreements to reduce greenhouse gas emissions) may introduce reporting of changes in all carbon stocks in broad land use categories such as forest management, grazing land management and crop land management, i.e. over most of the land surface of a country. Thus, monitoring of carbon stocks in savannas managed for grazing is required to improve understanding of the global carbon budget and potentially for documenting estimates of carbon fluxes for greenhouse gas inventories.

There are about 60 M ha of grassy woodlands (savannas) in Queensland (northeast Australia) subject to ongoing human activity involving management of the land for domestic livestock production (Burrows *et al.*, 1998). Much of this area is dominated by *Eucalyptus* and/or *Corymbia* spp., although significant *Acacia* and *Melaleuca* spp. dominated communities also occur. (The genus *Corymbia* was recently split from *Eucalyptus*). Monitoring of change at field sites is based on repeated observations at fixed locations, so that data are comparable between visits (Critchley & Poulton, 1998). We report the change in live and total standing biomass for 57 sites dominated by eucalypts (*Eucalyptus* and/or *Corymbia* spp.) in the woodland region of Queensland. Thirty sites were established between 1982 and 1988 with measurements of biomass being over a 14-years time frame on average, while a further 27 recently established sites have a mean measurement period of approximately 2 years.

A major feature of the climate of the woodland region of Queensland is extended periods (> 3 years) of above or below average rainfall (McKeon *et al.*, 1998). Severe drought periods such as 1991–94 have resulted in large reductions in live tree basal area at some locations. For example, Fensham & Holman (1999) measured an average reduction of 29% in live tree basal area across 195 sites in north east Queensland. Because of the impact of climate variability on long time scales (3–20 years), ecologists have recognized that measurement of vegetation change should ideally be conducted over extended periods (Walker *et al.*, 1986; Fensham & Bowman, 1992).

In this study we (i) document the measurement and calculation of tree/woody biomass; (ii) document the structure of stands in terms of tree basal area and calculated biomass; (iii) calculate the change in live and total standing biomass for both long-term (> 9 years) and short-term (< 3 years) sites; (iv) assess the representativeness of sites for the purpose of extrapolation across the eucalypt woodland region; (v) discuss the major factors affecting change in live and total biomass; and (vi) discuss the implications of this work for inventory of carbon stocks and greenhouse gas flux.

Methods

Permanent monitoring plots

Data on vegetation structure and growth in this study are from the Queensland Department of Primary Industries' network of permanent vegetation monitoring sites established within grazed woodland communities since 1982. A large number of different operators (>10) have been responsible for site selection over the years, avoiding areas close to obvious points of ongoing disturbance such as fences, yards and watering points. The sites were not randomly selected in a statistical sense, but have been progressively established on rural landholdings to provide a broad cover of vegetation community and prehistory, dominant species and geographical location across Queensland's grazed woodlands.

Woody plant composition and structure on these sites were determined using the transect recording and processing **s**ystem (TRAPS) methodology (Back *et al*., 1997, 1999) for monitoring permanently positioned transect lines within representative stands of woodlands (Burrows *et al*., 2000). A standard site comprised five parallel belt transects 100 m long arranged along a north–south axis 25 m apart. Each transect set was contained within a minimum 300 m × 300 m buffer of similar vegetation. Stem circumference at 30 cm above ground and height were measured for all live and standing dead woody plants (but see later) within a 2 m band either side of the transect line, at each successive recording.

Site representativeness

Fifty-seven TRAPS sites dominated by *Eucalyptus* and/or *Corymbia* spp. were selected for analysis of woody vegetation growth and carbon stock change. Selection was based on field inspection and information supplied by landholders so as to exclude sites subject to tree clearing activity during the period of observation and sites regrowing from tree clearing within the previous 20 years.

The study area was delimited to the north by 17 degrees south latitude, and to the west by either 141 degrees longitude, or the 450 mm rainfall isohyet, whichever was further east (Fig. 1 inset). The extent of eucalypt woodlands within this area was defined by firstly determining the historic coverage of eucalypt dominant woodlands from the Carnahan (1976) map of subjectively estimated pre-European vegetation cover and then assessing the current area from the woody vegetation cover in 1997, as mapped from satellite imagery (Department of Natural Resources, 1999).

The representativeness of the subset of 57 TRAPS sites in the present study was assessed in relation to (a) rainfall; (b) temperature; (c) soils; and (d) stand basal area based on the approach of Austin & Meyers (1996) for assessing the distribution of study plots in both environmental (defined by temperature, rainfall and lithology) and geographical space, for evidence of spatial bias in sampling. Environmental representativeness was assessed using an approach similar to common stratification techniques for vegetation resource surveys (for example, Thackway & Cresswell, 1992) based on the attributes of rainfall and temperature of the wettest quarter, and soil texture classes. Temperature and rainfall data were also used to assess how well the 57 sites represented spatial variation in the interaction of these environmental parameters.

Climatic variables were derived from the ANUCLIM software module which utilizes topographic data to obtain climatic interpolations of high resolution (McMahon *et al*., 1996) and soil classification was from the Atlas of Australian Soils (Northcote *et al*., 1960–68). Frequency distributions of average rainfall and temperature and of soil classes for the eucalypt woodlands of the study area, obtained by extracting the variable values at the intersections of a 5 km grid, were compared qualitatively and by χ^2 test with those for the TRAPS sites. To assess the representativeness of the interaction of temperature and rainfall, averaged data for the study area and TRAPS sites were classified into discrete classes of 1 °C and 50 mm increments. All areas with environmental conditions represented by at least one TRAPS site were mapped and the proportion of eucalypt woodlands sampled was determined.

The representativeness in terms of tree basal area was assessed by comparing the stand basal area at the TRAPS sites with values measured by using a combination of remote sensing and site data in the Statewide Landcover and Trees Study (SLATS) project (Danaher *et al*., 1992). The tree (or woody) basal area frequency distribution had been calculated from a raster of woody vegetation cover (foliage projective cover) from Landsat TM (30 m resolution) data using a relationship derived by Kuhnell *et al*. (1998). This relationship applies only to mature stands of vegetation, and therefore, was not applied to areas mapped as young regrowth. Kuhnell *et al*. (1998) estimated stand basal area at breast height (approximately 130 cm above ground) whereas basal area at the TRAPS sites was measured at 30 cm. To enable comparison of the two datasets a relationship between circumference (mm) at 30 cm and at 130 cm above ground level was developed based on circumference (C) at the two heights measured on 54 eucalypt trees (3 species) harvested for biomass measurement (Burrows *et al*., 2000), $C_{130}\,\mathrm{cm} = 0.789\,C_{30}\,\mathrm{cm}$ (R^2 through the origin $= 0.89$).

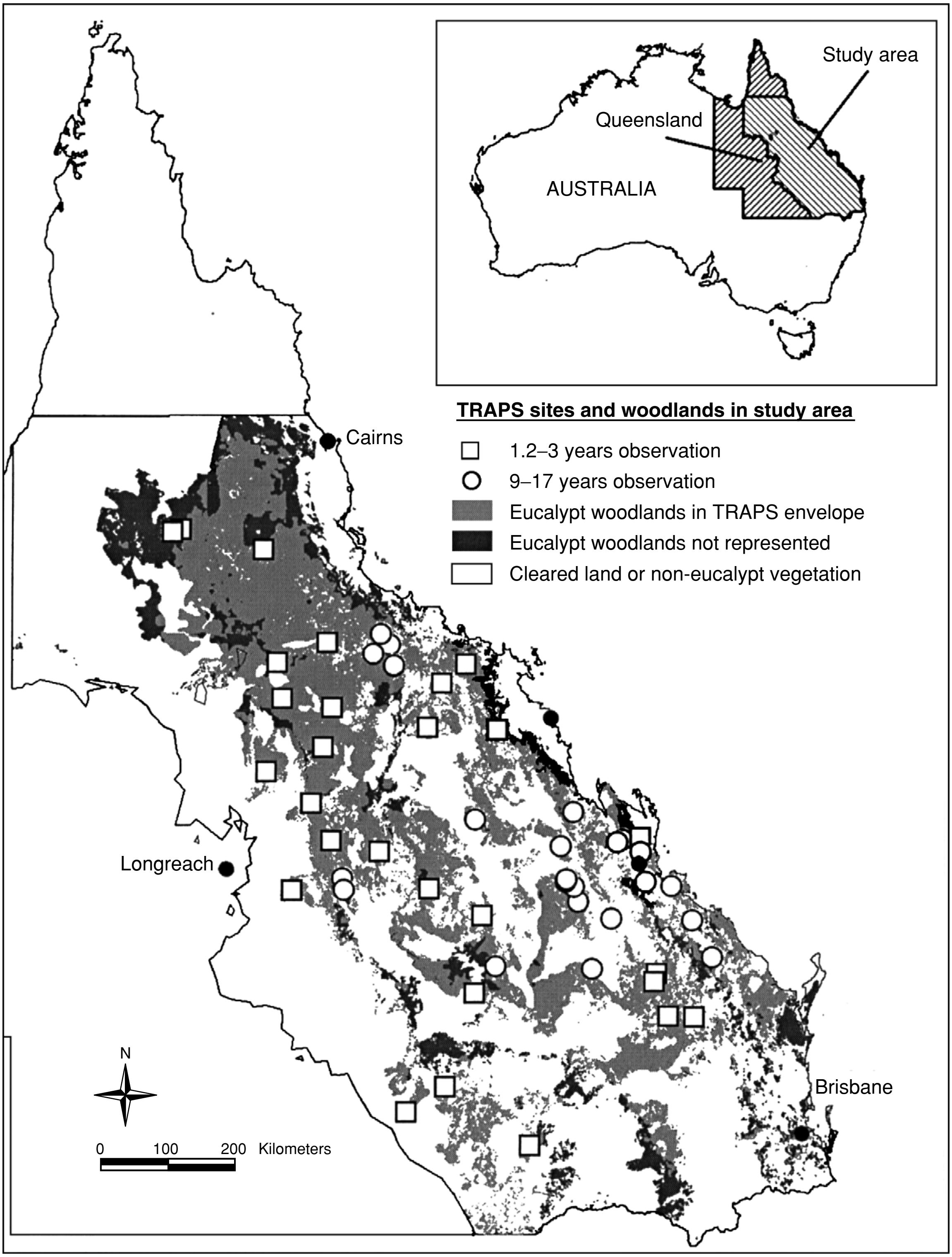


Fig. 1 The climatic envelope of the TRAPS monitoring sites (short-term □; and long-term ○) was compared with that of the current eucalypt woodlands using a combination of two variables, temperature and rainfall of the wettest quarter. Of the complete environmental range for the 27 M ha of eucalypt woodlands, 71% was represented by the TRAPS sites while 29% (black) was not within the climatic envelope of the 57 monitoring sites. The long-term sites were representative of 55% of the woodlands' environment. Unshaded areas within the study zone have been cleared of trees or support vegetation dominated by species other than eucalypts.

Representativeness of the climate history

To determine how well the TRAPS measurement periods represented the available climate history, the rainfall for each observation period at each site was compared to the long-term rainfall records for that site. Rainfall for 1889–2000 (SILO database 2000 – see Jeffrey *et al.*, 2001) for individual TRAPS sites was subdivided into observation records (moving windows) corresponding to the same calendar start day and duration of individual observation periods. This ensured the same sequence of seasons was compared throughout the climatic record. Rainfall during the TRAPS observation period, expressed as a percentile of rainfall in all moving windows (Kendall & Buckland, 1971) gave the rainfall for each site ranked in relationship to all available observations. The frequency of ranked site percentiles thus summarizes the relative dryness/wetness during the observation period, allowing comparison between sites.

Stand structure

Eucalyptus and/or *Corymbia* spp. plants alive at the initial and final recording of each site were grouped into 200 mm circumference classes (0–200, 200–400, ... 3600–3800 mm) to examine the size class distribution and interpret stand growth status. Basal area in each class was calculated and converted to carbon biomass as described below. There was a wide diversity of size class distributions amongst the 57 sites and statistical methods were used to select examples for illustration. Sites were firstly characterized using variables such as stand prehistory together with measures of standard deviation, skewness and kurtosis. Divisive Cluster analysis (Mathsoft, 1997) was used to group the sites and the stand structure of a representative individual site from each of the eight largest groups was subjectively selected for display in Fig. 5.

Tree basal area

Tree basal area at each site was calculated from the circumference at 30 cm for the live and standing dead pools shown in Fig. 2. The two major groups of woody plants, eucalypts and non-eucalypts, were recorded separately. Circumference measurements of all live woody plants at each observation enabled basal area to be calculated for those plants live at both initial and final recordings, plants live at the initial recording but which died during the observation period, and plants which established during the observation period (ingrowth). Standing dead woody plants were measured at the final recording enabling calculation of basal area for plants that died during the observation period and plants that were dead also at the initial observation (see later). The position of standing dead trees was recorded at the initial observation, but circumference was not measured. Coarse woody debris was not measured in this study. A small minority of plants that both established and died between the initial and final[1] recordings was ignored. The mean tree basal area increment ($m^2 ha^{-1} y^{-1}$) for all live trees present at both initial and final recordings was determined as the average across all sites and observation periods. This increment was also expressed as the mean percentage of the original basal area of live trees in each stand.

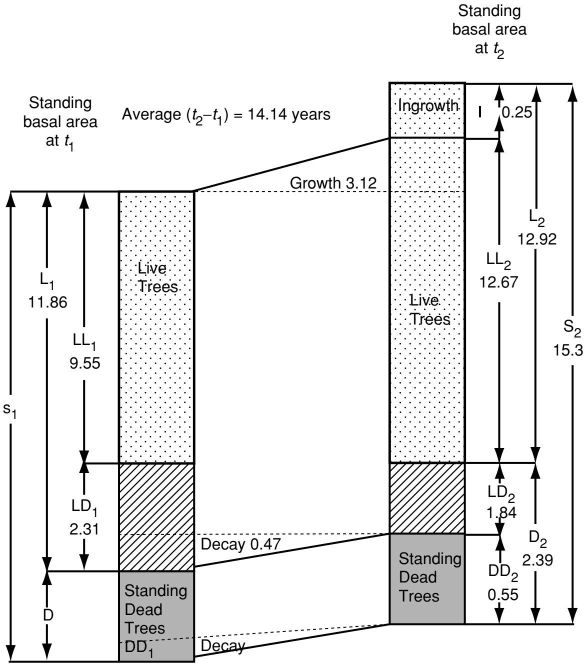
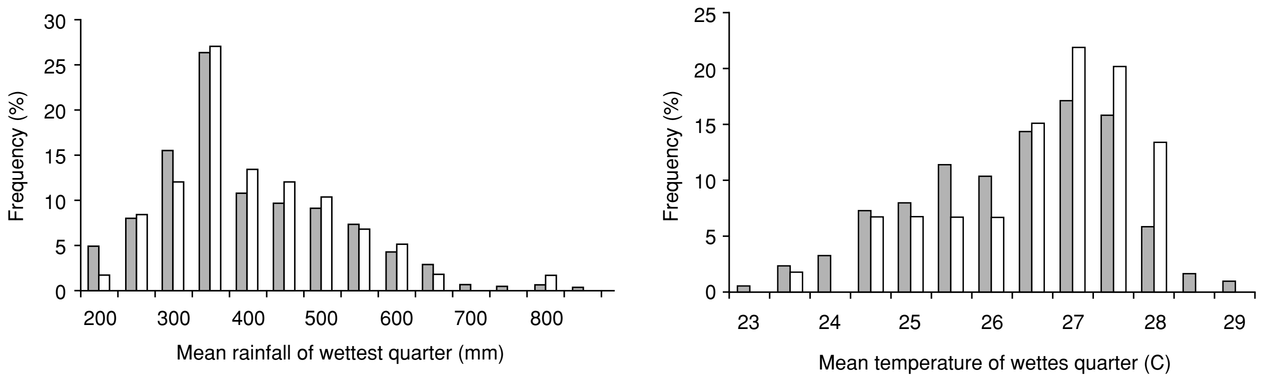


Fig. 2 Diagrammatic presentation of live and dead woody plant C pools and fluxes monitored in repeat site measurements. Values indicated are stand basal area at the initial and final observations of the 30 long-term monitoring sites. Growth was calculated as the net change due to growth of live plants, death of plants live at the initial recording (t_1) but dead at t_2 and establishment of new plants (ingrowth, I). Time between initial and final measurements varied from 9.4–17.0 years with a mean of 14.14 years.LL is the carbon biomass of woody plants live at initial and final recordings; LD is the carbon biomass of woody plants live at the initial measurement but dead at the final recording; DD is the carbon biomass of standing trees dead at the initial recording, measured only at t_2; I is the carbon biomass of ingrowth, i.e. woody plants which established between the initial and final recordings; L is the basal area of all live woody plants at the time of observation; D is the basal area of all standing dead woody plants at the time of observation; S is the total woody plant basal area at the time of measurement.
The most recent observation is referred to as the 'final' observation for purposes of this paper.

Live above-ground biomass

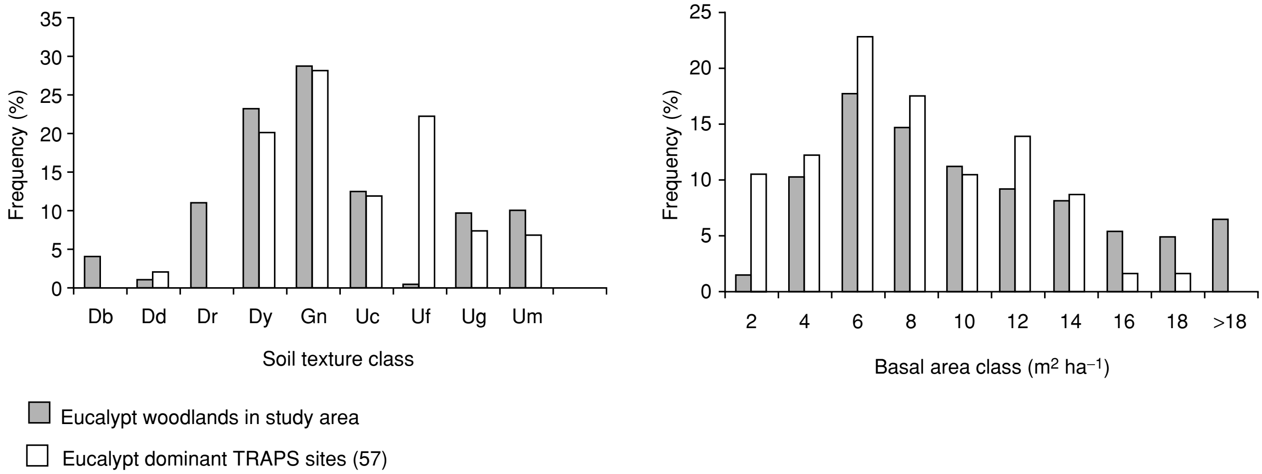
The procedure for calculating live biomass from stem circumference used in this analysis is a further development of the procedure described by Burrows *et al.* (2000) and outlined here in points 1–4.

1. Woodland stands within the same area as used in the present study were selected to represent three dominant species (*Eucalyptus crebra, E. melanophloia, E. populnea*).
2. The above- and below-ground biomass of 20–40 plants of each species was measured and used to derive tree species allometric equations (Table 2, Burrows *et al.*, 2000) and a generalized eucalypt equation (Fig. 1, Burrows *et al.*, 2000).
3. Specific or generalized equations for above-ground biomass were applied to individual eucalypt trees for 33 TRAPS sites where eucalypts contributed $>75\%$ of stand basal area. If the basal area of any individual eucalypt was greater than that of the largest tree used in developing the above equations then the biomass was set to the maximum biomass of trees measured in developing the equations.
4. Total above-ground biomass of the eucalypt component of the stand was calculated and regressed on stand eucalypt live tree basal area (Fig. 3, Burrows *et al.*, 2000) suggesting that stand biomass could be simply estimated from stand live tree basal area for the eucalypts.



(a) Rainfall

(b) Temperature



(c) Soils

(d) Basal Area

Fig. 3 Relative frequencies (%) of (a) rainfall classes (b) temperature classes (c) soil texture classes and (d) basal area for the current extent of eucalypt woodlands (■) and the TRAPS monitoring sites (□). [χ^2 comparisons (a) n.s. (b) n.s. (c) $P<0.05$ (d) $P<0.05$]. Soil texture classes (Northcote 1979) are: Db – brown duplex; Dd – dark duplex; Dr – red duplex; Dy – yellow duplex; Gn – gradational; Uc – uniform coarse; Uf – uniform fine; Ug – uniform cracking; Um – uniform medium.

The following additional steps were taken to extend this calculation procedure to other stands and other components of eucalypt stands:

5. Step 3 was repeated for an additional 24 TRAPS sites with eucalypt composition greater than 50% and a new relationship between stand live above-ground biomass and eucalypt basal area established.
6. The relationship derived in Step 5 was applied to total stand live tree basal area assuming that the biomass density (t dry matter per m^2 stand basal area) of eucalypt trees holds also for non-eucalypts. The appropriateness of this assumption is discussed later.

Above-ground biomass of standing dead trees

A decay function for standing dead *E. populnea* trees was derived in 1997 for a site in the Dingo region of central Queensland that had reliable records of individual trees ringbarked (girdled) or killed by chemical injection between 1933 and 1987 (Burrows, unpublished data). Standing dead trees (with no bark remaining) contributing to this function were harvested and weighed. Correction factors derived from harvesting tree fractions used to derive allometrics (Burrows *et al*., 2000) enabled over bark circumference at time of tree death, and hence final live weight, to be estimated. For decay periods less than 64 years, the biomass change can be derived from:

$$y = 24.4 + 75.6\mathrm{e}^{-0.14x} (R^2 = 0.99, P < 0.001), \qquad (1)$$

where $y = \%$ of original live standing above-ground biomass remaining; $x =$ time in years since tree death; $n = 14$.

The relationship was not extrapolated beyond the equivalent time range over which it was derived.

For trees that died during the observation period, the biomass at the initial recording was calculated from basal area using the generalized biomass to basal area conversion derived as above. Since the time of death within the observation period was not known, death was assumed to have occurred immediately following the first measurement and the decay function (1) used to estimate the proportion of the initial biomass remaining at the final observation. This assumption of maximum decay period, gave a conservative estimate of the final biomass.

Estimation of the biomass of trees dead at the initial recording

Standing trees that were dead at the initial recording were measured only at the final observation. These dead plants were mostly trunks with a few large lateral branches but with no small branches, leaves or bark remaining. We estimated that such dead trees on the TRAPS sites had been dead for an average of 20 years before the initial recording, based on our field observations of dead trees of known age. The same procedure used to derive the above decay function enabled conversion of stem circumferences of standing dead trunks, measured free of bark, to the original over bark circumference.

The generalized biomass to basal area relationship described previously was divided by the mean ratio of standing biomass to trunk mass for woodland eucalypt trees (Burrows *et al*., 2000) to give a conversion factor for the basal area (corrected to over bark) to biomass of trunk of standing dead. The derived trunk mass was assumed to approximate the standing dead tree mass at the final recording (t_2). The biomass of standing dead at the initial recording date (t_1) was estimated using the above decay function (1):

Biomass remaining at initial observation, t_1 (20 years since death),

$$B_{t_1} = \frac{B_0}{100}(24.4 + 75.6e^{-0.14t_1})$$

Biomass at final observation, t_2

$$B_{t_2} = \frac{B_0}{100}(24.4 + 75.6e^{-0.14t_2})$$

Thus,

$$B_{t_1} = B_{t_2}\frac{(24.4 + 75.6e^{-0.14t_1})}{(24.4 + 75.6e^{-0.14t_2})}, \qquad (2)$$

where $t_1 = 20$ years; $t_2 = 20 +$ (years between initial and final recording); $B_0 =$ biomass at time of death; $B_{t_1} =$ standing dead biomass at t_1; $B_{t_2} =$ standing dead biomass at t_2. Maximum time (t_2) since estimated death for standing dead trees on the oldest established TRAPS site was 38 years – well within the time range of the derived decay function.

Carbon stocks and fluxes

All biomass components (standing live and dead) were either measured or estimated by the above procedures for both initial and final recordings at each TRAPS site. An average carbon fraction in woody biomass of 0.5 was assumed for conversion of dry matter to carbon (IPCC, 1997; Houghton *et al*., 2000). The appropriateness of this value for Australian woody vegetation was confirmed for 19 eastern Australian native tree species, including 15 eucalypts, with a mean carbon content of woody tissues of 50 ± 2% (Gifford, 2000).

Change in carbon stocks (ΔS) in standing woody plants over the observation period was calculated as:

$$\Delta S = S_2 - S_1$$

where S_1 and S_2 are the live plus standing dead carbon stocks at the initial and final recordings, respectively, expressed in tonnes carbon per hectare.

Thus for each site, i, the total stock change (Fig. 2) was:

$$\Delta S_i = (LL_{i2} + LD_{i2} + DD_{i2} + I_{i2}) - (LL_{i1} + LD_{i1} + DD_{i1}),$$

where LL is the carbon biomass of woody plants live at initial and final recordings;

LD is the carbon biomass of woody plants live at the initial measurement but dead at the final recording;

DD is the carbon biomass of standing trees dead at the initial recording;

I is the carbon biomass of ingrowth, i.e. woody plants which establish between the initial and final recordings.

Results and Discussion

Representativeness of sites

The TRAPS sites, a subset of which were used in the present study, had been selected subjectively over a number of years by different operators according to a range of criteria including extent, accessibility, community type and site prehistory. At regional or country scales, random selection of permanent sampling plots within wooded areas is generally precluded by considerations such as accessibility (Austin & Meyers, 1996; Phillips *et al.*, 1998).

The study area (Fig. 1) was 89 M ha of which 52 M ha was mapped (estimated) as eucalypt woodland in pre-European time (Carnahan, 1976). The area of eucalypt woodlands within the study area in 1997 was 27 M ha, based on remotely sensed woody vegetation cover intersected with the area assessed as historically eucalypt dominant. The difference between the two assessments reflects differences in resolution of patchiness between the two mapping techniques as well as some tree clearing.

Environmental variables may interact in a complex way to influence the distribution of vegetation types (Austin, 1991). Temperature and rainfall in the wettest quarter provided the basis for assessing representativeness of the TRAPS sites. These variables are major drivers of growth and hence biomass accumulation. These two dimensional climatic comparisons demonstrated that 55% of the environmental range of present eucalypt woodlands was represented by the 30 long-term sites, and with the additional recent sites, 71% of the range was captured (Fig. 1).

Assessment using individual climatic variables demonstrated that the 57 TRAPS sites cover the range of the eucalypt woodlands expressed in terms of mean rainfall and temperature of the wettest quarter (Fig. 3a,b). The long-term sites were more representative of the modal and wetter/warmer half of the geographical distributions (data not shown). As the recent sites were chosen to extend the environmental range they were more representative of the dry half of mean rainfall distributions. The analysis identified that both high and low extremes of rainfall and temperature were slightly under-represented in sampling. The range of soils (texture classes) found in the study area (Fig. 3c) was also well represented by the TRAPS sites though the long-term sites have a greater frequency of dark duplex soils, while the recent sites had a greater frequency of uniform coarse textured soils (data not illustrated).

The mean basal area for all eucalypt woodlands in the study area, determined by converting remotely sensed foliage projective cover to basal area at 130 cm above ground level (Kuhnell *et al.*, 1998), was 10.47 $m^2 ha^{-1}$. The mean live basal area of the long-term and short-term TRAPS sites, calculated from circumference measured at 30 cm above ground at the most recent recording, was 12.92 $m^2 ha^{-1}$ and 10.92 $m^2 ha^{-1}$, respectively. The mean for all 57 TRAPS sites of 11.97 $m^2 ha^{-1}$ converts to an estimate of basal area at 130 cm of 7.66 m^2 ha^{-1}, lower than the value for all eucalypt woodlands assessed by remote sensing (Fig. 3d). This suggests that annual above ground growth estimates derived from the TRAPS sites could understate that for the eucalypt woodlands overall (see Fig. 7).

Representativeness of the climatic history

Because of the variability in weather patterns in the woodland region of Queensland (McKeon *et al.*, 1998), any short-term (2–3 years) monitoring period may give productivity results that are not representative of the longer term trend (Schimel *et al.*, 2000). Compared to the hundred year historical record, rainfall at the 30 sites measured for 9.4–17.0 years was generally low with 27 sites less than the median (Fig. 4), reflecting the below-verage rainfall conditions of the mid 1980s and early 1990s. In contrast, measurement of the recently established sites (monitored for 1.2–2.9 years) occurred during a period of above-average rainfall since 1996, with relative rainfall of 24 of the 27 sites greater than median. In summary, the mean percentile ranking of the long-term, short-term and total sites was 23, 71 and 45%, respectively.

Long-term temperature records for locations in Queensland's grazing lands are available for the period 1915–93 at 27 locations (Torok & Nicholls, 1996). Average minimum temperature has significantly increased over this time (McKeon *et al.*, 1998) with values for periods 1915–56, 1957–82 and 1983–93 being 14.3, 14.7 and 15.4 °C, respectively. Maximum temperatures have not changed

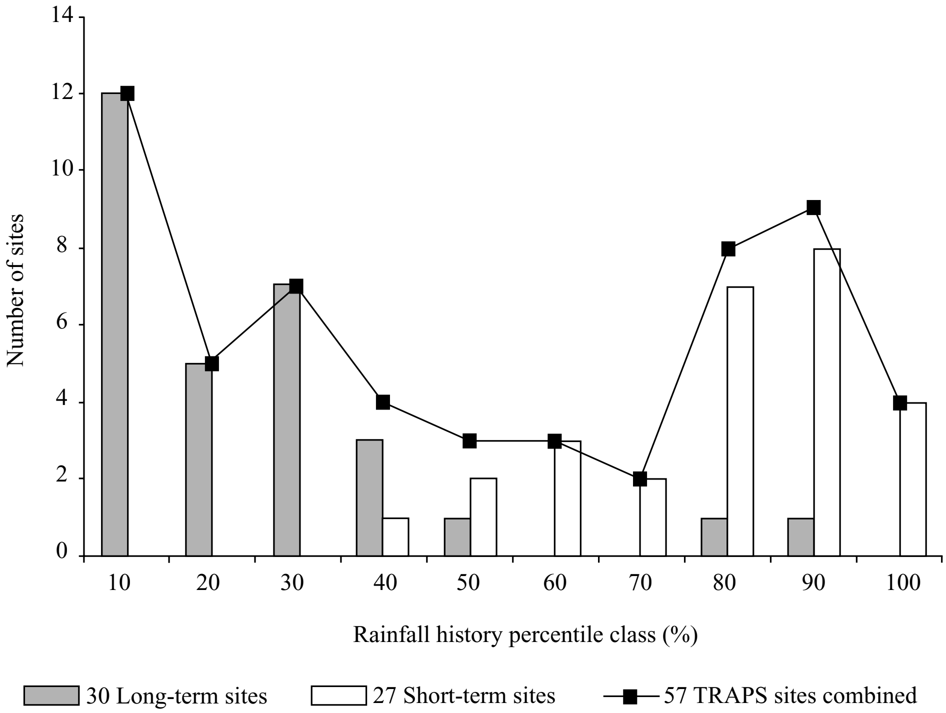


Fig. 4 Rainfall during the observation period for the 30 long-term TRAPS sites (▨) and the 27 short-term sites (☐) compared to the rainfall history (1889–2000) for each site ranked as a percentile (see Methods). Much of the observation period for long-term sites, initiated between 1982 and 1988, was characterized by below average rainfall whereas the short-term sites, initial observation 1996–98, were monitored only in recent above average rainfall years. Combining all 57 TRAPS monitoring sites (-■-) gave a mean percentile ranking of 45% compared with historic rainfall.

significantly with values 28.2, 28.3, and 28.4 °C for the three periods

Thus, the measured rates of growth in the short term sites were generally for conditions that were wetter and warmer than the historical mean, while growth conditions for the measurement period of the long-term sites were warmer and mostly drier than the historical average.

Stand structure

Size class distributions for the 57 woodland sites (Fig. 5 and data not presented) did not show a trend for the above-ground biomass to be concentrated in large diameter trees despite their not having been subject to clearing activity either during or in the approximately 20 years prior to the observation period. Brown *et al.* (1997) concluded that the presence of a large proportion of the above-ground biomass of moist tropical forests in large trees (> 70 cm diameter) is indicative of mature and undisturbed conditions. Further, these authors suggest that for hardwood forests of the eastern United States to be designated as old-growth, they must have 25% or more of their biomass in large trees. Based on these criteria the eucalypt woodland sites would not be regarded as mature stands and the highest annual net increase in biomass occurred in the 40–60 cm diameter class (averaged across all 57 sites).

Our assessment of stand structure in terms of above-ground biomass and productivity contrasts with the use of stem density (stems ha^{-1}), for this purpose. The latter has been used in most previous studies of the structure of forest and woodland trees in northern Australia. These have concentrated on the distinctly monsoonal and regularly burnt savanna vegetation of the coastal/subcoastal Northern Territory (Andersen *et al.*, 1998) and in this environment the woody plants commonly exhibit a bimodal size structure, comprising canopy trees distinct from ground layer woody sprouts (Fensham & Bowman, 1992).

Tree basal area

Because individual trees were repeatedly measured it is possible to reconstruct both pools and fluxes in terms of tree basal area to represent the population. Mean values of basal area at the 30 long-term eucalypt woodland sites are shown in Fig. 2 for the above-ground pools and fluxes

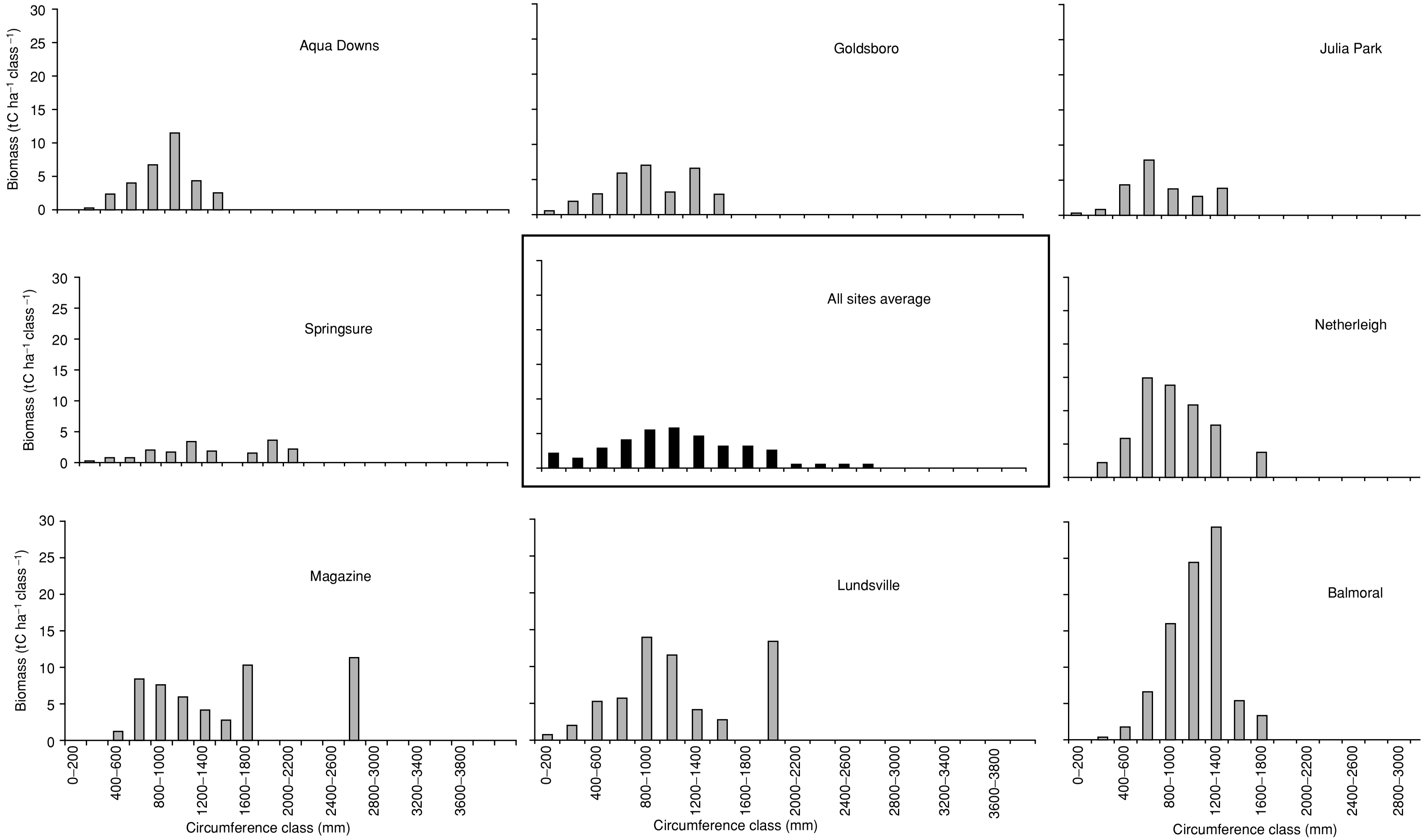


Fig. 5 Biomass carbon distributions for indicative TRAPS sites show wide variability. The centre diagram is the mean across all 57 sites. Circumference classes are in 200 mm intervals commencing at zero. Note variability in size class distribution and that growth not shown is occurring within most size classes.

Table 1 Mean stand basal area ($m^2 ha^{-1}$) of live and standing dead woody plants at the initial and final recordings for the 30 long-term sites monitored for 9–17 years and the 27 short-term sites monitored for 1.2–2.9 years. Values are expressed as the mean and standard error of individual site measurements

	Average stand basal area ($m^2 ha^{-1}$)			
	Long-term sites Average (t_2–t_1) = 14.14 year		Short-term sites Average (t_2–t_1) = 2.05 year t_1	
	t_1	t_2	t_1	t_2
Trees live at t_1 and t_2 (LL)	9.55 ± 1.34	12.67 ± 1.69	10.23 ± 0.85	10.84 ± 0.90
Trees live at t_1, dead at t_2 (LD)	2.31 ± 0.35		0.48 ± 0.11	
Ingrowth (I)		0.25 ± 0.07		0.09 ± 0.03
Total live	11.86 ± 1.38	12.92 ± 1.67	10.71 ± 0.86	**10.92 ± 0.90**
Trees live at t_1, dead at t_2 (LD)		1.84 ± 0.32		0.40 ± 0.11
Standing dead trees (DD)	Not measured	0.55 ± 0.14	Not measured	2.16 ± 0.56
Total dead		2.39 ± 0.34		**2.56 ± 0.59**
Total standing basal area		15.31 ± 1.71		**13.49 ± 1.08**

assessed in this analysis. The time period of measurement varied between 9.4 and 17.0 years due to the staggered start in establishing sites and variation due to time and ease of access to sites for repeat measurements. We have averaged pool sizes for the initial measurement (1982–88) and most recent measurement (1996–2000).

Total live tree basal area increased from 11.86 to 12.92 $m^2 ha^{-1}$ over the average period of 14.14 years. The increase in live tree basal area (average across sites) of 1.06 $m^2 ha^{-1}$ was the net result of three fluxes: (1) establishment of new plants (0.25 $m^2 ha^{-1}$); (2) growth of existing live trees (3.12 $m^2 ha^{-1}$); and (3) death of initial live trees (2.31 $m^2 ha^{-1}$) (Fig. 2 and Table 1). Thus, the major component of change in live basal area was the increase in basal area of existing trees and not in new plants. In the case of dead trees, 77% of the most recently measured (1996–2000) dead tree basal area comprised trees that died during the measurement period. The new sites chosen to extend the environmental range of monitoring sites had similar live and dead tree basal areas compared to the long-term sites (Table 1), despite the differences in location, mean rainfall of wettest quarter and soils previously reported.

Live stand above-ground biomass

The procedure for stand above-ground biomass calculation allowed a simple but robust relationship to be derived to estimate stand live above-ground biomass of all species in the eucalypt woodlands (Fig. 6):

Stand above-ground biomass = 6.286 * stand tree basal area ($m^2 ha^{-1}$).

This ratio was applied to all 57 sites to standardize the stand live above-ground biomass calculation and to estimate biomass of species, including non-eucalypts, for which allometric equations were not available.

The 57 sites selected from the TRAPS dataset had eucalypt (*Eucalyptus* and/or *Corymbia* spp.) composition greater than 50%. The mean percentage of non-eucalypt species in terms of live tree basal area was 7.1% ± 1.2 (SE) with a range of 0–44%. For the long-term sites the mean was 4.4% ± 1.1 (SE) and ranged from 0–24%. The percentage of non-eucalypt tree basal area was not related to the most important site attributes of stand live tree basal area or mean rainfall in the wettest quarter.

Most of the non-eucalypts were also woody sclerophyllous species, so the generalized biomass/basal area equation was applied to the whole stand. This gave an average stand live above-ground biomass for all woody plants in the 57 woodland sites at the initial recording of 71.1 t dm ha^{-1} of which 92.6% was eucalypts. In the long term sites there was 74.6 t dm ha^{-1} of which 95.3% was eucalypts. Therefore, application of the generalized above-ground biomass to basal area conversion to non-eucalypt species is unlikely to have substantially affected the estimates of above-ground biomass stocks and fluxes at these sites.

Above-ground biomass of dead trees

The mean ratio of total standing biomass to trunk mass for harvested eucalypts was 2.07 (Burrows *et al*., 2000) so the conversion factor for basal area (over bark) to biomass of trunks of standing dead trees was 6.286/2.07 = 3.04 t m^{-2}. This conversion factor was applied to derive the final biomass, and equation 1 was used to calculate the biomass of standing dead trees at the initial recording. The proportion of the total above-ground

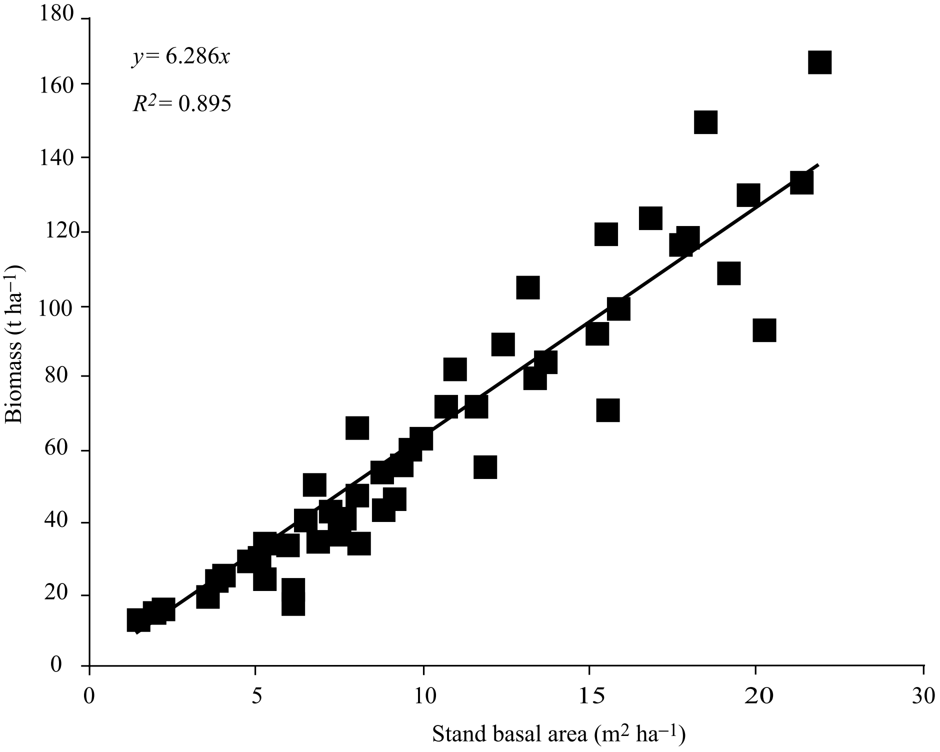


Fig. 6 Regression of above-ground biomass against stand basal area for live eucalypt trees at 57 TRAPS sites.

standing biomass in dead trees at the initial observation at the long-term and short-term sites, respectively, was 2.3% and 9.0% (Table 2). Averaged across all 57 sites, the proportion of the initial biomass in dead trees was 5.4%.

The sensitivity of estimates to the assumption that at the initial observation these trees had been dead for 20 years on average was tested. The average final standing dead above-ground biomass for the 57 sites was 4.0 t ha^{-1} (8.8% total stocks) and assuming values for t_1 of 10, 20, 30 and 40 years resulted in estimated values of initial standing dead above-ground biomass of 6.6, 4.7, 4.2 and 4.0 t ha^{-1}, respectively, or 4.8%–8.0% of total above-ground biomass. For the range of possible assumptions of the age of dead trees the mean loss in standing dead above-ground biomass through decay varied from 0.2%–10.7% of the total biomass change averaged across the long-term sites. Thus, the assumption of a mean 20 years since death for standing dead trees at the initial observation was assessed not to affect the conclusions on trends in stock change.

Carbon stocks and fluxes

The mean total standing carbon stocks increased from 38.16 t C ha^{-1} to 43.72 t C ha^{-1} over the average observation period of 14.14 years for the 30 long-term sites (Table 2). On average 97.7% of the initial carbon stock and 92.9% of the final carbon stock was in live trees. The mean annual carbon increment of 0.37 t C ha^{-1} y^{-1} over this period was significantly greater than zero ($P < 0.001$), made up of 0.21 t C ha^{-1} y^{-1} net increase in live woody above-ground biomass and 0.16 t C ha^{-1} y^{-1} in the standing dead above-ground biomass pool. Of the 30 long-term sites, 26 showed a net positive carbon increment over the observation period.

Carbon stocks in the 27 short-term sites increased from 36.99 t C ha^{-1}–38.58 t C ha^{-1} over an average 2.05 years. The mean annual carbon increment of 0.70 t C ha^{-1} y^{-1} was highly significant ($P < 0.001$), with the increase in the live woody pool being 0.29 t C ha^{-1} y^{-1}. The higher growth rate, compared with the long-term sites, may reflect the above-average rainfall during the measurement period (Fig. 4). For the short-term sites the higher proportion of the above-ground biomass in standing dead trees at the initial recording (8.8%), may have resulted from below average rainfall conditions in the decade prior to the commencement of monitoring these sites, but remains a minor component of total stock.

The mean total carbon increment over all 57 sites was 0.53 t C ha^{-1} y^{-1} of which about half (0.25 t C ha^{-1} y^{-1}) was due to increase in the live woody above-ground biomass stocks. This was similar to estimates of the annual total biomass increment in comparable forest types in India (Lal & Singh, 2000). These authors

Table 2 Carbon stock ($t\,C\,ha^{-1}$) in live and standing dead above-ground biomass pools at the 30 long-term and 27 short-term monitoring sites. Carbon fluxes were calculated for each pool and the average increment estimated as the balance between carbon sequestration in growth and loss through decay of dead plants. The long-term sites experienced below average rainfall during the observation period while the short-term sites were measured only over recent above average rainfall years. Values are expressed as the mean and standard error of values for each site

	Average stand C stocks (t C ha^{-1})			
	Long-term sites Average (t_2–t_1) = 14.14 year		Short-term sites Average (t_2–t_1) = 2.05 year	
	t_1	t_2	t_1	t_2
Trees live at t_1 and t_2 (LL)	30.01 ± 4.23	39.81 ± 5.32	32.15 ± 2.67	34.06 ± 2.84
Trees live at t_1, dead at t_2 (LD)	7.27 ± 1.10		1.50 ± 0.36	
Ingrowth (I)		0.80 ± 0.23		0.27 ± 0.08
Total live	37.28 ± 4.34	40.61 ± 5.26	33.65 ± 2.72	**34.33 ± 2.82**
Trees live at t_1, dead at t_2 (LD)		2.27 ± 0.41		0.96 ± 0.27
Standing dead trees (DD)	0.88 ± 0.22	0.84 ± 0.21	3.33 ± 0.86	3.29 ± 0.85
Total dead	0.88 ± 0.22	3.11 ± 0.44	3.33 ± 0.86	**4.25 ± 0.94**
Total standing C stocks	38.16 ± 4.45	43.72 ± 5.29	36.98 ± 2.92	**38.58 ± 2.97**
Average annual carbon increment	Long-term sites		Short-term sites	
$S = (LL2 + I + LD_2 + DD_2) - (LL1 + LD_1 + DD_1)$	0.37 ± 0.09* t C ha^{-1}y^{-1}		0.70 ± 0.20* t C ha^{-1}y^{-1}	

*Significantly different from zero at $P < 0.001$.

gave values ranging from 0.62–1.09 t dm ha^{-1} (0.31–0.55 t C ha^{-1} y^{-1} assuming a carbon content for the Indian tree species of 50% dry matter), though it isn't clear whether the estimates included loss due to decay of dead biomass. Similarly, Houghton *et al.* (1999) estimated rates of carbon sequestration due to woody encroachment in western grasslands and savannas of the United States at 0.55 t C ha^{-1} y^{-1} for the 1980s.

Attribution of the carbon sink in savannas and grasslands

In the present study, we have characterized the magnitude of the increase in carbon stocks in above-ground woody vegetation in grazed eucalypt woodlands in Queensland. Similar rates of carbon sequestration have been reported due to increased woody biomass in large areas of the grasslands and savannas in Africa and the Americas but the factors causing this change in vegetation structure are not well understood. Attribution of the sink to natural or anthropogenic causes will be a major determinant of whether and how this carbon sequestration is included in carbon accounting for greenhouse gas inventories prepared for UNFCCC and perhaps for Kyoto Protocol reporting.

Increase in woody biomass in savannas most likely requires a change in growth conditions brought about by a combination of factors that directly or indirectly affect ecosystem function. Reported examples of change in vegetation structure with change in local conditions (including fenceline comparisons) provide evidence that while atmospheric CO_2 concentration or climate (especially rainfall) affect growth and establishment of woody plants in arid and semiarid savannas, imposed management, particularly intensification of grazing and change in fire regimes, are more likely the trigger for increase in woody plant cover and biomass (Scholes & Archer, 1997; van Auken, 2000). Climatic conditions, particularly above average rainfall, that would favour growth may not result in an increase in growth and establishment of woody plants because the same conditions should promote competition from strong grass growth, as well as increasing the likelihood of subsequent fire. However, domestic livestock grazing may alter the balance towards successful establishment of woody plants and competitive advantage for existing trees and shrubs by reducing grass cover and fine fuel for fire, and by management for active fire suppression.

Implications for global carbon budgets

The mean annual carbon increment was estimated from the present analysis of 57 TRAPS permanent monitoring

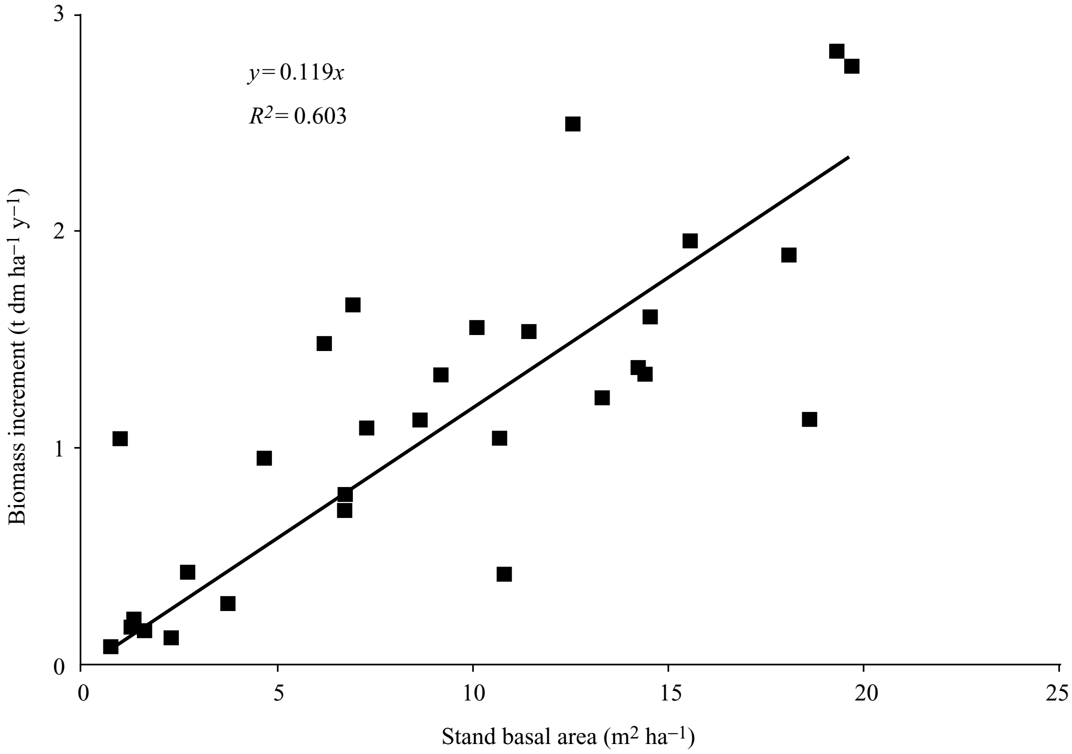


Fig. 7 Regression of above-ground biomass increment against stand basal area for live eucalypt trees at 30 long-term TRAPS sites for measurement periods of 9–17 years (mean 14.14 years).

sites to be 0.53 t C ha^{-1} or 14.3 Mt C y^{-1} over the 27 M ha eucalypt woodlands in the study area of Queensland. Assuming biomass stock change below-ground is proportional to that above-ground (Nihlgard, 1972) and an average root:shoot ratio to 1 m depth of 0.26 ± 0.02 (SE) (Burrows *et al.*, 2000), gives a total above- plus below-ground carbon sequestration rate of 18 Mt C y^{-1} over 27 M ha. The increase in biomass carbon stocks will potentially affect soil organic carbon levels but this possible flux is ignored in this analysis because there are currently insufficient data on the dynamics and magnitude of any change. If a similar rate of biomass carbon sequestration to that in the studied eucalypt woodlands were assumed in woodlands with non-eucalypt dominants or co-dominants, the annual sink in the *c.* 60 M ha grazed woodlands in Queensland would be approximately 35 Mt C y^{-1}.

This sink in native woodlands managed for grazing is equivalent in magnitude to approximately 25% of the total estimated national net emissions in 1999 (AGO 2001). It is currently not included in the Australian inventory of anthropogenic greenhouse gas emissions and removals. However this inventory does take into account net emissions from widespread land clearing in the study area including regrowth of woody vegetation following clearing (AGO, 2001). If estimates were only based on the long-term site data, this still suggests about 22 Mt C y^{-1} was fixed in the grazed woodlands, despite below average rainfall over the measurement period. The latter sink is equivalent to approximately 16% of Australia's total reported 1990 greenhouse gas emissions from all sectors (AGO, 2001).

At the long-term TRAPS monitoring sites, the mean annual increment in stand basal area, excluding change in those woody plants that were dead at the initial recording, was 2.1% (Table 1). This compares with estimates of 2–5% increase in stand basal area per year reported previously for woody savanna species (Scholes & van der Merwe 1996). The mean potential basal area across the eucalypt woodlands has been estimated to be 20–25 m^2 ha^{-1} (Burrows *et al.*, 1998) and on this basis the current rate of carbon sequestration in the eucalypt woodlands could continue (and probably increase – see Fig. 7) for more than 30 years.

Savannas cover approximately 1600 M ha or 11% of the world's terrestrial vegetated surface (Scholes & van der Merwe, 1996) including more than half the area of Australia and approximately 900 M ha (55% of the non-desert land area) in Africa (Scholes & van der Merwe, 1996). Whilst not all savannas are undergoing woody plant proliferation and some are being actively cleared for fuelwood or agriculture, studies indicate that bush encroachment is widespread in Africa (van der Schijff, 1957; Jeltsch *et al*., 1997; Moleele & Perkins, 1998) and North and South America (Buffington & Herbel 1965; Adamoli *et al*., 1990; van Auken, 2000) as well as in Australia. Houghton *et al*. (1999) estimated that woody encroachment in western grasslands and savannas of the United States due to fire exclusion and grazing could potentially occur on an area of 220 M ha which is neither forested nor cultivated, resulting in a potential rate of carbon accumulation in above-ground biomass of $0.122\,\mathrm{Pg\,C\,y^{-1}}$ during the 1980s. This is equivalent to a sink of approximately $450\,\mathrm{Mt\,CO_2}$ equivalent $\mathrm{y^{-1}}$. Similarly, Archer (1995) estimated that the mean area of closed canopy woodland in a study site in southern Texas increased by 38% over 50 years from 1941–1990 due to invasion of *Prosopis* spp.

These data with those from the present study in north-east Australia support the conclusion of Scholes & Hall (1996) and Scurlock & Hall (1998) that tropical savannas should make a significant contribution to vegetation sinks included in global carbon budgets.

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