10.1071/BT05138_ACappendix2

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Appendix 2. Validation of model estimates

NNCI

The estimated *NNCI* for the continent with the present (*c*. 1988) vegetation cover (pveg350) or the hypothetical 'natural' vegetation cover (nveg350) is ~1.6 Gt C year^{-1}. These estimates fall within the range of estimates derived from other modelling approaches. The 'potential' *NPP** for the continent (comparable to the nveg350 scenario) has been previously estimated at 2.7 Gt C year^{-1} (Gifford *et al.* 1992), 2.0 Gt C year^{-1} (DeFries *et al.* 1999), 2.5 Gt C year^{-1} (Miami model; Pittock and Nix 1986) and 1.7 Gt C year^{-1} (CEN-W; Kirschbaum 1999). The *NPP** of the present vegetation has been estimated at 0.96 Gt C year^{-1} (Raupach *et al.* 2001; BiosEquil model), 0.8–1.1 Gt C year^{-1} (between 1991 and 1998, Wang and Barrett 2003; VAST model) and 0.65 Gt C year^{-1} (Barrett 2002; VAST model). A comparison between *NPP** estimated by the BiosEquil model and the *NNCI* estimated by the TMSC model is shown in Fig. A1. There is good agreement spatially between these models. However, the slope of the regression relationship indicates that BiosEquil *NPP** is consistently about half of the TMSC (*NNCI*) estimate (Fig. A1). To obtain 1: 1 agreement between the BiosEquil *NPP** and our estimate would require rescaling the range of *NNCI*: *GPP* (Equation 2) from $0 \rightarrow 0.70$ to $0 \rightarrow 0.35$. For temperate and subtropical eucalypt forests the ratio of *NNCI*: *GPP* would then be ~0.17–0.25, much lower than the values reported for similar forest types (see preceding section).

$C_{living\_pveg350}$

The total carbon stock in living vegetation in 1988 ($C_{\mathrm{living\_pveg350}}$) was estimated at 21 Gt, and is in accord with previous estimates of 20 Gt (Gifford *et al.* 1992) and 26 Gt (Raupach *et al.* 2001). Although there are few published estimates of the continental carbon stock of the present vegetation, many studies within Australia and elsewhere have estimated above-ground or above- and below-ground drymass in living vegetation at specific sites. These estimates are generally derived from a mixture of direct measurement and from the application of allometric relationships, for study sites of one hectare (e.g. Burrows *et al.* 2002) or less. As vegetation type and age structure may vary considerably even across small spatial gradients (e.g. Battles *et al.* 2002), these site estimates cannot readily be scaled up to the surrounding pixel (~2700 ha in this study). Nonetheless, the data from these studies can be used to check whether model estimates are reasonable

A database of global tropical and subtropical rainforest estimates of C_{living} (Table A1) has been compared with TMSC model predictions for pixels of closed forest in Australia (see Fig. A2). C_{living} of most pixels ($C_{\mathrm{living\_pveg350}}$), along with the site data, falls within a range of 180–240 t C ha^{-1}. However, C_{living} in some small-scale studies greatly exceeds (by up to 100 t C ha^{-1}) the TMSC-derived maximum estimates for the pixels that are mapped as closed forest. A similar relationship between model estimates and study site estimates (Table A2) exists for the eucalypt forests (Fig. A3). In this case, site studies indicate that patches of forest may contain >600 t C ha^{-1}, whereas the maximum estimated by the TMSC model for pixels of eucalypt forest is ~230 t C ha^{-1}. The plots for which C_{living} exceeded 280 t C ha^{-1} were plantations established 30–60 years previously (Table A2). In Fig. A4 we compare TMSC model predictions with estimated C_{living} from a long-term monitoring study (Burrows *et al.* 2002). The 57 sites of this study are representative of 27 M ha of grazed woodlands in inland north-eastern Australia. Estimates of C_{living} from the TRAPS study and model estimates are generally consistent.

$C_{living\_nveg350}$ and $C_{living\_nveg280}$

Although the estimates for $C_{\mathrm{living\_pveg350}}$ show reasonable agreement with estimates derived from small-scale studies, we are not currently able to validate the model estimates of $C_{\mathrm{living\_nveg350}}$ and $C_{\mathrm{living\_nveg280}}$ for the entire continent. It should be noted that the estimates are very sensitive to the values used in the equations in Table 2, Step 6. However, as the same parameters were applied to the three [CO_2]–vegetation scenarios, the differences in the behaviour of the three scenarios should be insensitive to the actual values chosen.

We noted previously (Berry and Roderick 2004) that we may have underestimated $\overline{F_V}_{\,nveg350}$ for some pixels (as a result of errors associated with deriving it), and consequently the stocks and fluxes for this scenario. As $\overline{F_V}_{\,nveg280}$ and its T, M and S components were derived from the nveg350 estimates (Berry and Roderick 2002*a*), these would also be underestimated. Thus, if the effects of land degradation on $\overline{F_V}_{\,nveg350}$ could be accounted for, the values of $C_{\mathrm{living\_nveg350}}$ and $C_{\mathrm{living\_nveg280}}$ for some pixels would be larger than those presented here.

Estimated change in C_{living} from 1788 to 1988

Although we are currently not able to directly validate the estimates of $C_{\mathrm{living\_nveg350}}$ and $C_{\mathrm{living\_nveg280}}$, we can test their veracity through comparison of estimates of the *CSI* with measurements and published estimates from smaller-scale studies in Australia and elsewhere. Increases in the carbon stock in living vegetation during the last two centuries have been observed or simulated in several studies. Phillips *et al.* (1998) estimated that, in recent decades, carbon has been accumulating in the above-ground biomass of South American tropical forests at a mean rate of 70 ± 20 g C m^{-2} year^{-1}. Although this result was controversial at the time of publication, it has been confirmed by more recent studies (Baker *et al.* 2004; Lewis *et al.* 2004). By using the CQESTA model, Gifford *et al.* (1992) estimated the annual sequestration of carbon into the living plants resulting from increasing [CO_2] alone for the Australian continent in 1991 AD at 33 Mt C year^{-1}. For their simulation with increasing [CO_2] and increasing temperature ($\triangle T$=0.03°C year^{-1}), the annual sequestration to living plants in the study by Gifford *et al.* (1992; their fig. 1*c*) was nearly identical with the TMSC estimate at ~50 Mt C year^{-1}. Simulations of vegetation growth in African savannas with the DBM savanna demography model (Bond *et al.* 2003) predicted a 20% increase in the rate of grass dry-matter accumulation and a 20–60% increase in the annual increment to the carbon stock of tree stems. There is also evidence from air photo studies and measurements that the canopy cover and carbon stock in living vegetation have increased in North America (Knapp and Soule 1996; Polley *et al.* 2002), and northern Australia (Bowman *et al.* 2001; Burrows *et al.* 2002; Fensham *et al.* 2005).

Empirical estimates indicate that sequestration rates to C_{living} of the magnitude predicted by the TMSC model have occurred in Australia. On the basis of the data from the TRAPS study of 57 permanent monitoring sites within 27 Mha of grazed savanna woodlands in north-eastern Australia, Burrows *et al.* (2002) estimated the above-ground component of *CSI* (living and standing-dead woody vegetation that had died during the monitoring period) during the last two decades. Of these sites, 27 were short-term (average monitoring period of ~2 years), whereas 30 were relatively long-term (average monitoring period of ~14 years). These estimates are compared in Fig. A5 with predicted mean *CSI* of pixels based on an increase in [CO_2] from 344 μmol mol^{-1} to 366 μmol mol^{-1} over a 14-year period. (Over the 14 year period from 1984 to 1998 [CO_2], increased from ~344 μmol mol^{-1} to ~366 μmol mol^{-1}; Fig. 1). To estimate below-ground C_{living} for the data of Burrows *et al.* (2002), we assumed that the ratio of above-ground: below-ground C_{living} is 3: 1. The TMSC model predicts a *CSI* in Queensland's grazed eucalypt woodlands of ~128 g C m^{-2} year^{-1}. However, the averaged above-ground *CSI* of living plants in the TRAPS study was less than that at ~39 g C m^{-2} year^{-1} for the short-term sites and ~28 g C m^{-2} year^{-1} for the long-term sites (Fig. A5, points c and a, respectively). The model predictions are based on an average climate that has no inter-annual variability. In contrast, over the monitoring period for the long-term sites, rainfall was considerably below the historical average (Burrows *et al.* 2002; their fig. 4), and presumably contributed to the death of trees during the monitoring period. If no trees had died during the monitoring period, the above-ground *CSI* would likely have exceeded 53 g C m^{-2} year^{-1} (Fig. A5 point d; calculated as the *CSI* of the above-ground biomass of standing dead and living trees; Burrows *et al.* 2002), and the above- plus below-ground *CSI* would have been at least ~71 g C m^{-2} year^{-1} (Fig. A5, point e). This value is closer to, but still lower than the TMSC model estimate for this woodland type.

Table A1. Estimates of the mass of carbon in living rainforest vegetation (C_{living} t ha^{-1}) derived from published drymass data

Below-ground drymass is assumed to equal a one-third portion of above-ground drymass. Carbon is assumed to comprise 50% of the drymass of plant tissues

Study	Country	Site location	Floristics	C_{living} (t ha^{-1})
Odum (1970)	Puerto Rico	Tabonuco forest	Rain forest	192
Ogawa *et al.* (1965)	Thailand	Khao Chong	Rain forest	296
Whitmore (1984)	Malaya	Pasoh	Lowland evergreen rain forest	348
Müller and Nielson (1965)	Africa	Ivory Coast	Rain forest	192
Cummings *et al.* (2002)	Brazil	Amazon, alluvial terraces	Open tropical forest, Amazon alluvial	219
				192
		Sub-montane rolling hills, broken surface of the upper Xigu/Tapajos/Madeira	Open tropical forest, Amazon alluvial	230
				196
				207
				207
				210
				199
				213
		Amazon alluvial, alluvial plane periodically flooded	Dense tropical forest	271
				212
		Low plates of Amazonia, rolling lowlands	Dense tropical forest	199
		Sub-montane low hills, low hills of southern Amazonia	Dense tropical forest	355
				294
		Sub-montane broken surface, Precambrian platform cover	Dense tropical forest	198
				224
		Forest/savanna edge, lowland plates	Ecotone tropical forest (open forest)	232
				198
				281
				221
Ash and Helman (1990)	Australia	Kioloa, NSW	Mixed eucalypt and notophyll rainforest	339
Hegarty (1991)	Australia	Mt Glorious, Qld	Subtropical evergreen rainforest	268
Turner *et al.* (1989)	Australia	Wiangaree, northern NSW	Subtropical rainforest	237
Weber (1999)	Tierra del Fuego	Argentinean part	*Nothofagus pumilo* (Lenga)	225
Ryan *et al.* (1994)	Costa Rica	La Selva biological station	*Simarouba amara* and *Minquartia guianensis*	124

Table A2. Estimated C_{living} of eucalypt forest in Australia on the basis of drymass data given in Cannell (1982)

Below-ground drymass is assumed to equal a one-third portion of above-ground drymass. Carbon is assumed to comprise 50% of the drymass of plant tissues

Study	Location	Forest description	Treatment/soil type	Stand age (years)	C (t ha^{-1})
Hingston *et al.* (1979)	Western Australia, near Pemberton, 34°26′S, 116°0′E; 300–400 m	*E. diversicolor*	Lateritic red earth	36	148
		E. diversicolor and *Eucalyptus calophylla*	Yellow podzolic	100	189
Cromer *et al.* (1980)	Victoria, near Morwell, 38°20′S, 146°20′E; 150 m	*E. globulus* plantation	No fertiliser	10	20
		E. globulus plantation	34 kg ha^{-1} N; 15 kg ha^{-1} P	10	38
		E. globulus plantation	101 kg ha^{-1} N; 45 kg ha^{-1} P	10	49
		E. globulus plantation	202 kg ha^{-1} N; 90 kg ha^{-1} P	10	54
Bradstock (1981), Turner and Lambert (1981)	New South Wales, near Coffs Harbour, 30°20′S, 153°0′E; 10–100 m	*E. grandis* plantation	Fertilised, Lower Permian sediments	2	12
		E. grandis plantation	Fertilised, Lower Permian sediments	5	34
		E. grandis plantation	Fertilised, Lower Permian sediments	6	18
		E. grandis plantation	Fertilised, Lower Permian sediments	16	124
		E. grandis plantation	Fertilised, Lower Permian sediments	27	262
		E. grandis plantation	Fertilised, Upper Permian granodiorite	10	56
		E. grandis plantation	Fertilised, Upper Permian granodiorite	12	131
		E. grandis plantation	Fertilised, Upper Permian granodiorite	15	109
Hingston *et al.* (1981)	Western Australia, Dwellingup, 32°45′S, 116°0′E	*E. marginata* and *E. calophylla* with understorey shrubs	Burned 4 years previously	60	177
Stewart *et al.* (1979)	Victoria, 10 km N of Genoa, 37°25′S, 149°33′E, 350 m	*E. muellerana* 39%, *E. seiberi* 27%, *E. agglomerata* 19%	Loamy soils overlying mottled yellow clays	100	218
Attiwill (1966, 1979, 1981), Attiwill *et al.* (1978)	Victoria, Mt Disappointment, 37°25′S, 145°10′E; 545	*E. obliqua*	Red, friable porous krasnozems, pH 5.2–5.9	44	361
		E. obliqua	Red, friable porous krasnozems, pH 5.2–5.9	51	198
		E. obliqua	Red, friable porous krasnozems, pH 5.2–5.9	61	229
		E. obliqua	Red, friable porous krasnozems, pH 5.2–5.9	66	247
Feller (1980)	Victoria, 60 km NE of Melbourne, 37°38′S, 145°35′E; 560 m	*E. regnans* 96% with *Acacia* spp.	Krasnozems to podsols pH 3.9–5.0	39	409
	Victoria, 60 km NE of Melbourne, 37°38′S, 145°35′E; 180 m	*E. obliqua* and *E. dives*, 99%	Krasnozems to podsols pH 3.9–5.0	39	248

Ashton (1976)	Victoria, 65 km E of Melbourne, Beenak, 38°S, 146°E; 500–550 m	*E. regnans* with understorey shrubs	Wet sclerophyll forest on south-facing slope; brown, red-brown loams	27	554
		E. sieberi with understorey shrubs	Dry sclerophyll forest on north-facing slope; red podzolic soils	27	618
Turner (1980)	New South Wales, near Tumut, 35°06′S, 141°01′E; 680 m	*E. radiata, E. dalrympleana, Eucalyptus* spp. with *Acacia* spp. and other understorey shrubs	Red, permeable soils	45	89
Rogers and Westman (1977, 1981), Westman and Rogers (1977*a*, 1977*b*)	Queensland, North Stradbroke Island, 27°30′S, 155°30′E; 100 m	*E. signata* 55%, *E umbra* 18%, *Tristania conferta, Banksia aemula*, with understorey shrubs	Infertile podsols, with a sandy substratum	100	75

Table A3. Estimated C_{living} of Australian eucalypt forests derived from data not included in Cannell (1982)

Below-ground drymass is assumed to equal a one-third portion of above-ground drymass. Carbon is assumed to comprise fifty percent of the drymass of plant tissues

Study	Site location	Floristics	Successional stage (yeasr)	C_{living} (t ha^{-1})	Comments
Grove and Malajczuk (1985)	Near Pemberton, WA	*E. diversicolor*	4	17	Calculated from above-ground drymass
		E. diversicolor	8	34	As above
		E. diversicolor	11	42	As above
		E. diversicolor	36	126	As above
Borough *et al*. (1984)	Noojee, Vic.	*E. regnans*	9	124	Calculated from standing total volume and basic density estimates
		E. regnans	18	208	As above
		E. regnans	24	299	As above
		E. regnans	33	330	As above
		E. regnans	8	38	As above
		E. regnans	17	127	As above
		E. regnans	23	201	As above
		E. regnans	32	265	As above
		E. regnans	7	10	Aas above
		E. regnans	16	84	As above
		E. regnans	22	186	As above
		E. regnans	31	242	As above
Borough *et al*. (1984)	Bago, NSW	*E. delegatensis*	10	32	As above
		E. delegatensis	15	59	As above
		E. delegatensis	20	88	As above
		E. delegatensis	25	120	As above
		E. delegatensis	30	152	As above
		E. delegatensis	35	180	As above
		E. delegatensis	40	204	As above
		E. delegatensis	45	225	As above

		E. delegatensis	50	242	As above
		E. delegatensis	55	259	As above
		E. delegatensis	60	272	As above
Turner (1986)	Mill Site, north coast, NSW	*E. grandis* plantation	2	12	Calculated from above-ground drymass
Turner (1986)	Everinghams II, north coast, NSW	*E. grandis* plantation	5	34	As above
Turner (1986)	Niesh's II, north coast, NSW	*E. grandis* plantation	10	56	As above
Turner (1986)	Niesh's I, north coast, NSW	*E. grandis* plantation	12	131	As above
Turner (1986)	Everinghams I, north coast, NSW	*E. grandis* plantation	16	124	As above
Turner (1986)	Boyds, north coast, NSW	*E. grandis* plantation	27	262	As above
Westman and Rogers (1977*a*)	North Stradbroke Island	*E. signata* dominated forest 15m tall on infertile sands	Not stated	108	As above
Stewart *et al.* (1979)	Eastern Victoria	*E. agglomerata/E. sieberi* mixed sclerophyll forest	Not stated	228	As above
Keith *et al.* (1997*a*); Keith *et al*. (1997*b*)	Brindabella Range, ACT	Eucalypt forest	Not stated	145	Calculated from measurements of stocks

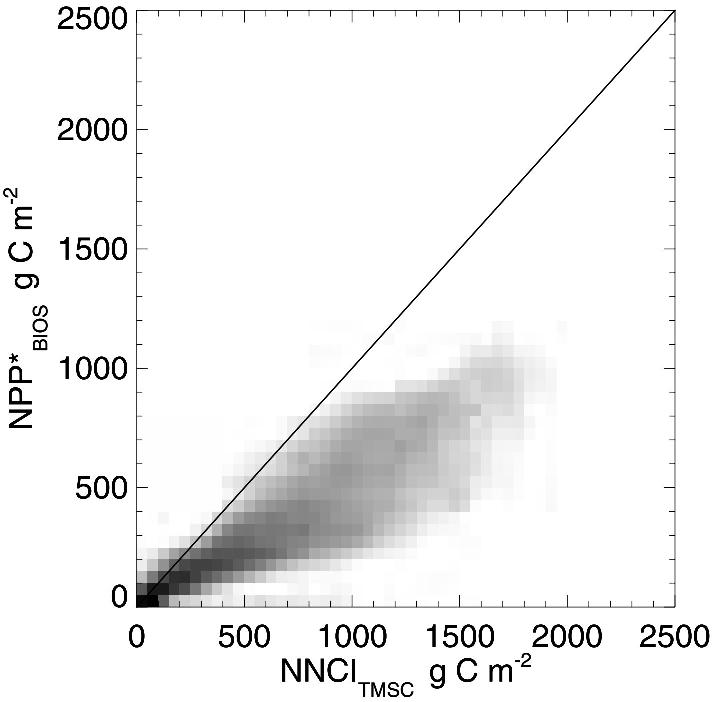
Fig. A1. Comparison of *NNCI* estimated by the TMSC model (pveg350) and *NPP** estimated by the BIOS Equil model (Raupach *et al.* 2002) for Australia. The relative frequency of occurrence of data points is indicated by shading, black (n = maximum) to white (n = 0) on a log scale. The solid line indicates a 1:1 relationship. The line of best fit, determined by using a linear regression analysis is $NPP^{*}_{BIOS} = 11.4 + 0.49\, NNCI_{TMSC}$; $R^2 = 0.89$, $n = 272549$.

Fig. A2. Histograms showing frequency distribution of C_{living} of pixels of closed forest (xM4, projected foliage cover of upper canopy layer (pfc) >70%, and height of upper canopy layer (h) = 10–30 m). Estimates of C_{living} derived from published studies (Table A1) are plotted (+) in the upper graph.

Fig. A3. Histograms showing frequency distribution of C_{living} of pixels of eucalypt forest (eM3 and eT3; projected foliage cover of upper canopy layer (pfc) = 30–70%, height of upper canopy layer (h) = 10–30 m (eM3) and >30 m (eT3). Estimates of distribution of C_{living} derived from published studies are plotted in the upper graph. Estimates derived from the database of Cannell (1982), Table A2, are plotted (+). Estimates derived from other sources, Table A3, are plotted (×).

Fig. A4. Histograms showing frequency distribution of C_{living} of pixels of eucalypt woodland (eM1 and eM2; projected foliage cover of upper canopy layer (pfc) < 10% and 10–30%; height of upper canopy layer (h) = 10–30 m) in the region bounded by 18.225°S–27.675°S and 143.375°E–151.675°E, comprising the area covered by the TRAPS study (Burrows *et al.* 2002). Values derived from the biomass data of Burrows *et al.* (2002) are plotted (+).

Fig. A5. Histogram showing frequency distribution of TMSC model estimates of the net average annual carbon increment to the carbon stock (*CSI*) of the eucalypt woodlands described in Fig. A4. Estimates of *CSI* from the TRAPS study are plotted (+) and are as follows: a, mean above-ground *CSI* of living trees for the 30 long-term sites; b, mean above-ground *CSI* of living trees for all 57 sites; c, mean above-ground *CSI* of living trees for the 27 short-term sites; d, mean above-ground *CSI* of living and dead trees for 57 sites; e, mean above- and below-ground *CSI* of both living and dead trees for 57 sites.



2500
2000
1500
1000
500
0
0
500
1000
1500
2000
2500
NPP^*_{BIOS} g C m^{-2}
$NNCI_{TMSC}$ g C m^{-2}

Figure A2

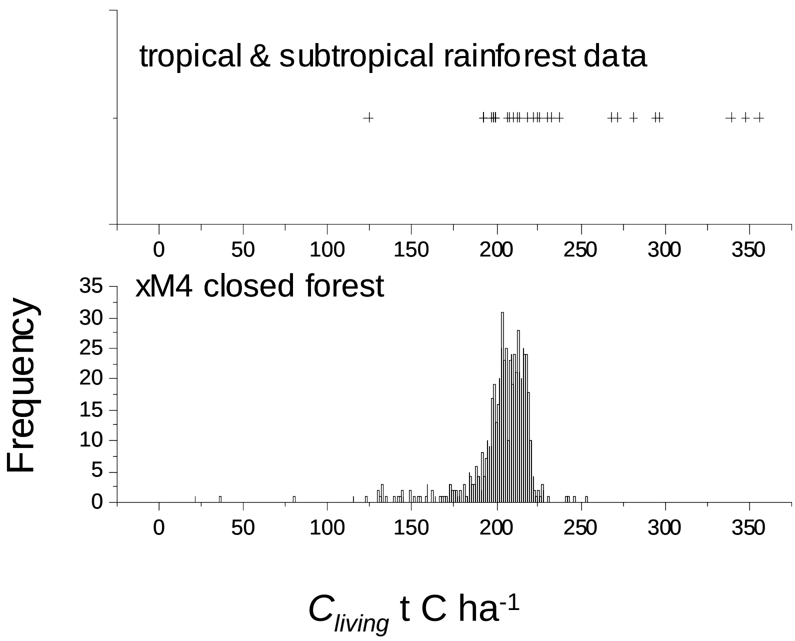
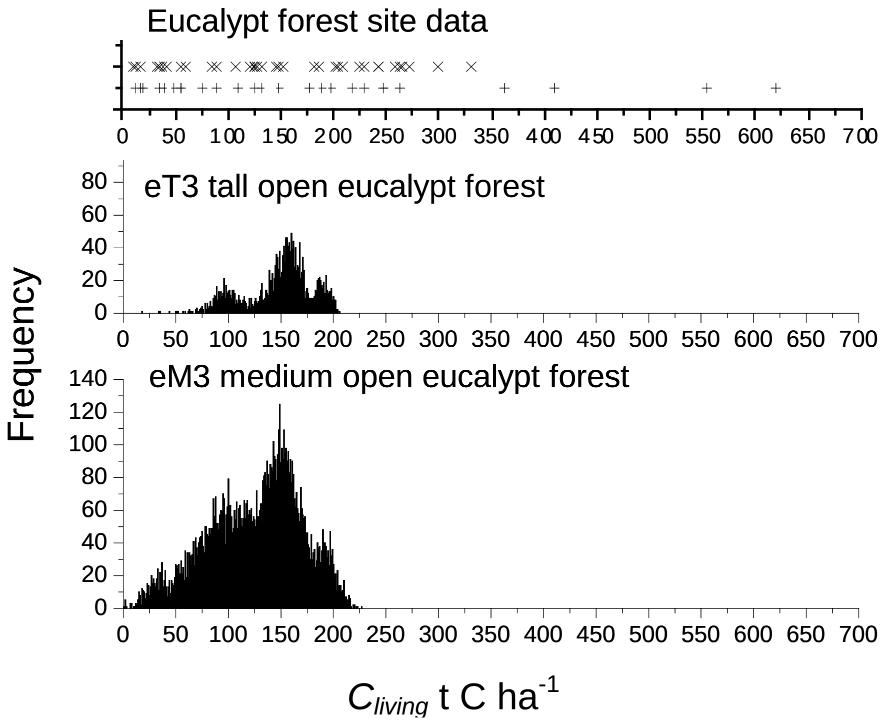

tropical & subtropical rainforest data
0
50
100
150
200
250
300
350
xM4 closed forest
35
30
25
20
15
10
5
0
Frequency
C_{living} t C ha^{-1}

Figure A3



Eucalypt forest site data
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700
80
60
40
20
0
eT3 tall open eucalypt forest
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Frequency
140
120
100
80
60
40
20
0
eM3 medium open eucalypt forest
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700
C_{living} t C ha^{-1}

Figure A4

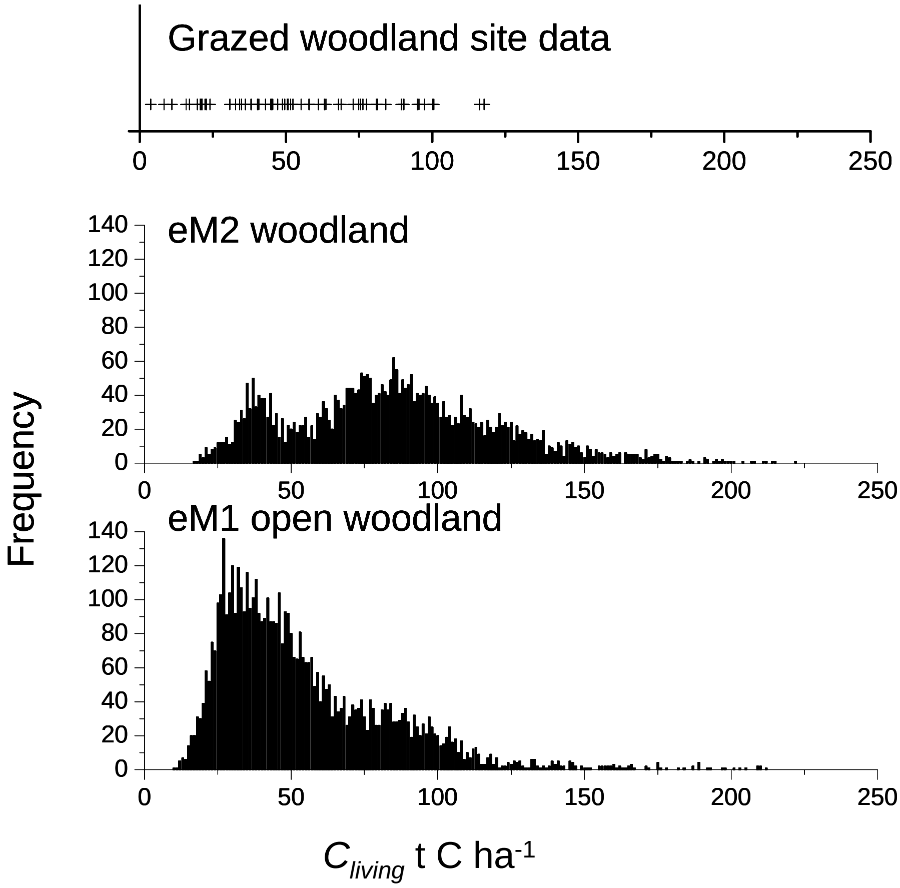
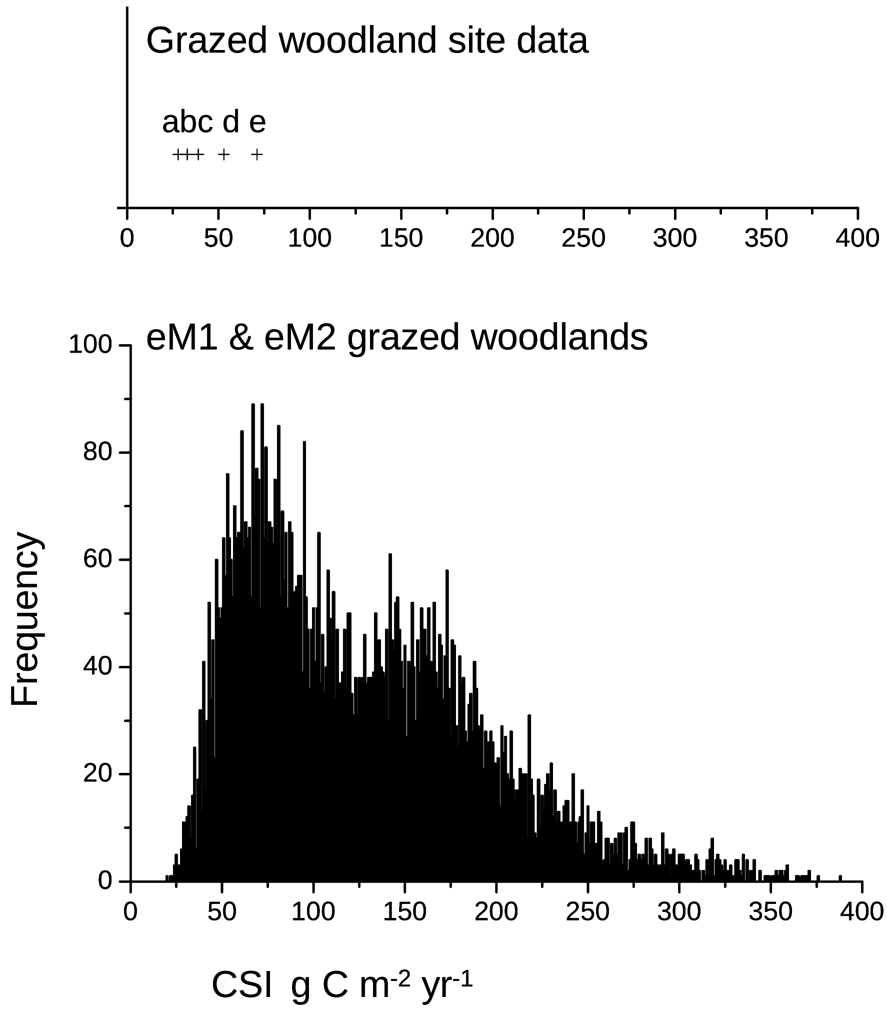

Grazed woodland site data
0
50
100
150
200
250
eM2 woodland
140
120
100
80
60
40
20
0
eM1 open woodland
Frequency
C_{living} t C ha^{-1}

Figure A5



Grazed woodland site data
abc d e
0
50
100
150
200
250
300
350
400
eM1 & eM2 grazed woodlands
Frequency
100
80
60
40
20
0
0
50
100
150
200
250
300
350
400
CSI g C m-2 yr-1