



## Accounting for carbon stock change in Australia's rangelands – a hybrid approach using remote sensing and empirical modelling

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### Abstract

Australia's rangelands are under varying types of land-use and management, including cattle grazing, Indigenous fire management, and activities encouraging regeneration of native vegetation to restore biomass and earn carbon credits. Despite the typically sparse vegetation, the vast area of the rangelands (almost 6 million km<sup>2</sup>) is a substantial stock of land sector carbon. Changes in these stocks, whether due to management or wet - dry climate fluctuation, are thus a major contributor to Australia's overall carbon fluxes. Improving estimates of greenhouse emissions and sinks in the rangelands is thus essential to fulfil Australia's climate change treaty obligations, and also to account for land management effects in carbon credit schemes.

Here we present a new approach to account for land-sector carbon, targeted principally at the rangelands. Recent work has quantified the relationship between canopy cover and above-ground biomass (AGB) across Australia's rangelands. We extend the widely-used Full Carbon Accounting Model (FullCAM), using a time-series of remotely-sensed woody cover to estimate changes in AGB through time. This time series is integrated with the FullCAM model, to combine observed changes in woody cover with the effects of fire, litterfall, decay and soil respiration, to account for greenhouse emissions and sinks through time.

We introduce and demonstrate this approach for rangeland areas. Once this approach, informed by satellite monitoring of woody cover, is scaled up, it is anticipated that FullCAM will reduce model uncertainty by integrating empirical biomass estimates with a process-based modelling framework.

### Introduction

Rangelands occupy approximately 40% of the global surface and provide critical ecosystem services, such as forage for livestock, soil stabilization, biodiversity habitat and climate change mitigation. Given their vast extent, even minor changes in carbon stocks can have significant impacts on the global and national

carbon budgets. Woody biomass is a key component of the carbon cycle in these environments, with increasing woody vegetation associated with benefits including enhanced carbon sequestration.

Estimating and monitoring woody biomass in Australia's rangelands is challenging due to diverse vegetation types, complex disturbance regimes (grazing, fire, drought) and associated high spatial and temporal variability. Australia's National Greenhouse Accounts (Australian Government, 2024) use the Full Carbon Accounting Model (FullCAM; Richards and Evans, 2004; Forrester et al., 2024), to monitor and report carbon emissions and sequestration from the land sector. The FullCAM framework estimates accumulation of tree biomass using an empirical growth relationship known as the Tree Yield Formula, with parameters including maximum above-ground biomass (AGB), age of maximum growth, and importantly, stand age. This approach to estimating biomass, and thus carbon, depends on the date from which a given stand began to grow. In rangeland systems where vegetation dynamics may be dominated by diffuse cycles of biomass increase and decrease in response to factors such as climate, grazing and low intensity fire, this approach has limitations.

Canopy cover is strongly correlated with AGB, and remote sensing (including Landsat and Sentinel time series) has been broadly adopted to map vegetation cover, including for aiding the estimation of AGB at large spatial scales (Allred et al., 2021; Jones et al., 2021; Kearney et al., 2022). Modelling AGB directly from time-series estimates of canopy cover may provide an alternative to generalized growth models to better estimate AGB change, and thus carbon flux, in sparse and diverse vegetation, such as Australian rangelands.

This study presents a novel prototype, a variation of the FullCAM model that combines a process-based model of vegetation carbon cycling, with remote-sensed observation of vegetation change, to improve estimation of carbon stocks and flows in the rangelands. By integrating dynamic carbon cycle processes with satellite-derived observations of vegetation cover, this model aims to capture the spatial and temporal variability in rangelands, offering a tool more applicable for carbon accounting and vegetation carbon sequestration projects in these more arid areas. In this paper, we outline the integrated workflow and share the preliminary results.

## **Methods**

We mapped carbon stock for woody vegetation in a rangeland area, through a process with three main stages. The first, a satellite derived time-series of the proportion of woody cover tracked changes in vegetation extent and density. Second, AGB was inferred at each location through time. The AGB was based on woody cover and vegetation structure relationships, previously calibrated over an extensive program of fieldwork. Third, the inferred AGB was incorporated into a model adapted from the Full Carbon Accounting Model (FullCAM; Forrester et al., 2024; Richards and Brack, 2004) alongside other carbon cycling processes such as litterfall and decay, to simulate movement between carbon pools, and overall carbon stock change in the woody component of rangeland environments. These steps are now described in more detail.

### ***Remote-sensed woody cover***

The FullCAM framework estimates spatial and temporal regeneration of AGB using a stand-age based empirical growth relationship (Tree Yield Formula, TYF; Paul & Roxburgh, 2020). In rangeland systems where vegetation dynamics are typically dominated by more diffuse cycles of increasing and decreasing biomass in response to factors such as climate, grazing and low intensity fire, this approach has limitations.

The current standard for estimating fluxes of greenhouse gases related to vegetation change in Australia's Greenhouse Accounts (DCCEEW, 2024) is the national forest and sparse woody vegetation data (Furby, 2002; DCCEEW, 2023) which uses Landsat satellite data for the period since 1988 to derive an annual classification of Australia's vegetation cover into 3 categories: woody vegetation (forest,  $\geq 20\%$  tree cover), sparse woody vegetation (5% to  $<20\%$  cover), and non-woody ( $<5\%$  cover). This dataset tracks changes through time in the extent of forest, particularly for well-defined changes such as clearing of forest, and the establishment of new or restored forest areas, but is not sensitive to changes in cover within those categories. Thus its use in carbon accounting relies on growth and recovery functions to simulate biomass accumulation through time (Forrester et al., 2024), calibrated to empirical datasets.

In this study we trialled a new remote sensing approach to capture the full range of variation in woody cover, enabling direct observation of changes in woody cover to be translated into time-specific estimates of above-ground biomass and carbon pools. This approach to estimate cover (Chia et al., 2024) partitions Landsat multi-spectral reflectance into multi-variate proportions (MVP) for four ground-cover classes: woody, dry grasses, green grasses and soil (bare) based on spectral unmixing algorithms described by Berman et al. (in prep). The timing of images is selected to provide a yearly value representing permanent woody cover, typically during the dry season (July for northern and northeastern Australia, and January for central and southern Australia). The time series covers the period 1988 to 2022 at 0.00025 degree ( $\sim 25$  m) resolution. Annual cover values were interpolated to monthly by assuming linear change between observed values and extrapolated to use the earliest observed value for years prior to 1988.

#### **Cover to biomass**

Our 'cover-to-biomass' model is based on the quantitative relationship between canopy cover and AGB which Pasut et al. (in press) derived from an extensive dataset of field measurements. These measurements, collected from 431 field sites across the Australian rangelands, included live AGB and standing dead AGB, with sites stratified to represent the region's variability. The resulting log-linear relationship between woody cover proportion and above-ground biomass, is expressed here as:

$$AGB = e^{b \ln(C)} * B_f \quad \text{Eq.1}$$

where AGB is above-ground biomass;  $b$  is the scaling factor for cover;  $C$  is the percentage of woody cover; and  $B_f$  is the Baskerville correction factor.

The model was calibrated for three broad vegetation structural types, *shrub-dominant*, *Acacia-dominant* and *tree-dominant*, with values of  $b$  and  $B_f$  for each vegetation structural type.

#### **Integrated land carbon model**

We adapted the FullCAM model framework to estimate AGB using remotely sensed cover data. For detail on the FullCAM framework see Forrester et al. (2024). The existing FullCAM uses a growth curve in which the annual increment in living tree biomass depends on parameters including tree-stand age (dated to detection of new forest cover) and time since disturbance. The cover-to-biomass model however, ties changes in AGB to continuous vegetation change, estimating AGB from annual observations of cover, rather than a growth curve.

Other model components follow the existing FullCAM approach, where the vegetation class at each location is defined from the National Vegetation Information System (NVIS) Major Vegetation Groups. AGB is allocated among living carbon pools (stem, bark, branches, leaves) using FullCAM proportions for allocation of live biomass which are specific to each vegetation class, with below-ground tree biomass

similarly assigned to fine and coarse root carbon pools in proportion to AGB. Turnover (such as litterfall of leaves and bark to debris) and decomposition of debris are predicted using an exponential decay model that quantifies the rate at which carbon moves between pools. Fire events were not directly simulated in this study, although the effects of fire on loss of woody biomass and its subsequent recovery, are included where they affect observed woody cover. Non-CO<sub>2</sub> greenhouse gasses are not included at this stage.

Flux of carbon between land and atmosphere occurs in this model in two ways. First, during the decay of non-living biomass, a proportion of the carbon is released as CO<sub>2</sub>, while the rest of the lost carbon moves to another pool, for example, soil carbon. Second, changes in site carbon mass, primarily due to changes in AGB indicated by the cover-to-biomass function, are treated as direct carbon removals from, or emissions to, the atmosphere, corresponding to increases or decreases in AGB.

In summary, the prototype cover-to-biomass model in this study is a hybrid, combining process-based modelling of carbon transitions / transformation between pools, with an observation-driven component where changes in biomass at each pixel are directly linked to satellite-detected variations in woody cover.

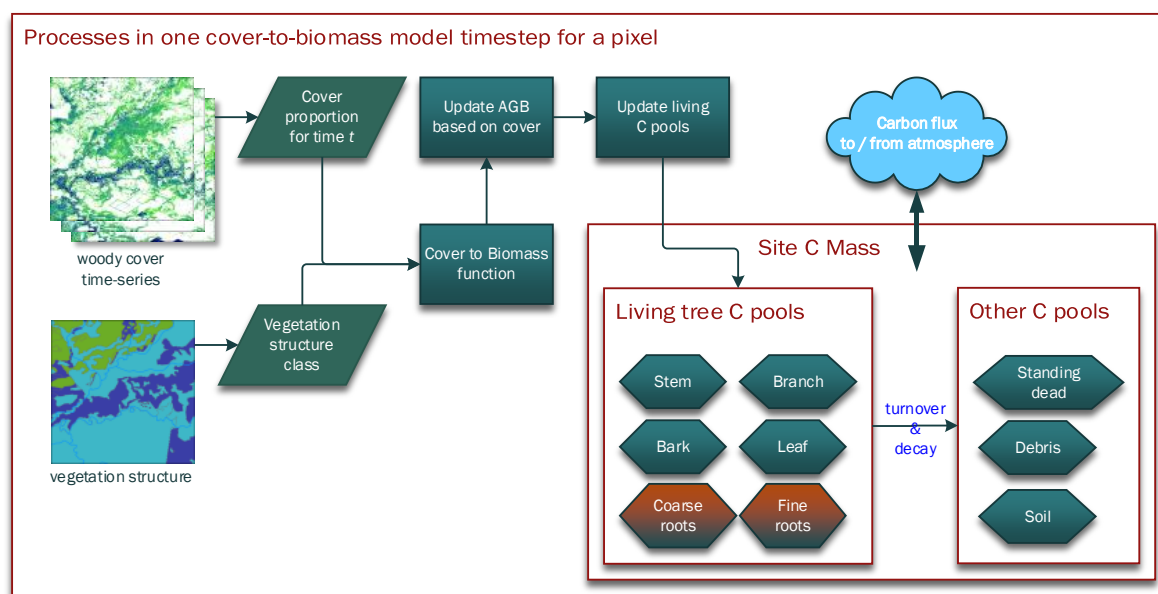


Figure 1. Main processes in the cover-to-biomass model per time-step, for one pixel. Vegetation structure and remote-sensed woody cover percentage for each timestep inform the cover-to-biomass function to update living biomass pools. Turnover and decay processes then populate the debris and soil carbon pools. Atmospheric carbon flux is inferred from changes to site carbon mass.

## Results

Results from running the prototype model for an area of 6 million ha (96 million pixels at 25 m resolution) in inland northern New South Wales and southern Queensland, returned values for aboveground living tree C mass ranging from 0 to 79 t C ha<sup>-1</sup>, and for total stand C mass ranging from 22 to 170 t C ha<sup>-1</sup>. As expected, results were strongly reflective of local topography and drainage as important drivers of C density, and of patterns of agricultural land-use. Figure 2 shows in detail the estimates of woody cover and of carbon pools for an area along the Barwon River east of Bourke, NSW for the year 2020.

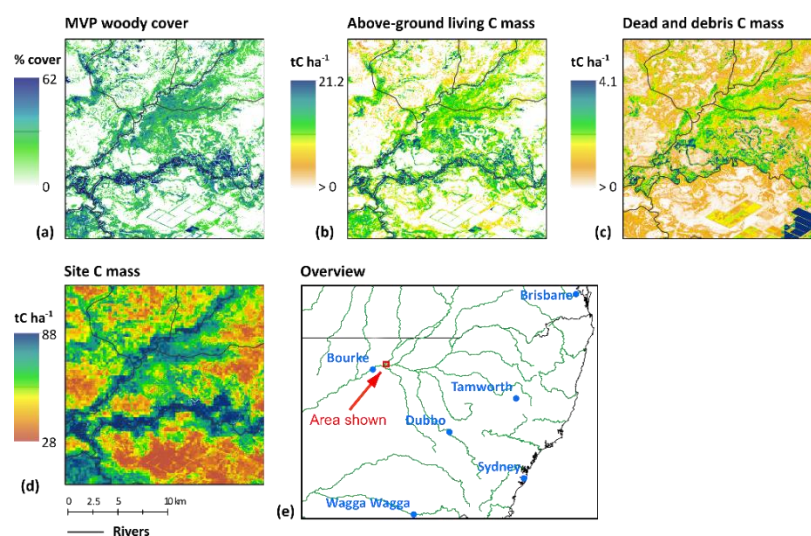


Figure 2. Example model outputs for 2020 along the Barwon River east of Bourke, New South Wales at 25 m resolution, showing a) % of woody cover from the multivariate proportion (MVP) model; b) carbon in aboveground tree biomass; c) carbon in debris and standing dead trees; d) total C mass, including above and belowground tree components, standing dead, debris and soil organic carbon; and e) overview map. The effects of floodplains on biomass are clear, as is irrigated agriculture near the south end of the area.

## Discussion

The method and results presented here illustrate the potential of a new approach to estimating land sector C stocks, and subsequently emissions and sinks, in rangeland environments where methods based on stand-level, growth curves may not reflect typical growth trajectories. They introduce an approach based on observed changes in woody cover through time, combined with modelled turnover and decay, which with further development, aims to improve to C accounting across Australia's vast rangelands. A comprehensive accounting approach will also need to include emissions of non-CO<sub>2</sub> greenhouse gasses, especially due to fires, to manage inter-annual variability in cover inferred from remote-sensed cover, and to demonstrate model performance across diverse rangeland environments in comparison to currently used approaches.

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