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Biomass retention and carbon stocks in integrated vegetation bands: a case study of mixed-age brigalow-eucalypt woodland in southern Queensland, Australia

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Abstract. Regrowth of native woody vegetation has the potential to provide an economically valuable source of carbon storage and other ecosystem services. There is a lack of readily applicable examples of how regrowth of forests and woodlands can be integrated with existing grazing production systems and provide soil-protection and water-retention benefits. A system of integrated vegetation bands (IVB) was applied to patchy regrowth of acacia and eucalypt vegetation in a grazed landscape of southern Queensland, Australia. Across a 39.8-ha catchment with 3–5% slope, regrowth of scattered native vegetation (18.4 ha) was surveyed and diameter at breast height and height for all woody plants were recorded. The IVB (6.3 ha) were then marked out as 25-m-wide bands set 100 m apart and offset at ~2–3% gradient to the contour line, retaining the densest/largest regrowth where possible. The data on diameter at breast height and height were analysed using allometric equations to compare aboveground biomass in the original regrowth condition (‘Original’) to that retained in the installed IVB (‘IVB-Riparian’). Estimates of aboveground biomass were calculated for the Original and IVB-Riparian and compared with three other potential regrowth-vegetation management ‘treatments’ in a desktop-modelling study. The models were designated as: (1) ‘Original’; (2) ‘Broad’ (broad-scale cleared with only a few large trees along a creek retained)’; (3) ‘Big Trees’ (only large trees >40 cm diameter at breast height retained); (4) ‘Riparian-IVB (bands of vegetation); and (5) ‘Riparian-IVB-Big Trees’ (large trees together with ‘IVB-Riparian’). In the non-forested area of the catchment, ‘Riparian-IVB-Big Trees’ (301 t), ‘Big Trees’ (249 t) and ‘Riparian-IVB’ (200 t) had the highest aboveground biomass retained, whereas ‘Broad’ resulted in the most pasture area (~33 ha) followed by ‘Riparian-IVB’ (~26 ha). The ‘Riparian-IVB’ treatment had the highest tree density within the vegetation bands and more than half (53%) of the original woody biomass in regrowth was retained on just under a quarter (23%) of the land area minimising the impact on the area of pasture/grazing land. This subsequently resulted in the ‘Riparian-IVB’ treatment having the highest carbon offset value (A\$605 ha^{-1}). The results demonstrate that the retention of native regrowth vegetation in either IVB or as large paddock trees can retain a large amount of aboveground biomass, with IVB having greater returns per hectare.

Additional keywords: aboveground biomass, carbon offsets, grazing land, large trees, regrowth of native vegetation.

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Introduction

With temperatures on Earth rising rapidly to a level almost equivalent to the Early Holocene, global food security is under pressure as land managers face significant constraints in their ability to adapt (Marcott *et al*. 2013). Although carbon emissions must be reduced to prevent unacceptable climate change, there is also a role for mitigation through sequestration of atmospheric carbon by photosynthesising vegetation (Keenan 2002). Although the links between vegetation and landscape functioning and emissions are not well understood, retained regrowth and plantations have the ability to increase carbon stocks in vegetation and soils and improve food security under increasing climate variability (Keenan 2002; Campbell 2008; Dargusch *et al*. 2010; Hochman *et al*. 2013). Their potential to act as sinks for the sequestration of greenhouse gas emissions also allows them to be traded as offsets in some parts of the world (Dargusch *et al*. 2010; Dargusch and Harrison 2011).

Identifying adaptive management approaches to the management of regrowth vegetation that create carbon sinks requires consideration of factors such as impacts on existing land use, pasture area and quality, shade and shelter for stock, total carbon sink retained, timber resources, the moisture retention and cooling effects on the landscape, protection against soil erosion, recycling of deep soil nutrients and conservation of biodiversity (Fischer and Lindenmayer 2002; Gibbons and Boak 2002; Wilson 2002; Graham *et al*. 2004; McKeon *et al*. 2008; McAlpine *et al*. 2010; Ryan *et al*. 2010; Barnes *et al*. 2011). While a balance must be struck between vegetation used to maintain landscape functioning with maintaining the productive potential of agricultural land (Back *et al*. 2009; Eckard *et al*. 2012), there are few practical measures available to land managers for actual implementation (Swallow and Goddard 2013). Measures or treatments that apply banded vegetation in some ratio to pasture area, such as alley-based silvopastural systems (Sudmeyer and Flugge 2005; Donaghy *et al*. 2009; Stephens 2010), may offer a means to manage regrowth and pasture as integrated systems. We applied the example of Ryan *et al*. (2010), termed integrated vegetation bands (IVB), to retain regrowth for carbon offsets, protect soil against runoff and strong winds, for biodiversity conservation and a timber resource, with areas between bands cleared to promote pasture growth. The main functions of IVB in this study were to buffer runoff and wind across the landscape, while also capturing existing and future potential for aboveground biomass (AGB t) in retained regrowth. There are significant eco-hydrological benefits from adding vegetation bands to landscapes in rural watersheds, for example, the role of woody debris and plant litter in increasing water retention in landscapes (Mitchell and Humphreys 1987; Eddy *et al*. 1999; Ryan *et al*. 2010) and the function of tree belts as wind shelterbelts (Cleugh and Hughes 2002; McKeon *et al*. 2008). As higher temperatures in the soil cause greater carbon losses (Luo *et al*. 2011), another benefit of retaining regrowth vegetation would be avoided soil carbon losses due to shading and cooling of the soil.

The aim of the paper is to compare AGB, carbon offset value and area of open pasture gained under the IVB system, with other potential (i.e. hypothetical) regrowth management approaches (‘treatments’). The IVB were applied to a small headwater catchment that supported regrowth vegetation of uneven age of patchy brigalow (*Acacia harpophylla* F.Muell. ex Benth.) and eucalypt within a grazing property of southern Queensland, Australia. The sizes of all plants were recorded and converted into ABG for the original vegetation configuration and for IVB and riparian areas. Estimates of AGB within the original and IVB and riparian areas were then compared in a desktop modelling study to three other hypothetical clearing treatments. The treatments were designated: (1) ‘Original’; (2) ‘Broad’ (only a few trees along a creek retained)’; (3) ‘Big Trees’ [only large trees >40 cm diameter at breast height of 130 cm (DBH^{130}) retained]; (4) ‘Riparian-IVB (the actual treatment applied at the study site); and (5) ‘Riparian-IVB-Big Trees’ (large trees together with all trees within ‘IVB-Riparian’ retained). We compared the effect of each approach on tree measurements and total and mean AGB, as well as effects on vegetation density. We also repeat this statistical procedure for each alternative treatment comparing differences in estimates of CO_2e and carbon offset value (A$) at various carbon prices. The potential implications for vegetation management for carbon in woodlands with uneven-age regrowth are discussed.

Methods

Conceptual approach

We applied an IVB treatment to the regrowth vegetation based on regrowth density (stems ha^{-1}) and AGB according to the landscape design illustrated in Fig. 1, which is based on Ryan *et al*. (2010). The design is adaptive and takes into consideration existing regrowth and remnant vegetation, topography, soil, drainage lines, predominant wind patterns, and stock and vehicle movement issues (Wang and Takle 1996*a*, 1996*b*; Ryan *et al*. 2010). For gently sloping topography, the IVB may follow a direction more perpendicular to the contour, whereas on steeper topography they may be more parallel with the contour.

Study area and site description

The study site (Fig. 2) was located 340 km west of Brisbane near the township of Miles, southern Queensland, Australia (26°464′S, 150°089′E, 380 m above sea level). The study site was a paddock within a small headwater catchment (39.8 ha) of Eleven Mile Creek, a tributary of the Condamine River. Average annual rainfall was 650 mm falling mostly in summer (BoM 2014). The soils are heavy cracking clays (Vertosols) on lower slopes, grading to sodic duplex soils (Sodosols) on the upper slopes. Sodosols on some of the more heavily disturbed areas, such as farm road tracks, exhibited sheet and rill erosion. The regrowth of native vegetation comprised both brigalow and eucalypt vegetation communities and was of various ages and structural classes. According to satellite imagery and aerial photographs, the area was initially cleared before 1962 and again around 1971 and 1997. The main regrowth area was on average 17 years of age, with older trees randomly scattered throughout the area. The area of regrowth was to be cleared by the land manager who wanted to strike a balance between re-establishing pasture, developing a timber resource, protecting against erosion, increasing runoff capture, providing shade and shelter for stock and habitat for biodiversity. A plan was formed to retain all regrowth in fenced-off riparian and IVB areas, along with most of the large trees (>40 cm DBH^{130}) in the open pasture areas.

Vegetation communities

The vegetation communities (Table 1) were predominantly brigalow (*Acacia harpophylla*) and belah (*Casuarina cristata*

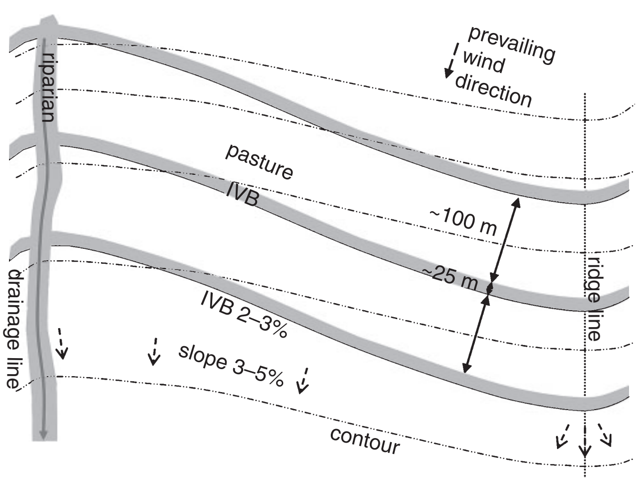

Fig. 1. Conceptual model of IVB in relation to topography, slope and wind. The IVB are 2–3% offset to the contour, set at 1 : 4 ratio to pasture area, and are perpendicular to prevailing winds. A riparian area can be connected to the top or bottom of IVB.

Miq.) woodland that contained an occasional Queensland bottle tree [*Brachychiton rupestris* (T.Mitch. ex Lindl.) K.Schum.] or pilliga box (*Eucalyptus pilligaensis* Maiden) (Fig. 3*a*). In the upper part of the sub-catchment (ridge areas) the vegetation graded into pilliga box and red ironbark (*Eucalyptus fibrosa* F.Muell.) woodland, then into open eucalypt forest containing spotted gum [*Corymbia citriodora* subsp. *variegata* (Hook.) K.D.Hill and L.A.S.Johnson] and red ironbark (Fig. 3*b*). There were also thickets of white cypress pine (*Callitris glaucophylla* Joy Thomps. and L.A.S.Johnson) in heavily disturbed areas on the slopes.

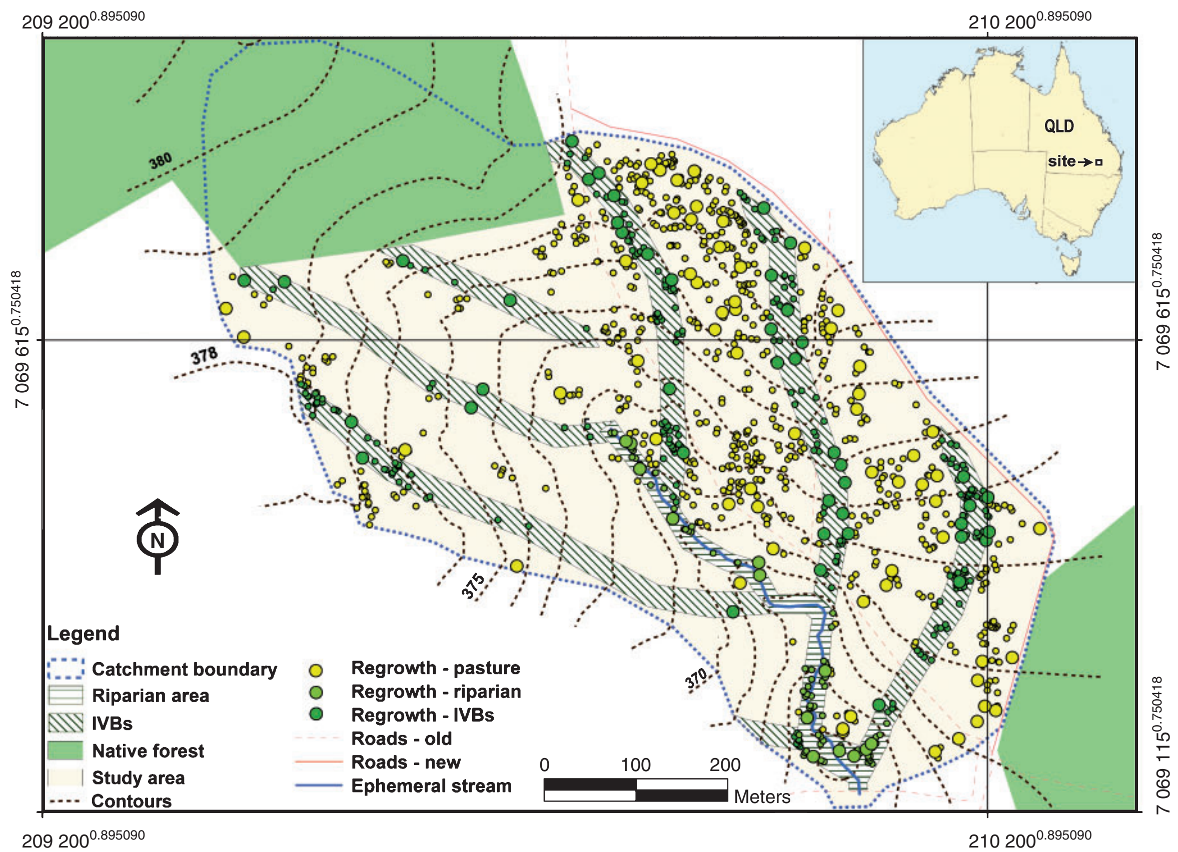

Fig. 2. Map of study site showing location in Queensland, the catchment and original regrowth areas for trees >10 cm DBH130, survey points, topography, drainage and location of IVB. AMG Zone 56.

Table 1. Species recorded at study site

Taxonomic name	Common name	Acronym	# records
Acacia harpophylla F.Muell. ex Benth.	Brigalow	BRIG	246
Alphitonia excelsa (A.Cunn. ex Fenzl) Benth.	Red ash, soap tree	SCRB	*n*
Brachychiton rupestris (T.Mitch. ex Lindl.) K.Schum.	Queensland bottle tree	BTL	14
Casuarina cristata Miq.	Belah	BEL	179
Citrus australasica F.Muell.	Native finger lime	SCRB	*n*
Corymbia citriodora subsp. *variegata* (Hook.) K.D.Hill and L.A.S.Johnson	Spotted gum	CORY	26
Callitris glaucophylla Joy Thomps. and L.A.S.Johnson	White cypress pine	CYP	40
Eremophila mitchellii Benth.	False sandalwood	SCRB	*n*
Eucalyptus fibrosa F.Muell.	Red ironbark	EFIB	174
Eucalyptus camaldulensis Dehnh.	River red gum	ECAM	1
Eucalyptus pilligaensis Maiden	Pilliga box	EPIL	288
Jacksonia scoparia R.Br.	Dogwood	SCRB	*n*
Pittosporum spinescens (F.Muell.) L.W.Cayzer, Crisp and I.Telford	Wallaby apple	SCRB	*n*
		Total	1011

Note: *n* = individual number unknown, part of dry rainforest trees recorded as one group totalling 43 records.

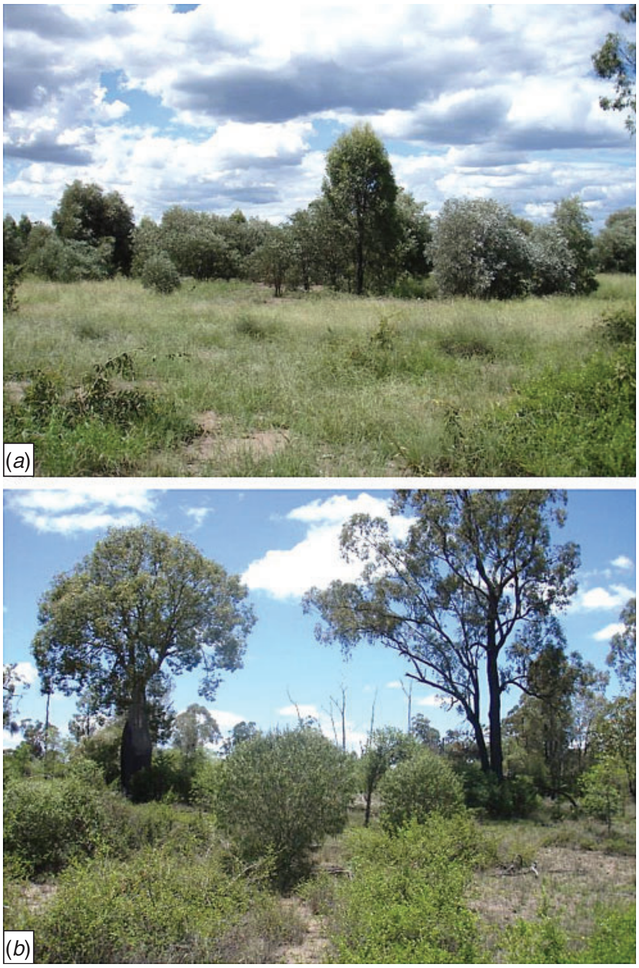

Fig. 3. (*a*) Scattered *A. harpophylla* and *E. pilligaensis* regrowth in open pasture on low slope areas; and (*b*) regrowth of *Citrus australasica* (finger lime) among *B. rupestris* and *E. fibrosa* woodland on the slopes.

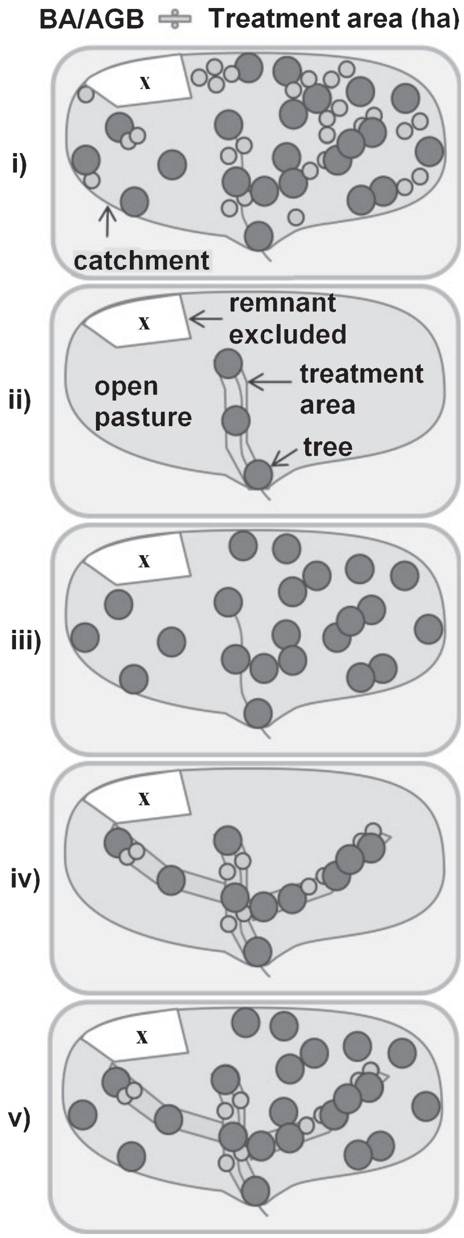

Fig. 4. Area of regrowth retained and method to determine density. The model reflects density measures based on species records per treatment extent (ha): (i) 'Original'; (ii) 'Broad'; (iii) 'Big Trees'; (iv) 'Riparian-IVB'; and (v) Riparian-IVB-Big Trees combined. These areas, minus the remnant forest (x), combine to form the study area.

Vegetation survey and IVB plan

All woody species >10 cm diameter over bark at DBH^{130} were measured across the study area of 33.4 ha (Fig. 2). A measuring tape, digital clinometer and a Magellan differential GPS system were used to estimate tree diameter and height and record the spatial position to within a few centimetres (AMG Zone 56). Multi-stemmed trees had all stems measured independently. The vegetation species was recorded, and a general classification based on their branching habit noted (i.e. tree, shrub). Small understorey dry rainforest trees were not identified individually; rather, they were recorded as 'scrub').

A real-time-kinematic survey was conducted using a differential GPS to determine the topographic profile of the sub-catchment, and was used to build a 2-m-resolution digital terrain model to estimate the topography and runoff pattern of the watershed. Based on the digital terrain model, the IVB were surveyed to maintain a 2–3% gradient down hillslopes to capture large trees, intercept stormwater runoff and cover erosional areas, and be perpendicular to prevailing winds. The IVB areas were marked with survey tape in bands ~25 m wide and ~100 m apart (Figs 2 and 4). A large proportion of the area within IVB contained very little regrowth vegetation (mostly on the better soils), but was included so as to allow for regeneration of regrowth over the long-term and provide greater vegetation density in the IVB.

Approach to spatial analyses

Survey data, containing 1011 plant records collected in July 2011, were used to analyse the potential effects of different treatments on regrowth vegetation size, density and AGB. The confined catchment area delineated by the watershed (39.8 ha), excluding remnant forest (6.4 ha), and the spatial area of the original and four possible treatment options (Fig. 4) were defined using ArcMap 10 (ESRI 2010). The alternative treatments modelled were:

(i) 'Original' (33.4 ha) – the original regrowth recorded over the entire study area, included large open pasture areas;
(ii) 'Broad' (1.3ha) – only big trees in the riparian area retained;
(iii) 'Big Trees' (33.4 ha) – all big trees retained over the entire study area;
(iv) 'Riparian-IVB' (7.6 ha) – all regrowth in riparian and IVB areas retained (the actual treatment applied at the site); and
(v) 'Riparian-IVB-Big Trees' (33.4 ha) – retaining big trees over the entire study area combined with all regrowth within IVB-riparian areas.

All treatment areas within the catchment (excluding remnant forest) formed the 'total study area', whereas the area within a treatment was termed 'treatment extent'. Given that much of the western section of the study area was open pasture with little regrowth, in contrast to the eastern section that contained dense regrowth vegetation, this had the potential to skew estimates of total AGB within each treatment as well as density estimates (AGB t ha^{-1}). The main issue was that treatment extents captured an arbitrary area depending upon the delineation of boundaries for each treatment modelled, whereas the density (i.e. stems ha^{-1}) of regrowth within those areas was randomly clumped with large open areas of pasture between. With these limitations in mind, the surveyed regrowth was extracted from each treatment extent as point shapefiles and exported as individual databases into Microsoft Excel. Estimates of mean DBH^{130} cm, height (H, m) and basal area (BA, m^2), and total and mean stems ha^{-1}, BA m^2 ha^{-1}, and AGB t ha^{-1} were generated for the original regrowth condition and all treatments.

Determining species dimensions

Tree DBH^{130} (cm) and H (m) for all species >10 cm were recorded within the non-remnant catchment area for the regrowth vegetation in its original state. All multiple-stemmed trees were grouped to a single stem, and figures for BA and circumference (Cir) obtained for each species. Stem area for single and multi-stemmed species were calculated using Eqn 1.

$$SA = \sum_{n_i}^{x} \left(\frac{x}{2}\right)^2 * \pi \tag{1}$$

where total stem area (*SA*) of any tree is given by the sum of BA for each stem (n_i) based on DBH^{130} (x). To calculate DBH^{130} for each species a circumference (*Cir*) was derived using Eqns 2 and 3. Tree DBH^{130} was used in most models, the remainder using DBH^{30} estimates derived from $DBH^{130} \times 1.2125$ following Butler *et al*. (2012).

$$Cir = \sqrt{\left(\frac{SA}{\pi}\right)\left(\frac{1}{0.5}\right)}\pi \tag{2}$$

$$DBH = \mathrm{Cir}/\pi \tag{3}$$

Allometric models and calculation of AGB

The non-destructive method to estimate tonnes of live AGB (t) was determined by applying three separate allometrics – Snowdon *et al*. (2000), Chave *et al*. (2005) and Butler *et al*. (2012). We compared the performance of each allometric for estimates of AGB. The 'Carbon Farming Initiative' (CFI) draft allometric models (Butler *et al*. 2012) were further applied to compare estimates of original regrowth data ('Original') to the IVB and the three other hypothetical regrowth treatments.

Snowden method

A simple approach based on the allometrics of Snowdon *et al*. (2000) was used to estimate AGB based on DBH^{130} data. One allometric model was applied for *Eucalyptus*/*Corymbia* trees based on 'woodland trees' (Eqn 4) whereas all other trees were based on 'pine plantation' (Eqn 5).

$$AGB = \frac{\exp - 1.4481 + 2.2364 * \ln(\mathrm{DBH}^{130})}{1000} \tag{4}$$

$$AGB = \frac{\exp - 2.1376 + 2.2476 * \ln(\mathrm{DBH}^{130})}{1000} \tag{5}$$

where DBH^{130} is the diameter over bark at 130 cm and ln is the natural log.

The method of Chave et al.

Wood basic density is an important factor that affects estimates of AGB (Ilic *et al*. 2000; Baker *et al*. 2004). Chave *et al*. (2005) developed a set of generalised allometric models for use in different types of forests, while factoring in allowances for DBH^{130}, height and wood density for specific species. We applied the Chave *et al*. (2005) dry forests allometric model (Eqn 6) with independent wood density values (g cm^{-3}) for each species (Table 2).

$$\frac{AGB = \exp(-2.187 + 0.916 * \mathrm{LN}(p(DBH^2 * H)))}{1000} \tag{6}$$

where *p* is wood density (g cm^{-3}).

Draft CARBON Farming Initiative approach

The draft CFI approach was based on allometric models developed for the Commonwealth Government of Australia's

Table 2. Wood density (g cm^{-3}) values used in model and source

Species	Source: Zanne *et al.*	Source: Ilic *et al.*	Source: Hobbs
A. harpophylla	0.90[A]	0.88	
Brachychiton sp.[B]	0.33[A]	0.38	0.37
C. cristata	0.98	0.95[A]	0.73
C. citriodora subsp. *variegata*	0.85[A]	0.81	–
C. glaucophylla	–	0.87[A]	0.60
E. fibrosa	0.96	0.85[A]	0.80
E. camaldulensis	0.77	0.76[A]	0.49
E. pilligaensis	0.93	0.82	0.90[A]
Atalaya sp.[C]	0.73[A]	0.68	0.75

[A]Selected in model; wood density values (g cm^{-3}) from Ilic *et al*. (2000), Hobbs (2008), and Zanne *et al*. (2009).
[B]Generic for *B. rupestris*.
[C]Generic dry rainforest tree (e.g. *A. hemiglauca*).

Carbon Farming Initiative as outlined in Butler *et al*. (2012), and similarly in Lucas *et al*. (2010) and Williams *et al*. (2005). The allometric equations were applied for *Eucalyptus*/*Corymbia* sp., *Acacia harpophylla*/*Casuarina cristata*, *Brachychiton* spp., *Callitris* spp. and mixed dry rainforest ('scrub') species (Eqns 7–11, respectively).

$$AGB = \frac{\exp(-2.0596 + 2.1561 * \ln(\mathrm{DBH}) + (\ln(\mathrm{H})^2))}{1000} \quad (7)$$

$$AGB = \frac{\exp(-3.568 + 2.384 * \ln(Cx10) + (0.2589^2/2))}{1000} \quad (8)$$

$$AGB = 0.25.\exp(-0.667 + 1.784\ln(\mathrm{DBH}) + 0.0207\ln(DBH)^2 - 0.0281Ln(DBH)^3) \quad (9)$$

$$AGB = \exp(-4.316 + 2.290\mathrm{k} + (0.135^2/2)) \quad (10)$$

$$AGB = \exp(-1.8957 + 2.3698.\ln(DBH) + (0.2942^2/2))) \quad (11)$$

where C is circumference at 30 cm above the ground and k is circumference at 130 cm above the ground.

Estimating carbon offsets

Econometric analyses were based on tonnes of combined live aboveground and belowground biomass (AGB-BGB t) using the draft CFI method (Butler *et al*. 2012). An average carbon proportion in woody biomass of 0.5 was assumed for conversion of dry matter to carbon (Williams *et al*. 2005). Although the ratio of AGB (BGB) can vary with rainfall (Zerihun *et al*. 2006), BGB was assumed to be 0.25 × AGB, similar to the 0.26 suggested by Burrows *et al*. (2002) for eastern Queensland 'TRAPS' sites. The value for BGB was added to AGB to give total carbon including roots (C_r t). To estimate potential value of carbon offsets generated by retaining regrowth, carbon equivalents (t CO_2e) were calculated for each tree (Eqn 12). The potential value of the offset in Australian dollars (A$) was derived for each treatment scenario presented for carbon offset value (A$) at carbon market prices of A$5, A$10, A$25 and A$50 per tonne (Eqn 13).

$$CO_2\,e = \mathrm{C\_r}\,t \times 3.67 \quad (12)$$

$$\mathrm{C\$} = \mathrm{A\$x} \times CO_2\,e \quad (13)$$

Results

Effect of treatments on land use area and total AGB

Despite the large gaps in regrowth within the actual 'Riparian-IVB' treatment implemented at the study site, it retained 53% (200 t) of the original regrowth AGB (375 t) across 23% (7.6 ha) of the total study area (33.4 ha). Considering the alternative (hypothetical) treatments, 'Big Trees' treatment had the potential to retain 66% (249 t) of the original AGB on 55% of the land area (18.4 ha). For trees in 'Riparian-IVB-Big Trees' combined, 80% (301 t) of the original AGB could have been retained on approximately the same land area as 'Big Trees'. In contrast, the 'Broad' treatment would have retained just 7% of the original regrowth AGB (26 t) on 4% (1.3 ha) of the land area.

Effect of treatments on DBH, H and BA

The mean DBH^{130}, H and BA of regrowth vegetation increased from the original (23 cm, 8 m and 0.06 m^2, respectively), for all treatments (Fig. 5). The 'Big Trees' treatment had the greatest increases (58 cm, 14 m, 0.31 m^2) followed by 'Broad' (54 cm, 13 m and 0.25 m^2). These increases are reflective of the larger trees being selectively retained whereas most of the smaller saplings would be removed. The remainder of the treatments changed only slightly from the original regrowth area, including Riparian-IVB, which increased to 27 cm, 8.39 m and 0.09 m^2, respectively.

Effect of treatments on density ha^{-1}

Unlike total and mean values for treatment extent, estimates of regrowth density based on unit area [i.e. AGB (t ha^{-1}), BA ($m^2\,ha^{-1}$) and stems (ha^{-1})] showed a markedly different pattern (Fig. 6). Whereas the original regrowth vegetation had values of 11 t AGB ha^{-1}, BA 2 $m^2\,ha^{-1}$ and 55 stems ha^{-1}, the 'Riparian-IVB' treatment installed at the site showed the greatest increases to AGB (26 t ha^{-1}) and BA (4 $m^2\,ha^{-1}$), whereas stems decreased to 48 ha^{-1}. The 'Broad' treatment also showed increases in AGB (19 t ha^{-1}) and BA (2.5 $m^2\,ha^{-1}$) and a decrease in stems per hectare (10 ha^{-1}). All other treatments showed reductions in density across all measures.

Performance of allometric models

All three allometric models tested resulted in very similar estimates of AGB, with 22 t or 6% difference between all three models. These estimates were 368 t, 390 t and 375 t using the models of Snowdon *et al*. (2000), Chave *et al*. (2005) and Butler

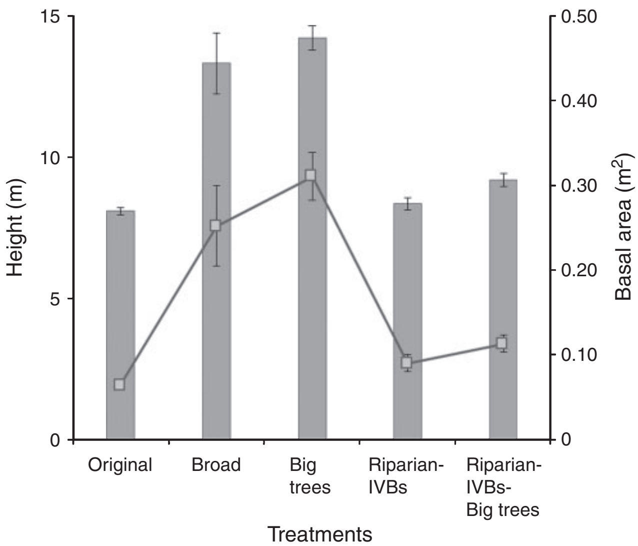

Fig. 5. Effect of treatments on mean height (m) (□) and basal area (m^2) (shaded bar). (Error bars represent standard error.)

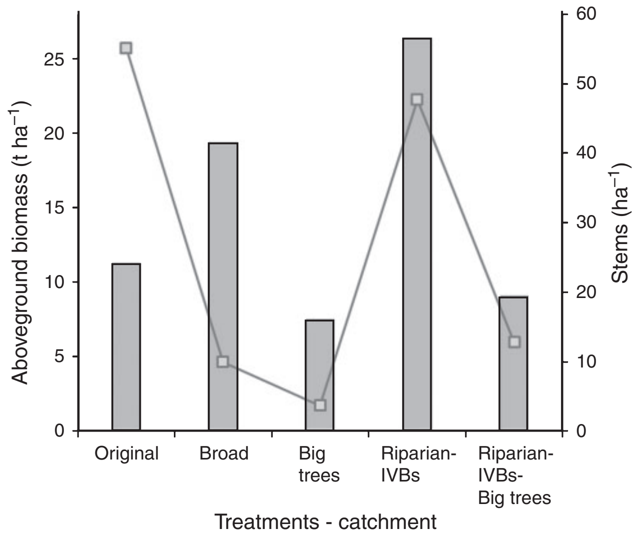

Fig. 6. Effect of treatments on regrowth density expressed as stems ha^{-1} (□) and aboveground biomass (t ha^{-1}) (shaded bar).

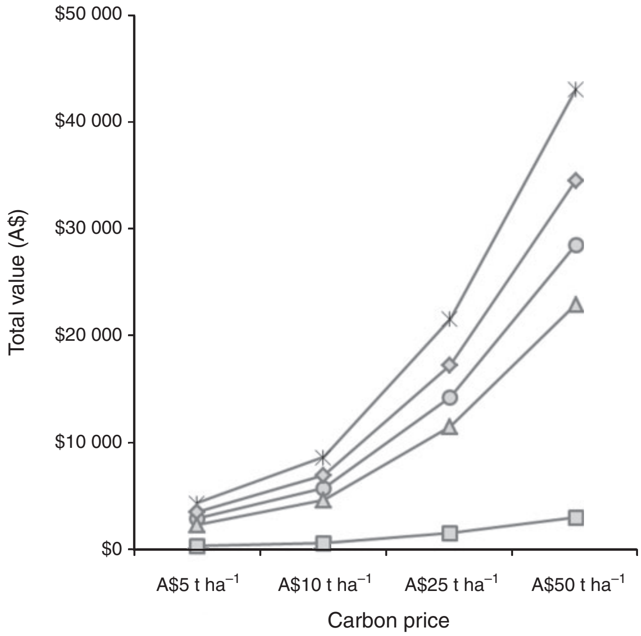

Fig. 7. Total carbon (C) value ($A) at four different carbon prices for each treatment. Original (∗), Broad (■), Big Trees (●), Riparian-IVBs (▲), and Riparian-IVBs-Big Trees (♦).

et al. (2012), respectively. The Snowdon *et al*. (2000) model was the oldest and simplest approach and estimates seemed high for *B. rupestris* and low for *A. harpophylla* and *C. cristata*. The Chave *et al*. (2005) method had the highest overall estimates, whereas estimates generated from the draft CFI allometrics (Butler *et al*. 2012) fell between the other two models. Overall, eucalypt and brigalow trees contained the most AGB and carbon due to their size and wood density. Estimates of AGB derived from the draft CFI were used for further analyses of carbon value due to their direct applicability to Australian vegetation species.

Carbon value

As may be expected, the carbon price markedly affects the value of the regrowth in each treatment (Fig. 7). Considering a carbon price of A$10, the original regrowth contained ~A$8600 worth of carbon offsets compared with ~A$6900 for 'Riparian-IVB-Big Trees', ~A$5700 for 'Big Trees', ~A$4600 for 'Riparian-IVB' and ~A$295 for 'Broad'. Using an approximate age of 17 years for the younger regrowth and ignoring the effects of the older and large trees, ~A$505 $year^{-1}$ worth of carbon (at $10 t^{-1}) was contained in the original regrowth area. On a per-hectare basis, this equates to ~$257 ha^{-1} in total or ~A$15 ha^{-1} $year^{-1}$ for the original regrowth.

Discussion

Major findings

The AGB was highest in the 'Riparian-IVB-Big Trees' (301 t), then 'Big Trees' (249 t), 'Riparian-IVB' (200 t) and the lowest (26 t) in 'Broad'. The 'Broad' treatment resulted in the greatest pasture area (~33 ha) followed by 'Riparian-IVB' (~26 ha), 'Big Trees' (15 ha) and 'Riparian-IVB-Big Trees' (15 ha). In terms of treatment effects on DBH^{130}, H and BA, the greatest increase was for 'Big Trees' and 'Broad'. Although this reflected a bias towards keeping the bigger trees, it did not equate to higher estimates per hectare for BA or AGB (Figs 5 and 6). The 'Riparian-IVB' retained the greatest area of regrowth as a ratio of regrowth to treatment area (i.e. density) despite the large gaps of open pasture found in these areas. Under the 'Riparian-IVB' treatment more than half (53%, 200 t) of the original regrowth of woody biomass (375 t) was retained on about a quarter (23%, 7.6 ha) of the total land in the study area (33.4 ha), namely due to an increase in the density of regrowth per hectare (AGB t ha^{-1}).

About 860 t CO_2e was contained in the regrowth at the site in its original state, equating to an approximate value of A$8600 (at A$10 t^{-1}) as carbon offsets. Not surprisingly, the highest carbon offset values were directly related to the amount of AGB retained in a treatment. The 'Riparian-IVB retained A$4600 worth of carbon value, 'Big Trees' A$5700, and 'Riparian-IVB-Big Trees' A$6900. These potential values are after at least a 17-year period, and are perhaps too low to cover the expenses of retaining regrowth in comparison to costs and returns from establishing pasture. If the carbon price was raised to A$25 t CO_2e, the value in the original vegetation would be A$21 500, perhaps a more viable return to the landowner. However, this would depend on other factors, such as livestock production costs and returns, as well as the costs of broad-scale clearing versus costs associated with surveying out and carefully clearing around IVB.

In terms of carbon value per hectare, the original regrowth vegetation was valued at A$469 ha^{-1}. Value per hectare was highest under the 'Riparian-IVB' (A$605 ha^{-1}) treatment, ahead of 'Broad' (A$444 ha^{-1}); 'Riparian-IVB-Big Trees' (A$376 ha^{-1}), and 'Big Trees' (A$311 ha^{-1}) treatments. If the original regrowth is 17 years of age, the value of carbon accrues at ~A$505 $year^{-1}$ across the study area, leading to estimates of ~A$257 ha^{-1} or ~A$15 ha^{-1} $year^{-1}$. The carbon value per hectare follows the greatest density of AGB per hectare, with 'Riparian-IVB' potentially returning the highest value. This would be expected to be much greater still when the 'Riparian-IVB' begins to in-fill with regrowth over time, particularly in the more open western section of the catchment where IVB contained little regrowth cover.

Potential impacts on pasture production

The income derived from carbon offsets needs to balance the loss of pastures and competition from trees such as through root competition and shading (Bray and Golden 2009; Donaghy *et al.* 2009). At the same time, trees can provide beneficial effects by sheltering soil and livestock from wind, lowering soil temperatures, increasing retention of runoff and through additions of leaf litter to the soil (Wilson 2002; Lee and Lucas 2007; Ryan *et al.* 2010; Barnes *et al.* 2011). Donaghy *et al.* (2009) demonstrated the competitive influence between the BA (m^2 ha^{-1}) of *A. harpophylla* tree strips and pasture yield in grazed landscapes of central Queensland. For a BA value of 20 m^2 ha^{-1}, the pasture yield was ~1.2 t $year^{-1}$, whereas for a BA of 4 m^2 ha^{-1}, yield actually increased to 2.4 t $year^{-1}$. In a mulga landscape of western Queensland, Beale (1973) found that, as the BA (m^2 ha^{-1}) of mulga increased, pasture yield decreased. As mulga is used for feed during drought, the suggested approach was to keep areas of high tree density interspersed with open pasture areas.

Numerous windbreak studies have also used tree height for estimating 'zones of influence' of trees on pasture production (Bird 1998; Cleugh *et al.* 2002; Bird *et al.* 2007; McKeon *et al.* 2008). Although this study did not assess the subsequent effects of retaining IVB on adjacent pasture production, other studies have shown a mixed response of pasture to tree bands. McKeon *et al.* (2009) investigated tree-grass competition across three central Queensland sites and found that at some sites the losses in pasture production near and within tree bands were partially offset by gains in increased pasture quality in areas shaded by regrowth and increased pasture growth in areas protected from winds. It is acknowledged that under any regrowth retention treatment, tree-grass competition does occur and this will likely reduce the economics of retaining regrowth in a particular configuration. The true economic position will vary widely, and the land manager will need to balance the potential costs and returns from livestock against the price of each tonne of CO_2e returned, as well as the potential value in timber products and other ecosystem services and amenity values.

Donaghy *et al.* (2009) reviewed the potential for carbon offsets against costs to pasture production from incorporating vegetation bands (alley strips) into a grazing system located in the Fitzroy Basin of Queensland. Their analyses suggested that, without carbon offsets, there is a small cost to the grazier from retaining vegetation bands, but when carbon was priced at \$10 t CO_2e this markedly improved the economic benefit to the grazier. Based on bio-economic modelling to estimate the benefits of retaining brigalow or eucalypt forest within a 1000-ha grazing operation in central Queensland, Gowen *et al.* (2012) found that, during a 20-year period, woody vegetation retained within a grazing operation had greater returns than a pasture-only grazing operation. Stephens (2010) modelled a 1 : 3 (20 : 60 m) system of regrowth vegetation bands in open pasture and found the return from carbon offsets after 25 years would be ~A\$84 000 and A\$137 000 for brigalow and eucalypt forests, respectively. Our analyses resulted in low returns for carbon offsets at A\$10 t CO_2e. This could be due to past clearing, pasture management and stocking densities, fire or slow growth rates of woody vegetation in low and variable rainfall areas, all of which set-back and thin out regrowth vegetation.

Factors affecting regrowth characteristics

The vegetation in the study area was mixed-age regrowth, with varying tree densities, amounts of open pasture and numbers of large paddock trees. Approximately half of the regrowth area was *Eucalyptus* and *Corymbia* woodland with older and larger remnant trees, and the other half a mix of young *A. harpophylla*, *C. cristata* and older dry scrub species such as *B. rupestris* (retained from previous clearing events). Thus, the stem density of the regrowth vegetation varied markedly, and it was low (~61 stems ha^{-1}) compared with other studies (Table 3). In contrast, the AGB was similar to other studies, suggesting in our study there were fewer but larger trees. While mean BA (m^2 ha^{-1}) of any native or regrowth woodland is highly variable due to disturbances such as fire, clearing and self-thinning (Bray *et al.* 2006), the delineation of boundaries and mapping scale will also affect area and stem density estimates (Fig. 6). For example, the spatial scale of the vegetation mapping, where gaps between canopies are either mapped or excluded depending on the resolution of the datasets used to delineate individual trees or clumps of trees, will affect the areas included within a category and estimates of AGB.

Implications for regrowth management

All treatments have benefits and constraints and the 'best' treatment to apply depends on the management goals, the

Table 3. Site BA m^2 ha^{-1}, AGB t ha^{-1} and stems ha^{-1} compared with other studies

m = mature; r = regrowth; y = young regrowth; o = old regrowth, g = annual growth rate measured across 14 years

Study	Woodland species/type (m, r)	Stems ha^{-1}	BA m^2 ha^{-1}	AGB t ha^{-1}
This study (sample of original regrowth)	*A. harpophylla*, *E. pilligaensis*, *E. fibrosa*, *Casuarina cristata* (r)	61	4.07	26.76
Scanlan (1991)	*A. harpophylla* (r, m)	2750–15 000	12–16	12.69
McIvor (2001)	*E. crebra*, *E. drepanophylla* (m)	64–127	3.49–5.53	–
Burrows *et al.* (2002)	*Eucalyptus* sp., *Corymbia* sp. (m)	–	15.31, 1.06 (g)	74.6
Williams *et al.* (2005)	*E. populnea* (m)	–	8–16	3.69
Bray *et al.* (2006)	*Eucalyptus* sp. (m)	–	13–14	–
Chandler *et al.* (2007)	*A. harpophylla*, *C. cristata* (r, m)	16856 (y), 2024 (o)	23.23 (y), 16.29 (o)	55.81 (y), 49.73 (o)
McKeon *et al.* (2008)	*A. harpophylla* (a), *E. populnea* (b) (m)	2085 (a), 175–192 (b)	15.0, 14.9–16.9	–

economics of each treatment approach and considerations for soil conservation, catchment protection and biodiversity. As retained AGB t ha^{-1} increases, pasture area decreases and, together with a greater area of tree-grass competition, this will likely result in a reduction in livestock carrying capacity at higher densities (Beale 1973). As canopy areas and root systems extend out into pasture, there will be competition with the pasture but there are also potential benefits as trees have a significant influence on the soil, hydrology, microclimate, biota, and other vegetation in the surrounding landscape (Wilson 2002; Bowen *et al*. 2009; Barnes *et al*. 2011; Verma *et al*. 2014). If areas are fenced off from livestock and managed for regrowth retention as a priority, regrowth density will increase over time leading to greater AGB (t ha^{-1}) and carbon offsets per hectare. Of course it will be dependent on the value derived from carbon offsets and timber, and improved landscape functioning, covering the expense of fencing. If trees of the same volume of wood are retained and density of wood is ignored, species with a low wood density, such as *B. rupestris* (Table 2), will lower AGB per unit area. Similarly, if trees are retained based on their timber potential, then AGB may be high but be comprised of mostly *Eucalyptus* and *Corymbia* species.

The time and costs for surveying and clearing the IVB were not costed in this analysis, although at least 2–3 days would be needed with equipment comprising topographic maps, GPS and survey equipment. The costs to the land manager compared with broad-scale clearing would include some additional fuel and time to follow surveyed and flagged boundaries of IVB or to avoid the large scattered paddock trees.

Fire is an important factor that would also need to be managed in any woody regrowth system as it can greatly modify carbon storage. The fire frequency interval (10–50 years) in Acacia-dominated woodlands of Australia is very low (Hodgkinson 2002) However, these fire regimes in brigalow woodland could potentially change due to increasing drought and invasion from exotic grasses (Murphy *et al*. 2012). For example, although the sparse understorey of brigalow is inherently resistant to fire (Fensham 1997), the presence of invasive grasses can modify the behaviour of fire so as to eventually create a positive feedback within the vegetation community that reinforces fire and the further establishment of exotic grasses, particularly in the absence of livestock grazing (Butler and Fairfax 2003; Murphy *et al*. 2012). As increased fire frequency and intensity will reduce any potential gains in carbon stored within the landscape as woody vegetation, a fire management regime would need to be developed for banded vegetation systems such as IVB.

Conclusion

Regrowth provides a carbon sink of potential economic value when retained, but the value is dependent on the size and density of trees retained, the area over which they compete or provide benefits to pasture grasses, the time and costs to implement and future manage a treatment, value of timber products or livestock, and the price of carbon. In terms of ideal treatments to retain AGB, the ‘Riparian-IVB-Big Trees’, ‘Big Trees’ and ‘Riparian-IVB’ treatments had the highest totals. Under the ‘Riparian-IVB’ treatment more than half (53%) of the original woody biomass in regrowth was retained on less than a quarter (23%) of the total land in the study area, resulting in the highest carbon offset value per hectare of land (A$605 ha^{-1}). Over time, as the open areas of the IVB are ‘in-filled’ with regrowth to become more dense, their carbon value per hectare will increase further depending on the characteristics of the regrowth vegetation (e.g. health). The most cost-effective treatment may vary among regions as well as between areas within the one grazing operation. Ultimately, it may be a combination of CO_2e price, livestock returns and timber and amenity values that will determine the viability of managing native regrowth forests in a particular configuration.

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References

Back, P. V., Anderson, E. R., Burrows, W. H., and Playford, C. (2009). Woody plant responses to various clearing strategies imposed on a poplar box (*Eucalyptus populnea*) community at Dingo in central Queensland. *Tropical Grasslands* **43**, 188–190.

Baker, T., Phillips, O. L., Malhi, Y., Almeida, S., Arroyo, L., Di Fiore, A., Erwin, T., Higuchi, N., Killeen, T. J., Laurance, S. G., Laurance, W. F., Lewis, S. L., Lloyd, J., Monteagudo, A., Neill, D. A., Patino, S., Pitman, N. C. A., Silva, J. N. M., and Vasquez, M. R. (2004). Variation in wood density determines spatial patterns in Amazonian forest biomass. *Global Change Biology* **10**, 545–562. doi:10.1111/j.1365-2486.2004.00751.x

Barnes, P., Wilson, B. R., Trotter, M. G., Lamb, D. W., Reid, N., Koen, T., and Bayerlein, L. (2011). The patterns of grazed pasture associated with scattered trees across an Australian temperate landscape: an investigation of pasture quantity and quality. *The Rangeland Journal* **33**, 121–130. doi:10.1071/RJ10068

Beale, I. F. (1973). Tree density effects on yields of herbage and tree components in south west Queensland mulga (*Acacia aneura*) scrub. *Tropical Grasslands* **7**, 135–142.

Bird, P. (1998). Tree windbreaks and shelter benefits to pasture in temperate grazing systems. *Agroforestry Systems* **41**, 35–54. doi:10.1023/A:1006092104201

Bird, P. R., Jackson, T. T., Kearney, G. A., and Roache, A. (2007). Effects of windbreak structure on shelter characteristics. *Australian Journal of Experimental Agriculture* **47**, 727–737. doi:10.1071/EA06086

BoM (2014). Climate statistics for Australian locations: Miles Post Office. Available at: www.bom.gov.au/climate/averages/tables/cw_042023.shtml (accessed 5 March 2015).

Bowen, M. E., McAlpine, C. A., Seabrook, L. M., House, A. P. N., and Smith, G. C. (2009). The age and amount of regrowth forest in fragmented brigalow landscapes are both important for woodland dependent birds. *Biological Conservation* **142**, 3051–3059. doi:10.1016/j.biocon.2009.08.005

Bray, S. G., and Golden, R. (2009). Scenario analysis of alternative vegetation management options on the greenhouse gas budget of two grazing businesses in north-eastern Australia. *The Rangeland Journal* **31**, 137–142. doi:10.1071/RJ08055

Bray, S., Back, P., Hoffmann, M., and Myles, D. (2006). ‘Understanding the dynamics of Queensland’s grazed woodlands.’ Brisbane, Queensland

Department of Primary Industries and Fisheries. Final Report – NBP.333. (Meat and Livestock Australia: North Sydney, NSW.)

Burrows, W. H., Henry, B. K., Back, P. V., Hoffmann, M. B., Tait, L. J., Anderson, E. R., Menke, N., Danaher, T., Carter, J. O., and McKeon, G. M. (2002). Growth and carbon stock change in eucalypt woodlands in northeast Australia: ecological and greenhouse sink implications. *Global Change Biology* **8**, 769–784. doi:10.1046/j.1365-2486.2002.00515.x

Butler, B. D. W., and Fairfax, R. J. (2003). Buffel grass and fire in a gidgee and brigalow woodland: a case study from Central Queensland. *Ecological Management & Restoration* **4**, 120–125. doi:10.1046/j.1442-8903.2003.00146.x

Butler, B. D. W., Fensham, R., Freudenberger, D., Henry, B. K., Jackson, M., van Oosterzee, P., Preece, N., and Stark, P. (2012). 'Draft CFI Methodology for Forest Regrowth in NE Australia.' (Department of Climate Change and Energy Efficiency: Canberra, ACT.)

Campbell, A. (2008). 'Managing Australia's Soils: A Policy Discussion Paper.' (National Committee on Soil and Terrain: Canberra, ACT.)

Chandler, T. S., Buckley, Y. M., and Dwyer, J. M. (2007). Restoration potential of brigalow regrowth: insights from a cross-sectional study in Southern Queensland. *Ecological Management & Restoration* **8**, 218–221. doi:10.1111/j.1442-8903.2007.00370.x

Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J. P., Nelson, B. W., Ogawa, H., Puig, H., Riéra, B., and Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* **145**, 87–99. doi:10.1007/s00442-005-0100-x

Cleugh, H. A., and Hughes, D. E. (2002). Impact of shelter on crop microclimates: a synthesis of results from wind tunnel and field experiments. *Australian Journal of Experimental Agriculture* **42**, 679–701. doi:10.1071/EA02005

Cleugh, H., Prinsley, R., Bird, R. P., Brooks, S. J., Carberry, P. S., Crawford, M. C., Jackson, T. T., Meinke, H., Mylius, S. J., Nuberg, I. K., Sudmeyer, R. A., and Wright, A. J. (2002). The Australian National Windbreaks Program: overview and summary of results. *Australian Journal of Experimental Agriculture* **42**, 649–664. doi:10.1071/EA02003

Dargusch, P., and Harrison, S. (2011). Foreword for the special issue on carbon markets in small-scale forestry. *Small-scale Forestry* **10**, 271–272. doi:10.1007/s11842-010-9146-7

Dargusch, P., Lawrence, K., Herbohn, J., and Medrilzam, M. (2010). A small-scale forestry perspective on constraints to including REDD in international carbon markets. *Small-scale Forestry* **9**, 485–499. doi:10.1007/s11842-010-9141-z

Donaghy, P., Bray, S., Gowen, R., Rolfe, J., Stephens, M., Williams, S., Hoffman, M., and Stunzner, A. (2009). 'The Bioeconomic Potential for Agroforestry in Northern Cattle Grazing Systems: An Evaluation of Tree Alley Scenarios in Southern and Central Queensland.' (Rural Industries Research and Development Corporation: Barton, ACT.)

Eckard, R., Kelly, A., and Barlow, S. (2012). Epilogue – future challenges for the national climate change research strategy. *Crop & Pasture Science* **63**, 297–301. doi:10.1071/CP12149

Eddy, J., Humphreys, G. S., Hart, D. M., Mitchell, P. B., and Fanning, P. C. (1999). Vegetation arcs and litter dams: similarities and differences. *Catena* **37**, 57–73. doi:10.1016/S0341-8162(98)00055-1

ESRI (2010). 'ArcMap 10.' (Redlands, CA.)

Fensham, R. J. (1997). Aboriginal fire regimes in Queensland, Australia: analysis of the explorers' record. *Journal of Biogeography* **24**, 11–22. doi:10.1111/j.1365-2699.1997.tb00046.x

Fischer, J., and Lindenmayer, D. B. (2002). The conservation value of paddock trees for birds in a variegated landscape in southern New South Wales. 2. Paddock trees as stepping stones. *Biodiversity and Conservation* **11**, 833–849. doi:10.1023/A:1015318328007

Gibbons, P., and Boak, M. (2002). The value of paddock trees for regional conservation in an agricultural landscape. *Ecological Management & Restoration* **3**, 205–210. doi:10.1046/j.1442-8903.2002.00114.x

Gowen, R., Rolfe, J., and Donaghy, P. (2012). A bioeconomic model of carbon trading within an Australian grazing enterprise. *In*: '56th AARES Annual Conference'. Freemantle, W. Aust. (Australian Agricultural and Resource Economics Society.)

Graham, S., Wilson, B. R., Reid, N., and Jones, H. (2004). Scattered paddock trees, litter chemistry, and surface soil properties in pastures of the New England Tablelands, New South Wales. *Australian Journal of Soil Research* **42**, 905–912. doi:10.1071/SR03065

Hobbs, T. J. (2008). Review of wood products, tannins and exotic species for lower rainfall regions of southern Australia. FloraSearch 1c. Joint Venture Agroforestry Program (JVAP) and the Future Farm Industries CRC RIRDC, Canberra.

Hochman, Z., Carberry, P. S., Robertson, M. J., Gaydon, D. S., Bell, L. W., and McIntosh, P. C. (2013). Prospects for ecological intensification of Australian agriculture. *European Journal of Agronomy* **44**, 109–123. doi:10.1016/j.eja.2011.11.003

Hodgkinson, K. C. (2002). Fire regimes in *Acacia* wooded landscapes: effects on functional processes and biological diversity. *In*: 'Flammable Australia: The Fire Regimes and Biodiversity of a Continent'. (Eds R. A. Bradstock, J. E. Williams and A. M. Gill.) pp. 259–277. (Cambridge University Press: Cambridge, UK.)

Ilic, J., Boland, D., McDonald, M., Downes, G., and Blakemore, P. (2000). 'Woody density phase 1 – State of Knowledge.' Technical Report No. 18, National Carbon Accounting System. (CSIRO Forestry and Forest Products: Canberra, ACT.)

Keenan, R. J. (2002). Historical vegetation dynamics and the carbon cycle: current requirements and future challenges for quantifying carbon fluxes in Australian terrestrial ecosystems. *Australian Journal of Botany* **50**, 533–544. doi:10.1071/BT01047

Lee, A. C., and Lucas, R. M. (2007). A LiDAR-derived canopy density model for tree stem and crown mapping in Australian forests. *Remote Sensing of Environment* **111**, 493–518. doi:10.1016/j.rse.2007.04.018

Lucas, R., Armston, J., Fairfax, R., Fensham, R., Accad, A., Carreiras, J., Kelley, J., Bunting, P., Clewley, D., Bray, S., Metcalfe, D., Dwyer, J., Bowen, M., Eyre, T., Laidlaw, M., and Shimada, M. (2010). An evaluation of the ALOS PALSAR L-band backscatter-above-ground biomass relationship Queensland, Australia: impacts of surface moisture condition and vegetation structure. *Selected Topics in Applied Earth Observations and Remote Sensing - IEEE Journal* **3**, 576–593.

Luo, Z., Wang, E., Sun, O. J., Smith, C. J., and Probert, M. E. (2011). Modeling long-term soil carbon dynamics and sequestration potential in semi-arid agro-ecosystems. *Agricultural and Forest Meteorology* **151**, 1529–1544. doi:10.1016/j.agrformet.2011.06.011

Marcott, S. A., Shakun, J. D., Clark, P. U., and Mix, A. C. (2013). A reconstruction of regional and global temperature for the past 11300 years. *Science* **339**, 1198–1201. doi:10.1126/science.1228026

McAlpine, C. A., Ryan, J. G., Seabrook, L., Thomas, S., Dargusch, P. J., Syktus, J. I., Pielke, R. A., Etter, A. E., Fearnside, P. M., and Laurance, W. F. (2010). More than CO2: a broader paradigm for managing climate change and variability to avoid ecosystem collapse. *Current Opinion in Environmental Sustainability* **2**, 334–346. doi:10.1016/j.cosust.2010.10.001

McIvor, J. G. (2001). Litterfall from trees in semiarid woodlands of north-east Queensland. *Austral Ecology* **26**, 150–155. doi:10.1046/j.1442-9993.2001.01097.x

McKeon, G. M., Chilcott, C., McGrath, W., Paton, C., Fraser, G., Stone, G. S., and Ryan, J. G. (2008). 'Assessing the value of trees in sustainable grazing systems.' Brisbane, Queensland Department of Natural Resources and Water, Queensland Department of Primary Industries and Fisheries, Environmental Protection Agency. Final report for MLA – Project NBP.316. (Meat and Livestock Australia: North Sydney, NSW.)

McKeon, G. M., Stone, G. S., Syktus, J. I., Carter, J. O., Flood, N. R., Ahrens, D. G., Bruget, D. N., Chilcott, C. R., Cobon, D. H., Cowley, R. A., Crimp, S. J., Fraser, G. W., Howden, S. M., Johnston, P. W., Ryan, J. G., Stokes,

C. J., and Day, K. A. (2009). ‘Climate change impacts on Australia’s rangeland livestock carrying capacity: a review of challenges.’ (Land & Water Australia: Canberra.)

Mitchell, P. B., and Humphreys, G. S. (1987). Litter dams and microterraces formed on hillslopes subject to rainwash in the Sydney Basin, Australia. *Geoderma* **39**, 331–357. doi:10.1016/0016-7061(87)90052-8

Murphy, H., Liedloff, A., Williams, R. J., Williams, K. J., and Dunlop, M. (2012). Queensland’s biodiversity under climate change: terrestrial ecosystems. CSIRO ‘Climate Adaptation Flagship Working Paper No. 12C. Brisbane, CSIRO Climate Adaptation Flagship. Available at: www.csiro.au/resources/CAF-working-papers.html (accessed 5 March 2015).

Ryan, J. G., McAlpine, C. A., and Ludwig, J. A. (2010). Integrated vegetation designs for enhancing water retention and recycling in agroecosystems. *Landscape Ecology* **25**, 1277–1288. doi:10.1007/s10980-010-9509-7

Scanlan, J. C. (1991). Woody overstorey and herbaceous understorey biomass in *Acacia harpophylla* (brigalow) woodlands. *Australian Journal of Ecology* **16**, 521–529. doi:10.1111/j.1442-9993.1991.tb01081.x

Snowdon, P., Eamus, D., Gibbons, P., Keith, H., Raison, J., and Kirschbaum, M. (2000). ‘Synthesis of allometrics, review of root biomass, and design of future woody biomass sampling strategies.’ National Carbon Accounting System Technical Report. (Australian Greenhouse Office: Canberra, ACT.)

Stephens, M. (2010). Silvopastoralism: an opportunity waiting. *Farming Ahead* **216**.

Sudmeyer, R., and Flugge, F. (2005). The economics of managing tree-crop competition in windbreak and alley systems. *Australian Journal of Experimental Agriculture* **45**, 1403–1414. doi:10.1071/EA04155

Swallow, B. M., and Goddard, T. W. (2013). Value chains for bio-carbon sequestration services: lessons from contrasting cases in Canada, Kenya and Mozambique. *Land Use Policy* **31**, 81–89. doi:10.1016/j.landusepol.2012.02.002

Verma, N. K., Lamb, D. W., Reid, N., and Wilson, B. (2014). An allometric model for estimating DBH of isolated and clustered eucalyptus trees from measurements of crown projection area. *Forest Ecology and Management* **326**, 125–132. doi:10.1016/j.foreco.2014.04.003

Wang, H., and Takle, E. S. (1996*a*). On shelter efficiency of shelterbelts in oblique wind. *Agricultural and Forest Meteorology* **81**, 95–117. doi:10.1016/0168-1923(95)02311-9

Wang, H., and Takle, E. S. (1996*b*). On three-dimensionality of shelterbelt structure and its influences on shelter effects. *Boundary-Layer Meteorology* **79**, 83–105. doi:10.1007/BF00120076

Williams, R. J., Zerihun, A., Montagu, K. D., Hoffman, M., Hutley, L. B., and Chen, X. (2005). Allometry for estimating aboveground tree biomass in tropical and subtropical eucalypt woodlands: towards general predictive equations. *Australian Journal of Botany* **53**, 607–619. doi:10.1071/BT04149

Wilson, B. (2002). Influence of scattered paddock trees on surface soil properties: a study of the Northern Tablelands of NSW. *Ecological Management & Restoration* **3**, 211–219. doi:10.1046/j.1442-8903.2002.00115.x

Zanne, A. E., Lopez-Gonzalez, G., Coomes, D. A., Ilic, J., Jansen, S., Lewis, S. L., Miller, R. B., Swenson, N. G., Wiemann, M. C., and Chave, J. (2009). Global wood density database. D. I. Available at: http://hdl.handle.net/10255/dryad.235 (accessed 1 August 2014).

Zerihun, A., Montagu, K., Hoffmann, M., and Bray, S. (2006). Patterns of below- and above-ground biomass in *Eucalyptus populnea* woodland communities of Northeast Australia along a rainfall gradient. *Ecosystems* **9**, 501–515. doi:10.1007/s10021-005-0155-x