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Assessing woody plant health in rangeland ecosystems: implications for estimates of aboveground biomass

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Abstract
Rangelands are subject to episodic droughts, regular fires and grazing pressure, all of which impact woody plant (tree/shrub) health. Consequently, standing dead and senescent woody plants are key components of these ecosystems. Stand-level, woody aboveground biomass (*AGB*), an important component of the terrestrial carbon budget, is typically scaled using individual-based allometric relationships with predictor variables such as stem diameter or crown area measured through on-ground inventories of woody plants. Current data are lacking to allow assessment of the influence of woody plant condition on allometry and subsequent scaling of *AGB*. To address this, we undertook field measurements across 431 Australian rangeland sites to improve understanding of the variation in the condition of woody plants across rangelands, including how condition of different plant functional types affects overall stand condition, and how stem diameter-crown area allometry varies with condition and plant functional type. Field measurements included stem diameter, crown width and vigour, and health scores of live and standing dead woody plants. Over one-quarter of individual woody plants were either dead or senescing across all sites. Stem diameter-crown area allometric relationships differed among plant functional types, with those found for trees differing from those of shrubs and multi-stemmed acacias. For a given stem diameter, allometry-predicted crown area declined as health score decreased. Our findings suggest that if traditional allometric relationships developed for live, healthy woody plants are applied to predict *AGB* in these ecosystems, substantial over-estimations may result, particularly for stands with a relatively high proportion of woody plants of poor condition. Results will inform ongoing improvements to the accuracy of stand-level biomass estimates in rangelands.

Introduction
Stand-level aboveground biomass (*AGB*) is a key component of the terrestrial carbon budget and typically scaled using allometric relationships with predictor variables such as stem diameter (Paul et al. 2016) or canopy area (Suganuma et al. 2006; Chieppa et al. 2020) measured through on-ground inventories of woody plants. However, most allometric relationships have been developed using young, healthy woody plants (Baker et al. 2004), and there is a paucity of data available to assess the influence of plant condition on this

allometry and subsequent scaling of stand-level *AGB*. Uncertainty in *AGB* estimates will result when variance in condition of woody plants within a population to which the allometric relationship is being applied differs from that within the population of woody plants upon which the relationship was originally developed. This leaves a potential over-prediction bias in *AGB* when typical allometric relationships are applied to a population of woody plants containing relatively high proportions of over-mature, or dead woody plants.

In Australia, rangeland ecosystems encompass a broad range of woody vegetation types that are increasingly being monitored to assess the impact of changed climate and management on provision of ecosystems services through estimating changes in *AGB* (Fensham et al. 2011). Further, rangelands are subject to episodic droughts, regular fires and grazing, all of which impact woody plant health (e.g., Fensham et al. 2003; Fensham 2005; Cook et al. 2020). Rangeland ecosystems therefore provide a good case study for exploring implications of health of woody plants on allometry-predicted biomass and subsequent scaling of stand-level *AGB*.

The objectives of this study were to: (i) develop a protocol to quantify plant condition and apply this to extensive plot-based inventories to quantify typical proportions of woody plants that are senescent or dead, (ii) assess how health condition of individual woody plants influences their biomass to inform how allometry-predicted biomass may be adjusted based on condition of woody plants of different types and sizes, and (iii) explore implications of health condition of woody plants on allometry-predicted biomass and subsequent scaling of stand-level *AGB*.

Methods

A total of 431 sites (each 90 m × 90 m) from 51 properties across Australian rangelands were selected to cover a range of rangeland vegetation types. We measured 278,478 individual woody plants for health score of the stem (H_S) and crown (H_C) of live woody plants, or health score of standing dead woody plants (H_D) (Table 1) and recorded plant functional type (PFT, as per Paul et al. 2016), including Shrubs, Multi-stemmed acacia trees, *Eucalyptus* and *Corymbia* (Eucalypt) trees, Mallees, and Other trees of relatively high wood density. Live aboveground biomass of individual woody plants ($AGBi_{Live}$) was estimated from the application of PFT-based allometric relationships described by Paul et al. 2016. Standing dead aboveground biomass of individual woody plants ($AGBi_{Dead}$) was estimated using theoretical PFT-based allometric relationships developed for standing dead woody plants (Paul and Roxburgh 2024), noting that these allometrics were representative of an H_D score of 1. Stand-level total aboveground biomass (AGB_{Total}, Mg DM ha^{-1}) was calculated from the sum of all $AGBi_{Live}$ and $AGBi_{Dead}$ divided by site area.

For each individual tree/shrub, stem diameter (*D*) was measured at either 130 cm (*D130*; trees) or 10 cm (*D10*; shrubs), and the width and length of the crown was measured at the smallest and longest diameters of the crown, respectively. Measurements of crown width and length were used to estimate the crown area of the individual woody plant (*CAi*, m^2), assuming an ellipse.

Influence of condition on crown cover of individual woody plants

Crown vigour of the *CAi*, defined as the percentage of the *CAi* occupied by branches and/or leaves (Table 1), was visually assessed for 1,201 individuals of varying PFT and health score, excluding stumps, across 45 sites covering a range of vegetation types and site conditions. The effect of health score on *CAi* of a given *D* was tested, where *D* is a surrogate of aboveground woody biomass of individual trees/shrubs currently used in existing allometric relationships. Separate relationships were developed for different groupings of PFT, starting with the five PFTs, and further grouping into broader life-forms of 'Trees'

(Eucalypt, Other trees, Mallee) and Shrubs/Multi-stemmed acacias. Analysis of variance was used to test whether crown vigour differed significantly between health scores and life-forms.

D-CAi allometric relationships were developed with the form:

$$CAi = aD^{b} \quad \text{Eqn 1}$$

where *CAi* was individual crown area (m^2), *D* was *D130* for trees and *D10* for Shrubs and Multi-stemmed acacia, constant *a* was a scaling factor and constant *b* was the exponent, determining rates of growth. Dead woody plants with H_D scores of 4 and 5 where there was no crown were excluded.

Sensitivity of stand-scale allometry-predicted woody biomass to plant health

Sensitivity of allometry-predicted AGB_{Total} to variations in plant condition were assessed by comparing ‘uncorrected’ *AGB* derived from application of existing allometric equations as described above, with alternative estimates of *AGB* where downward ‘corrections’ for different health scores based on assumed typical reductions in *AGB* components (stem, branch and foliage) were applied (Table 1). Due to the paucity of information on typical reductions in these components associated with differing health, these corrections were informed using published data on typical allocations to different biomass components (e.g., Forrester et al. 2024; Paul and Roxburgh 2024), and then proportionally reducing all or part of different components in line with the health scores as described in Table 1.

Table 1: Description of health scores applied to crown and stem components of live woody plants and to standing dead woody plants, and assumed corrections for downward adjustment of allometry-predicted biomass used in sensitivity analyses.

Health Score	Description	Assumed corrections[1]
	Live woody plants: Crown (H_C)	
1	Crown very healthy; almost no dead branches	1.00
2	Crown fair; some small dead branches	1.00
3	Crown poor; most small branches dead	0.50[2]
4	Crown very poor; most small branches dead and one or more large dead branches	0.40[2]
5	Crown nearly dead; most small and large branches dead	0.30[2]
	Live woody plants: Stem (H_S)	
1	Stem live, bark intact	1.00
2	Stem live, bark breached/shallow scars but still intact	1.00
3	Stem live, bark breached/deep scars and heartwood exposed	0.30[2]
4	Stem live, but heartwood extremely hollowed or stem mostly dead	0.20[2]
	Standing dead woody plants (H_D)	
1	Dead, with small canopy branches	1.00
2	Dead, with only large canopy branches	0.80[3]
3	Dead, main bole and few large branches remaining	0.50[3]
4	Dead, only main bole remaining or most of stem height	0.10[3]
5	Dead, more than half of main stem missing	0.05[3]

[1] assumptions for downward adjustment of *D*-based allometry-predicted biomass used in sensitivity analyses. Note: A value of 1 indicates no correction and a value of 0.5 indicates a reduction of 50%.

[2] assumptions for H_C and H_S were only applied for for large (*D130* >55 cm) highly-senescent (H_S of 3-4 and/or H_C of 3-5) Euc trees.

[3] assumptions were only applied for dead woody plants (H_D 2-5).

Results

Characteristics and condition of woody plants in rangelands

Across all stands, over one-quarter of individuals were either dead or senescing (mean ± SD: 26.1 ± 23.3%). The proportion of dead individuals averaged 15.9 ± 18.3%; 10.6 ± 16.0% were standing dead (with branches remaining, H_D scores of 1 or 2), and 5.3 ± 9.5% were stumps (only the main stems remaining at various heights, H_D scores of 3-5). The distribution of data for the proportion of dead was strongly positively skewed with only one-third of sites having >16% of individuals being dead.

Influence of condition on crown cover and biomass of woody plants

Crown vigour of individual woody plants significantly (F = 49.12, P<0.001) increased as condition increased. For live trees, crown vigour increased from a mean of 32% at an H_C score of 5, to a mean of 69% at an H_C of 1, and for Shrub/Multi-Ac, increased from a mean of 68% to 88% as condition score improved from an H_C of 5 through to an H_C of 1. Similarly, vigour of standing dead (dead woody plants with branches remaining) increased from 20% to 43% as condition increased from H_D 3 to 1. Within the broader groupings of ‘Tree’ and ‘Shrub/Multi-stemmed acacia’, there were no statistical differences (P>0.05) between PFTs.

D-CAi allometric relationships varied between broader life-form groupings of Trees and Shrubs/Multi-stemmed acacias (data not shown). For both live and dead Trees, *D-CAi* allometric relationships differed with condition (Fig.1). For a given *D*, allometry-predicted *CAi* declined as condition declined. Model efficiency (*EF*) of *D-CAi* allometric relationships decreased with decreasing condition (H_C 1-5: EF = 0.63 to 0.32; H_D 1-3: EF = 0.52 to 0.25), largely attributable to differences in sample size for live Trees (H_C 1-5: N = 22,746 to 123), but not dead Trees (H_D 1-3: N = 821 to 1,201).

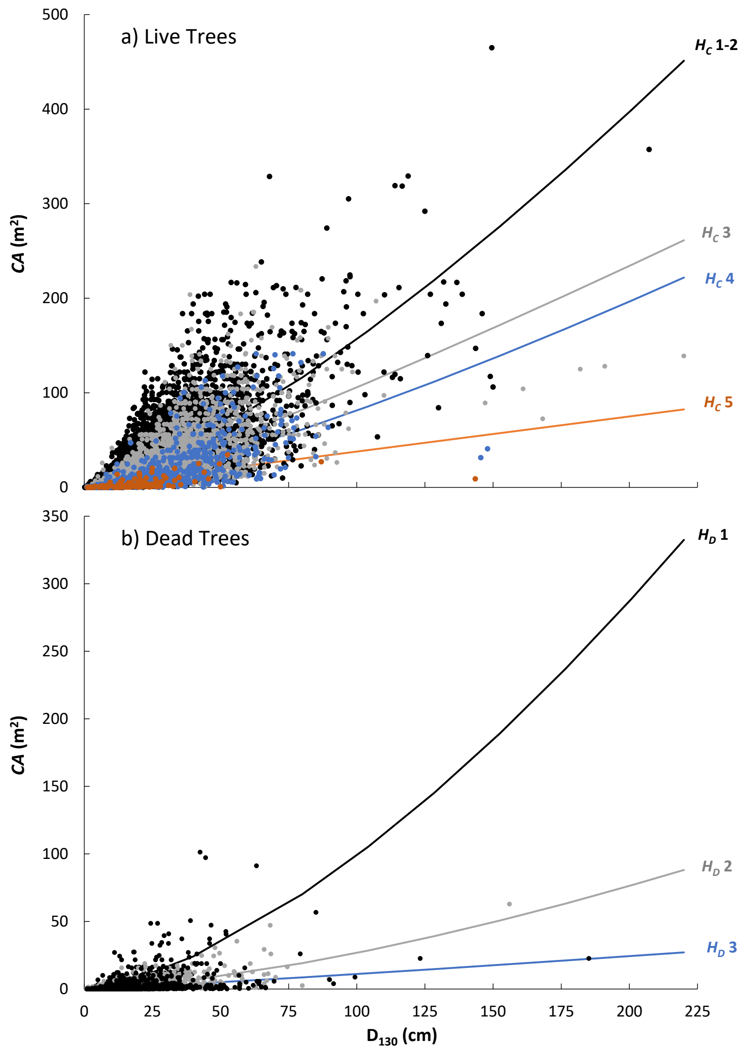

Figure 1. Allometric relationships between stem diameter (*D*) and crown area (*CA*) corrected for crown vigour for the Trees grouping representing the Eucalypt, Other hardwood tree and Mallee plant functional types: (a) live Trees and b) dead Trees. Lines represent fitted power functions. Health scores for live (H_C 1-5) and dead (H_D 1-5) trees are defined in Table 1.

Across all sites (N = 431), allometry-predicted AGB_{Total} was on average 9 ± 12% (but up to 72%) lower when multipliers were applied to account for standing dead and, where present, large senescing Eucalypt trees, relative to existing allometric equations (Fig. 2a). These corrections had a particularly high influence on sites of relatively high biomass (AGB_{Total} > 100 Mg DM ha^{-1}; N = 22), where allometry-predicted AGB_{Total} was on average 34 ± 19% lower after applying the recommended corrections. By comparison, when only considering sites where there were no large senescing Eucalypt trees (N = 317), allometry-predicted AGB_{Total} was on average 5 ± 8% (but up to 50%) lower when multipliers were applied to account for standing dead (Fig. 2b).

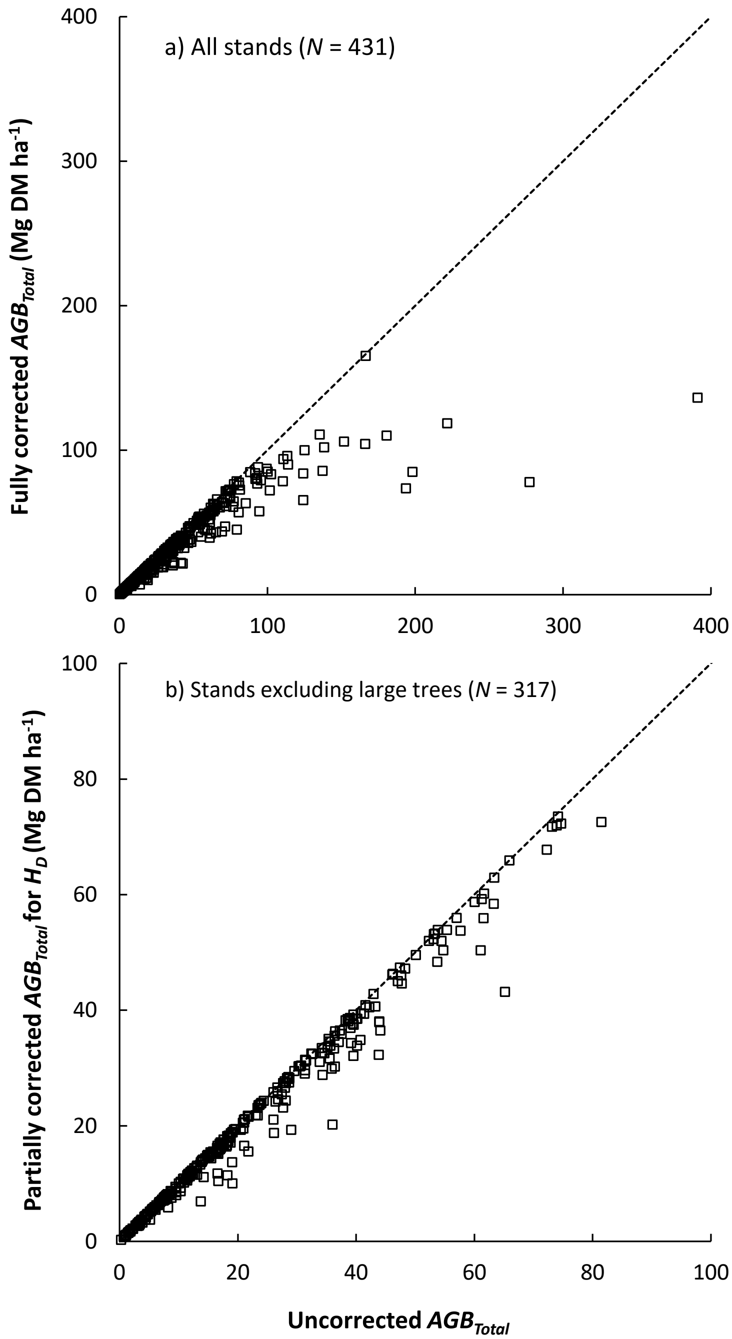

Figure 2. Relationship between uncorrected stand-level allometry-predicted total aboveground biomass (AGB_{Total}, Mg DM ha^{-1}) and AGB_{Total} where a) full corrections were applied to account for H_C, H_S and H_D scores, and where present, large senescent Euc trees, for all of the 431 rangeland sites, and b) AGB_{Total} where partial corrections were applied to account for H_D scores for 317 rangeland sites where there were no large trees (*D130* >55 cm). Corrections are provided in Table 1.

Discussion

A key finding of this study was that across the 431 measured sites, around 16% of individuals were standing dead. A review found in Australian woodlands that 8.1-23.0%, and in dry sclerophyll forests, 0.2–4.5% of total biomass was standing dead (Woldendorp et al. 2002). Mortality events in rangelands tend to be episodic, for example, Fensham and Holman's (1999) survey suggested that ~25% of live basal area was converted to dead standing wood during 5 years of intense drought over a large area of Northern Queensland. Cook et al. (2020) reported that standing dead was 9.6% of total biomass in savannas subjected to regular fires.

This is the first study in rangelands to provide evidence of the influence of health condition of woody plants on their *AGB* – both directly via a significantly lower *D* (and hence, *AGB*) for a given *CAi* (Fig. 1), and indirectly via a significantly decreased *CA* with decreased canopy vigour. Our results suggest that the condition of individual woody plants within rangelands are likely to influence the observed canopy cover of the stand.

Assuming these 431 diverse rangelands stands were representative of Australian rangelands more broadly, these results suggest that if traditional *D*- or *CA*-allometric relationships developed for healthy live trees or shrubs were applied to these ecosystems to predict *AGB*, substantial over-estimation may result, particularly for stands with a relatively high proportion of trees of relatively poor condition. The fact that there was decreasing efficiency in the *D*-*CAi* relationship with decreasing health score of woody plants (Fig. 1) indicated that not only will condition impact the relationship required to predict *AGB*, it will also impact the precision of that relationship. This may be expected because a poor health score is qualitative and will likely encompass varying effects on *AGB* given it will not accurately account for the extent of stem hollowing. Internal hollows within the stem and large branches are typically not visible to the on-ground observer seeking to provide a health score, yet these hollows are likely to substantially influence the actual *AGB*.

Conclusions/Implications

This study provides improved understanding of the variation in woody plant condition across a wide range of rangeland vegetation types, and its impact on allometric relationships, which are critical for predicting woody biomass. To avoid substantial over-prediction of total stand *AGB*, corrections to existing allometric relationships derived from predominantly healthy woody plants are required to account for differences in *AGB* of dead woody plants, and a decline in *AGB* of live woody plants, particularly as they age and over-mature. The results inform improved accuracy of stand-level woody biomass estimates in rangelands.

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