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A national accounting framework for fire and carbon dynamics in Australian savannas

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ABSTRACT

Background. Tropical savannas represent a large proportion of the area burnt each year globally, with growing evidence that management to curtail fire frequency and intensity in some of these regions can contribute to mitigation of climate change. Approximately 25% of Australia's fire-prone tropical savanna region is currently managed for carbon projects, contributing significantly to Australia's National Greenhouse Gas Inventory. **Aims.** To improve the accuracy of Australia's national carbon accounting model (FullCAM) for reporting of fire emissions and sequestration of carbon in savanna ecosystems. **Methods.** Field data from Australian savannas were collated and used to calibrate FullCAM parameters for the prediction of living biomass, standing dead biomass and debris within seven broad vegetation types. **Key results.** Revised parameter sets and improved predictions of carbon stocks and fluxes across Australia's savanna ecosystems in response to wildfire and planned fire were obtained. **Conclusions.** The FullCAM model was successfully calibrated to include fire impacts and post-fire recovery in savanna ecosystems. **Implications.** This study has expanded the capability of FullCAM to simulate both reduced emissions and increased sequestration of carbon in response to management of fire in tropical savanna regions of Australia, with implications for carbon accounting at national and project scales.

Keywords: carbon, carbon accounting, emissions, fire, fuel, FullCAM, litterfall, mortality, savannas, standing dead.

Introduction

Tropical savannas currently account for most of the global area burnt (van der Werf *et al.* 2017; Giglio *et al.* 2018). In Australia, tropical savanna represents 26% of the land area (Edwards *et al.* 2021), burning at frequencies of 0.158–0.362 $year^{-1}$ (Whitehead *et al.* 2014; Cook *et al.* 2020). Traditional Indigenous use of fire as a land management tool is again becoming common practice in these regions (Cook *et al.* 2012; Edwards *et al.* 2021). This entails igniting cool and patchy fires in the early dry season (EDS) to decrease prevalence of large high intensity late dry season (LDS) wildfires. This management decreases greenhouse gas emissions (Russell-Smith *et al.* 2013) and may also lead to increased storage of carbon in pools of dead (Cook *et al.* 2016, 2020) and live (Ryan and Williams 2011; Murphy *et al.* 2023) biomass.

This change in land management is having a significant impact on Australia's National Inventory Reporting (NIR) and greenhouse gas emissions (expressed in units of carbon dioxide equivalents: CO_2-e). Australia's savanna region was initially (1990–2015) a major source of emissions ($\sim +20$ Mt CO_2-e $year^{-1}$), but more recently (2016–2020) has become a net sink (~ -5.5 Mt CO_2-e $year^{-1}$), coinciding with an increased proportion of fires in the EDS, and hence accounting for both a decrease in total emissions from fire and increased storage of carbon in dead and live biomass (NIR, Commonwealth of Australia 2022).

To inform Australia's annual NIR for savanna regions, remote sensing of fire scars provides inputs to the spatial-temporal carbon accounting model, FullCAM

(Paul and Roxburgh 2019). FullCAM is an empirical carbon tracking model, and therefore, its accuracy directly relates to the quality and quantity of underlying calibration datasets. The aim of the present study was to improve the accuracy of FullCAM for reporting fire emissions and sequestration of carbon in savanna ecosystems through collating extensive field data to calibrate model parameters for the prediction of living biomass, standing dead biomass and debris. Through more accurate simulations of both fire emissions and sequestration of carbon, the primary outcome of this work was enhanced accuracy of Australia's NIR (as recently implemented in Commonwealth of Australia 2022). A secondary outcome of this study was to provide options to enhance the accuracy in accounting for net abatement from savanna fire management projects. A comprehensive methodology encompassing the impacts of different fire types on both avoided emissions and sequestration of carbon is required given current methodologies available either only account for avoided emissions (Commonwealth of Australia 2015), account for sequestration only in dead pools rather than both live and dead pools (Commonwealth of Australia 2018), or do not distinguish between effects of fires of different intensities (Voluntary Carbon Standard 2015).

Methods

Description of the FullCAM model and its simulation of fire events

For any given pixel (approximately 25 × 25 m area of application of the model, as applied in the NIR) or 'site' (0.02–2 ha transects or plots measured in field assessments, as applied during model calibration), FullCAM simulates carbon dynamics of live and dead pools of both woody and grass components in response to regular mortality and turnover (and corresponding recruitment and recovery), as well as stochastic disturbance events such as fires (Fig. 1 and Supplementary Material A). Because FullCAM is a pool-based model and does not simulate populations of individuals, mortality, recruitment and recovery are simulated via increases and reductions in standing biomass. The model includes: (i) live biomass of trees and shrubs, simulated as woody Above-Ground Biomass (AGB); (ii) heavy woody fuel, including stags (elevated dead trees or shrubs) and Coarse Woody Debris (CWD, on-ground components of debris ≥5 cm diameter), simulated together in the model as the 'standing dead' pool; (iii) coarse woody fuel, including on-ground branch and bark litter of 0.6–5 cm diameter,

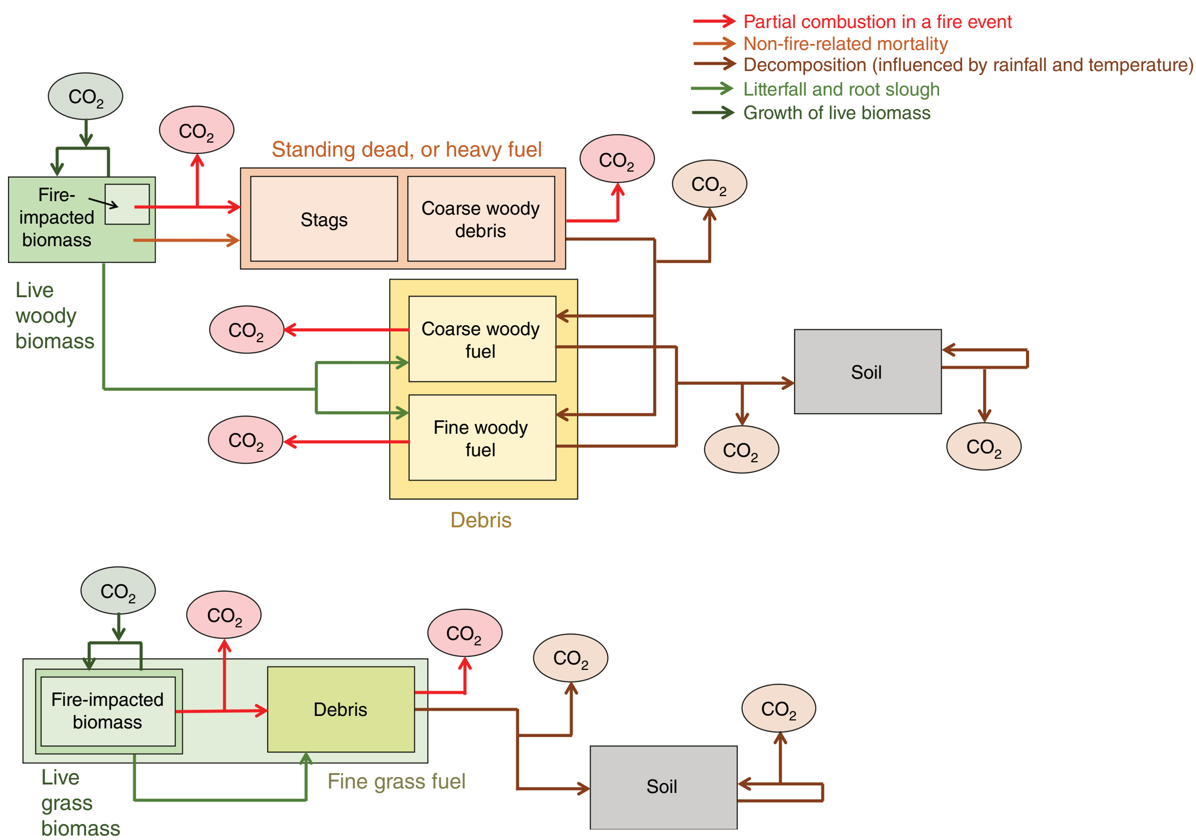

Fig. 1. Flow of carbon in a typical savanna woodland system as simulated by FullCAM. Flows of carbon associated with fire events are indicated in red.

simulated as 60% of branch and bark debris; (iv) fine woody fuel, including foliage litter and some of the ≤0.6 cm diameter branch and bark litter that is partially decomposed or broken down, simulated as foliage debris plus the remaining 40% of branch and bark debris; and (v) fine grass fuel, simulated as grass leaf biomass and grass litter.

A key spatially explicit input influencing productivity, and therefore predicted rates of post-fire recovery, is the maximum above-ground woody biomass, M, (Roxburgh *et al.* 2019) that a pixel or 'site' can support given long-term average site resources (e.g. rainfall), which for savanna regions is well validated (Supplementary Fig. S2; although this could still be further improved; Supplementary Material F). In the current implementation of the model, M is therefore constant, and thus FullCAM is insensitive to potential changes in M driven by changes in resource availability, such as a change to the hydrological regime leading to increases (or decreases) in soil water availability (Supplementary Material B). To further account for spatially explicit differences in sensitivity of biomass to fire, the model also accounts for seven different types of savanna vegetation (Supplementary Material A), as fire impacts these differently, largely because of their differing wood-to-grass composition (Table 1). Subsuming groundcover types (tussock, hummock, mixed grassed) into the vegetation structural classes outlined in Table 1 is a simplification of previous vegetation categories that accounted for differences in recovery rates of these groundcovers as it was assumed that over the extent of fire-prone savannas, such differences might be negligible.

Different types of fire are simulated, depending on the season (EDS, April–July inclusive; or LDS, August–December inclusive) and intensity (with subscripts of 1, 2 or 3 indicating fire intensity of <1, 1–2 and >2 MW m^{-1}, respectively, e.g. EDS_1 indicating early dry season fire of low intensity) (Russell-Smith and Edwards 2006). In FullCAM, the fire type influences combustion factors (C_F = CO_2-C released per unit of dry fuel C consumed, expressed on a dry weight basis and represented below as a percentage C loss term), and in the case of live pools of biomass, fire type also influences an additional loss of carbon from live pools of biomass accounted for via live-to-dead biomass pool transfer factors (T_F = proportion of carbon in live biomass pools transferred to standing dead pools in response to fire, expressed on a dry weight basis). To account for emissions of methane (CH_4) and nitrous oxide (N_2O) in response to changed fire management (IPCC 2006), the simplifying assumption was made that FullCAM-predicted CO_2-C emissions (Mg C ha^{-1}) are multiplied by the emission factors (E_F) listed in Supplementary Table S1 (Surawski *et al.* 2016). Differences

Table 1. Categories of savanna vegetation, including whether they are within the high rainfall zone (H, average rainfall >1000 mm year^{-1}) or low rainfall zone (L, average rainfall 600–1000 mm year^{-1}), and whether they are woodland (W), shrubland (S) or pindan acacia (P) systems, and any sub-division required to account for differing woody canopy covers.

Rainfall zone	Vegetation category	Sub-division	Woody canopy cover (%)[A]	Previous vegetation types
H	WH[B]	$WH_{0.6}$	60	hOFM[G]
		$WH_{0.3}$	30	hWMi[H], hWHu[I]
	SH[C]		15	hSHH[J]
L	WL[D]	$WL_{0.2}$	20	lWHu[K], lWMi[L], lWTu[M]
		$WL_{0.1}$	10	lOWM[N]
	SL[E]		10	lSHH[O]
	PL[F]		30	Not previously applied

Also indicated are the previous definitions of savanna vegetation applicable to these categories (Meyer *et al.* 2015). Further explanation of these different categories of vegetation is given in Supplementary Material A.

[A]This FullCAM parameter influences the assumed woody-to-grass cover, with grass biomass increasing with decreased woody canopy cover. This parameter does not influence growth of the woody vegetation.
[B]Woodland – High rainfall.
[C]Shrubland – High rainfall.
[D]Woodland – Low rainfall.
[E]Shrubland – Low rainfall.
[F]Pindan.
[G]High rainfall Open Forest with Mixed grasses of tussock and hummock.
[H]High rainfall Woodland with Mixed grasses of tussock and hummock.
[I]High rainfall Woodland with Hummock grass.
[J]High rainfall Shrubland (heath) with Hummock grass.
[K]Low rainfall Woodland with Hummock grass.
[L]Low rainfall Woodland with Mixed grasses of tussock and hummock.
[M]Low rainfall Woodland with Tussock grass.
[N]Low rainfall Open Woodland, with Mixed grassed.
[O]Low rainfall Shrubland (Heath) with Hummock grass.

in emissions between vegetation types were partly attributed to local variability in fire intensity and flame height (Meyer and Cook 2015).

The capacity for vegetative regeneration post-fire is well developed in savannas (e.g. Lacey 1974), and so although trees or shrubs may experience partial mortality due to fire, they typically survive and recover (e.g. Lonsdale and Braithwaite 1991; Williams *et al.* 1999). This is attributable to a combination of resprouting from epicormic buds and/or regrowth of saplings (Bond *et al.* 2012; Lawes *et al.* 2022). Hence, FullCAM simulations ensure fire-induced changes in AGB inversely impact standing dead mass (via the T_F), consistent with the creation of heavy fuel when trees die (Cook *et al.* 2015*a*) (Supplementary Fig. S3).

When high-intensity fires are frequent, predicted AGB does not fully recover to M between fire events, with a fire-induced suppression of AGB (e.g. as occurs in 1972–1980 in Supplementary Fig. S3), ensuring simulations produce negative correlations between predicted AGB and fire frequency where fires are frequent and severe (e.g. Murphy *et al.* 2013). Hence, fire simulation in FullCAM temporarily decreases AGB below M, the climatically determined upper bound (e.g. Liedloff and Cook 2007; Murphy *et al.* 2015) (Supplementary Material B). Consistent with findings of Cook *et al.* (2017), a modelled assumption was that increased fire intensity results in increased fire impact on AGB (which in FullCAM is $C_F + T_F$), and hence, time to recover. Given Cook *et al.* (2017) reported recovery times of savanna biomass of 2–17 years, as fire impact on AGB increases from 2.5 to 15%, predicted recovery time increases from 1 to 5 years, with a maximum time to recover of 20 years (Supplementary Fig. S4).

As FullCAM can be applied spatially across the landscape, patchiness of fire is accounted for by simulating the fire event across only a proportion of the pixels within the total fire scar area (Paul and Roxburgh 2019). For EDS fires, this was 70.9 and 79.0% of the fire scar in high and low rainfall zones, respectively, whereas for LDS fires, it was 88.9 and 97.0% in high and low rainfall zones, respectively (Russell-Smith and Yates 2007; Russell-Smith *et al.* 2009*a*; Yates *et al.* 2015).

In summary, the type and frequency of fire event has an impact on carbon stocks in live and dead pools (both in total mass and in vegetative composition), which, in turn, impacts subsequent fire emissions owing to the availability of volatile components of live and dead biomass. Hence, the FullCAM structure allows for interactions and feedbacks between fire emissions and carbon stocks.

Model calibration

Calibration of FullCAM to savanna fires was a two-step process: firstly, constraining parameter values based on review of the collated datasets, and secondly, optimising remaining 'unknown' parameters by ensuring predicted pools of AGB and heavy, coarse, fine and grass fuel matched observations. Across these steps, calculations were required to estimate observed AGB and fuel pools from the available field data (details provided in Supplementary Material C). It was beyond the scope of this work to calibrate FullCAM for fire impacts on soil carbon.

Parameters constrained to observed data: data collected and assumptions made

Allocation of live biomass to components

To derive stand-level biomass allocation (AGB components of stem, branch, bark, foliage, and below-ground biomass components of coarse roots (BGB_C) and fine roots (BGB_F), data were collated from: (a) biomass sampling studies demonstrating proportions of AGB allocated to components for the different Plant Functional Types (PFTs, Supplementary Tables S2 and S11), and (b) 1091 stand inventories across Australian savannas (Supplementary Tables S3 and S4) that indicated the relative contribution of each PFT to total stand AGB (Supplementary Fig. S11*a*), and the BGB_C:AGB ratio (Supplementary Fig. S11*b*). Given the paucity of data, contribution of BGB_F (<2 mm diameter) to total root biomass (BGB_F:BGB_{Total}) was calculated via application of the empirical relationship derived by Mokany and Raison (2004).

Regular turnover of carbon from live to dead pools of carbon

To calibrate FullCAM biomass turnover parameters (Fig. 1 and Supplementary Fig. S1), litterfall datasets were collated from 61 stands across Australia's savannas (Supplementary Table S12). As outlined in Supplementary Material C, additional calculations were required to (a) estimate total litterfall attributable to foliage, branch and bark; and (b) determine a multiplier to convert litterfall measured from litterfall traps into total litterfall, given these traps often fail to capture spatially heterogeneous litterfall arising from large branches (and pieces of bark, and any twigs or foliage attached to these larger branches).

Decomposition of different fuel types

FullCAM parameters for decomposition of standing dead (stags), deadwood debris (components of heavy and coarse fuels) and bark debris (also components of heavy and coarse fuels) pools were calibrated to be constrained within the range reported by Cook *et al.* (2020).

Combustion factors of heavy, coarse and fine fuels

Previous C_F estimates (Fensham 2005; Russell-Smith *et al.* 2009*a*; Yates *et al.* 2015) provided only a guide in constraining the FullCAM C_F parameters as they were estimates for pools as a whole, whereas FullCAM separately simulates different components of each of these broad categories (Fig. 1 and Supplementary Fig. S1).

Parameters calibrated via model optimisation and testing

Three parameter sets required fitting via optimisation given the paucity and/or high uncertainty of available data. The first was mortality, defined here as the regular annual rate of death of live stems not attributable to fire, and assumed to occur in November of each year (consistent with the seasonal observations of coarse litter production), but with resulting AGB loss being replaced within 1 year via regrowth that maintains the assumed steady-state condition. The other two were fire event parameters that determine, for different types of fire, C_F and T_F of different components of AGB. These parameters were calibrated together to ensure their combination resulted in dynamic predictions of AGB that matched those observed across the monitored transects (Supplementary Table S3 and Fig. 2).

Calibration stands were simulated to replicate field plot or transect areas (averaging 0.24 ha, range 0.03–2.00 ha) where: (i) measurements were made across a range of savanna vegetation types based on field assessments of tree stem density, cover and growth forms of dominant grasses, or when not available, vegetation maps of Thackway *et al.* (2014) and Lynch *et al.* (2018); (ii) recent (~5 years) fire history for each of these calibration stands was derived from aerial photos with on-site observations, or when not available and for earlier time-periods, time series of satellite-based observations (1-km resolution) as described by Meyer *et al.* (2015); and (iii) climatic conditions (monthly rainfall, temperature, evaporation over the period of simulation) for each of these calibration stands were derived from Commonwealth of Australia (2022).

As outlined in Supplementary Material B, the model input *M* is important in providing the upper limit for AGB increases following savanna fire management. The *M* applied to each calibration site was the maximum observed AGB at that site (i.e. maximum observed AGB in a time-series of observations for a given site, Supplementary Material B). A 500-year model spin-up period was applied (where satellite-derived fire histories for that site or region were assumed to also apply prior to 1988), such that by the time of interest (when predictions were compared with observations), predicted stand biomass and fuel pools were in a state of equilibrium with respect to the fire regime simulated, with simulated fire events at this time only influencing interannual variations in predicted stocks and fluxes. Where the fire intensity was unknown, it was assumed to be moderate, EDS_2 or LDS_2.

In addition to *M*, the predicted AGB of a stand is also influenced by the assumed rates of mortality. Annual rates of *total* mortality (fire- and non-fire-related) in stands of Australian savannas have been estimated to range from <0.1 to 4% per year (e.g. Lonsdale and Braithwaite 1991; Prior *et al.* 2009; Cook *et al.* 2016, 2020). There is a paucity of data to indicate how fire- and non-fire-related mortality

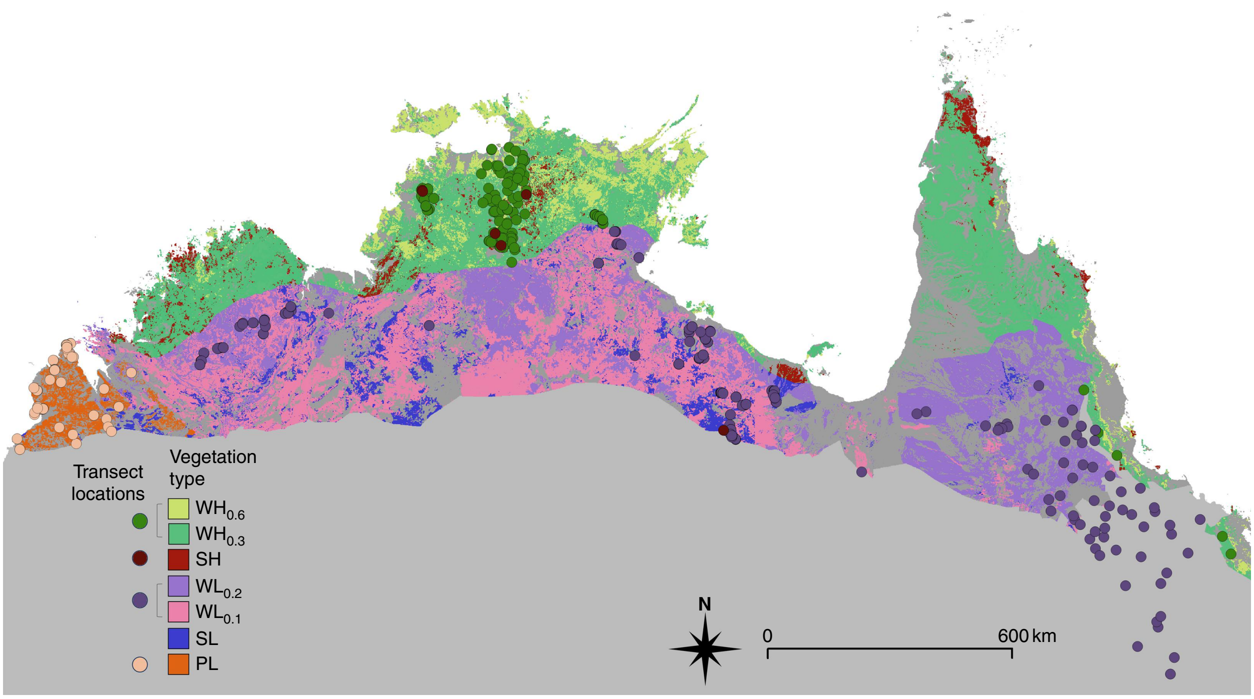

Fig. 2. Location of the transect-based surveys used to assess live biomass and heavy fuel in the different types of tropical savanna vegetation. Data source: Lynch *et al.* (2018), Cook *et al.* (2020), Murphy *et al.* (2023), S. Bray, pers. comm. (2020). WH, Woodland – High rainfall; WL, Woodland – Low rainfall; SH, Shrubland – High rainfall; SL, Shrubland – Low rainfall; PL, Pindan. Full vegetation type definitions are provided in Table 1.

interact, but an assumption was made that fire-related mortality would be between ~50 and 75% of these estimates of total mortality (Cook *et al.* 2020), but declining to a negligible contribution of total mortality under conditions of low fire intensities (Murphy *et al.* 2023). Based on these estimates, when calibrating typical rates at which AGB declines (and subsequently regrows) owing to non-fire-related mortality, values of 2.24% year^{-1} (or 2.70% year^{-1}) for categories of vegetation from high (or low) rainfall zones were assumed to be the upper limit, and were implemented within FullCAM as percentage transfers from the above- and below-ground standing biomass pools to the standing dead pool.

When calibrating C_F and T_F parameters for AGB, it was ensured that the total impact of fire on AGB ($= C_F + T_F$) was consistent with that previously observed. Previous workers (Russell-Smith *et al.* 2009*a*; Yates *et al.* 2015) have estimated that total fire impact on AGB (previously defined as the 'shrub fuel' pool comprising individuals <2 m tall) in high (or low) rainfall zones was 0.29 (or 0.10) and 0.39 (or 0.11) in EDS and LDS fire respectively. These previous estimates were for the AGB as a whole, whereas FullCAM simulates a different C_F and T_F for stem, branch, bark and foliage components of AGB. Therefore, again, previous estimates provided only broad constraints on the calibrations.

Different combinations of parameter values for mortality and the C_F and T_F of components of AGB were tested to determine which provided the highest model efficiency (EF; Soares *et al.* 1995) and least bias of prediction of AGB for each category of vegetation while also ensuring that, across the different categories of vegetation, the extent of fire impact on AGB increased with the observed average proportion of total woody biomass that was heavy fuel:

$$EF = [1 - \overline{e^2}/\overline{o^2}] \times 100$$

where $\overline{o^2}$ is the mean square deviation of each observation from the mean of the observations and $\overline{e^2}$ is the mean squared residual. An EF of 100% indicates perfect match between observations and predictions; 0% indicates the predictions are no better than simply using the mean of the observations, and <0% indicates that residual variation is greater than the variation in the data.

In addition to testing the efficiency of prediction of AGB, performance of the calibrated model was also tested by comparing the predicted biomass with that observed for each of the various pools of fuel: heavy, coarse, fine and grass, including their rates of recovery from time since last burn.

Scenarios of fire management: implications

To demonstrate how FullCAM can be applied to predict the impacts of fire management on avoided emissions and sequestration of carbon, hypothetical savanna burning scenarios were simulated for each of the different savanna vegetation types (Table 1, Supplementary Material D). Project areas were assumed to be 25 ha, comprising 25 × 1 ha strata. Each stratum had a unique hypothetical fire history and was therefore separately simulated using a FullCAM plot file with a unique sequence of fire events to replicate the assumed fire histories, as indicated in Supplementary Fig. S12. For simplicity, only EDS_2 and LDS_2 fire types were simulated.

After a 500-year model spin-up period to bring carbon pools to equilibrium, the average frequencies of EDS_2 and LDS_2 fires across the project area were assumed to change between a 25-year early baseline period, and subsequent 5-year intermediate period (where fire management was assumed to commence, and pools of carbon begin to re-equilibrate) and followed by a 25-year project period. The strata 25-year average differences (and standard deviation) between baseline and project were calculated for: (a) carbon stocks, and (b) fire emissions using the vegetation types in Table 1: Woodland – High rainfall ($WH_{0.6}$, $WH_{0.3}$), Shrubland – High rainfall (SH) and Pindan (PL) scenarios (assumed to be in localities of relatively high *M*, and where the baseline fire frequency was relatively high), and Woodland – Low rainfall ($WL_{0.2}$, $WL_{0.1}$) and Shrubland – Low rainfall (SL) scenarios (assumed to be in localities of relatively low *M*, and where the baseline fire frequency was relatively low) (Supplementary Table S13).

Results and discussion

Parameters constrained to observed data

Allocation of live biomass to components

Allocation parameters among the four vegetation types were broadly similar, with allocation to stem ranging from 0.337 to 0.420; allocation to branch ranging from 0.158 to 0.178; allocation to bark from 0.093 to 0.121; allocation to leaf from 0.044 to 0.099; allocation to coarse roots from 0.219 to 0.230; and allocation to fine roots from 0.051 to 0.064 (Table 2).

Regular turnover of carbon from live to dead pools of carbon

When the resulting data-constrained turnover rates were applied in the model (Table 2), the model-predicted turnover-to-AGB relationship matched that observed (Fig. 3). Moreover, the FullCAM-predicted contributions of branch and bark to total litterfall were 25 and 16% respectively, which was similar to those expected (Supplementary Material C).

Seasonality of turnover is also important when accounting for the impact of fire management on fuel dynamics, with higher peaks of total standing litter in LDS cf. EDS, contributing to LDS fires being of relatively high intensity

Table 2. Summary of FullCAM parameter values applied for allocation of biomass, turnover, decomposition and combustion factors.

		Stem	Branch	Bark	Leaf	BGB_C	BGB_F
Live biomass							
Allocation	WH[A]	0.376	0.158	0.121	0.064	0.230	0.051
	WL[B]	0.420	0.158	0.108	0.044	0.219	0.051
	SH[C] or SL[D]	0.371	0.175	0.098	0.083	0.221	0.054
	PL[E]	0.337	0.178	0.093	0.099	0.229	0.064
Turnover (half-life, years)[F, G]	H	–	9	10	1.2	6.56	0.431
	L	–	9	10	1.5	6.56	0.431
Standing dead							
Decomposition (half-life, years)[F]	All	8.00	4.00	2.00	0.50	–	–
C_F (%)	H-EDS	20	30	70	80	–	–
	H-LDS	30	40	80	90	–	–
	L-EDS	10	20	70	80	–	–
	L-LDS	10	30	80	90	–	–

		Dead wood	Bark	Leaf	BGB_C	BGB_F
Debris biomass						
Decomposition (half-life, years)	All	2.00	1.00	0.866[H]	4.00[A]	0.0001[A]
C_F (%)	H-EDS	20[I]	75[J]	80	–	–
	H-LDS	40[I]	85[J]	90	–	–
	L-EDS	10[I]	75[J]	80	–	–
	L-LDS	20[I]	85[J]	90	–	–
Grass						
C_F (and T_F) (%, live)	All	–	–	93 (2.0)	–	–
C_F (%, dead or litter)	All	–	–	99	–	–

H, High rainfall zone; L, Low rainfall zone; EDS, Early Dry Season; LDS, Late Dry Season; C_F, Combustion Factor; T_F, Transfer Factor; BGB_C, coarse roots; BGB_F, fine roots.
[A]Woodland – High rainfall.
[B]Shrubland – High rainfall.
[C]Woodland – Low rainfall.
[D]Shrubland – Low rainfall.
[E]Pindan.
[F]Defaults taken from the NIR (Commonwealth of Australia 2022).
[G]Only average annual values provided. In FullCAM, turnover parameters for branch, bark and foliage varied monthly (see Fig. 3).
[H]Given decomposition of foliage litter was predicted using a two-phase exponential decomposition function, the given decomposition value was the decomposition rate for the fairly resistant component of foliage litter, with 23% of the foliage litter that was fairly decomposable having a decomposition rate with a half-life of 0.053 years.
[I]60% of these components are assumed to be coarse fuel, with 40% contributing to fine fuel.
[J]40% of these components are assumed to be coarse fuel, with 60% contributing to fine fuel.

(Yates *et al.* 2020). Therefore, monthly turnover parameters were also constrained by datasets on seasonality of turnover collated from 11 stands within the high-rainfall zone (Williams *et al.* 1997; Cook 2003; Cuff and Brocklehurst 2015; Yates *et al.* 2020), and in four stands within the low-rainfall zone (McIvor 2001; Cuff and Brocklehurst 2015; Yates *et al.* 2020). These datasets showed foliage litterfall was typically highest in the months May to September in high-rainfall zones (Fig. 4*b*), but slightly later (August to November) in low-rainfall zones (Fig. 4*c*). In contrast, there was large variability in the seasonality of branch and bark litterfall (relatively large error bars in Fig. 4*a* cf. Fig. 4*b*, *c*), probably because a majority of branch and bark litterfall tends to be associated with stochastic severe wet season storms (i.e. October to December) (Yates *et al.* 2020).

Although most of the grass curing in Australian savannas occurs in April and June (Meyer *et al.* 2012), it was beyond

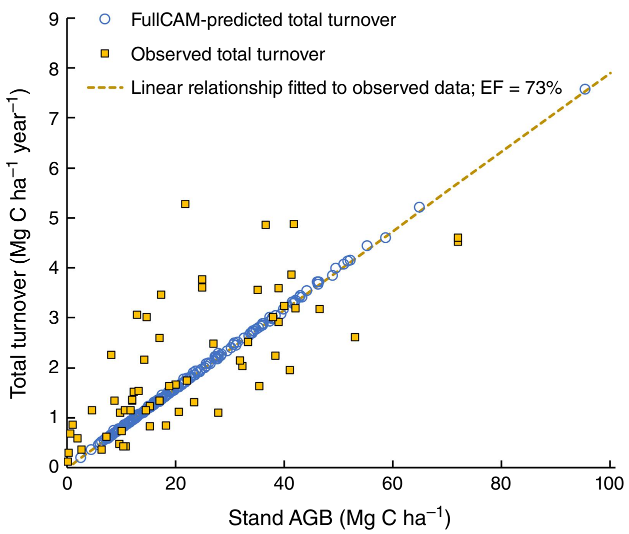

Fig. 3. FullCAM-predicted and observed relationships between total turnover (Mg C ha^{-1} year^{-1}) and the above-ground biomass carbon (AGB, Mg C ha^{-1}) of a stand. Source of observed data is given in Supplementary Table S12, but the observed litterfall data have been multiplied by a factor of 1.33 to account for additional turnover typically attributable to larger litter components not generally captured in traditional litter traps monitoring. FullCAM-predicted turnover and AGB are the average across years for which fire history data were available (1988–2018). EF, model efficiency.

the scope of the present study to collate datasets on seasonality of turnover of grass, with default monthly parameters and seasonality for grass die-back being applied (Fig. 4*d*, Commonwealth of Australia 2022). Similarly, default values were applied for turnover rates of grass roots (Commonwealth of Australia 2022).

Decomposition of different fuel types

FullCAM parameters for decomposition of standing dead (stags), deadwood debris (components of heavy and coarse fuels) and bark debris (also components of heavy and coarse fuels) were 8, 2 and 1 years, respectively (Table 2). The slower decomposition for larger standing dead cf. debris deadwood was attributable to the finding that decomposition rates appear to be functions of both the density and size of the deadwood (O'Connell 1997; Mackensen *et al.* 2003). Half-life of wood samples of 2.2–6.5 cm diameter ranged between 0.49 and 26.7 years over a 2-year period at a savanna stand in the high-rainfall zone (Cook *et al.* 2020). Similarly, studies from non-savanna regions of Australia indicate decomposition rates of eucalypt deadwood ranging from 8 to 15 cm diameter had a half-life that varies from 4 to 32 years (Brown *et al.* 1996; O'Connell 1997). In Australian savannas, attack from termites is another important factor influencing decomposition of deadwood (e.g. Dawes 2010), but was beyond the scope of the present study to explicitly consider, with termite impacts on decomposition assumed to be subsumed into the available observations of decomposition rates.

When considering the fine fuel decomposition rates in Australian savannas, observations were also varied. Dawes (2010) reported a half-life of between 0.58 and 1.61 years (average 0.79 years) for decomposing 'dry straw mulch', withdecomposition rates varying with the type of litter bag and whether or not termites were present. Studying a species of native grass, Rossiter-Rachor *et al.* (2017) reported a half-life of only 0.33 years. Cook (2003) reported a half-life of 0.866 years for decomposing savanna 'tree litter and grass' within litter bags. This value was applied to calibrate the decomposition parameter for the resistant fraction of foliage litter (Table 2). Relatively high rates of decomposition were assumed for the small proportion (23%) of foliage litter assumed to be highly decomposable (see footnote H in Table 2).

Combustion factors for heavy, coarse and fine fuel

Estimates of C_F for heavy fuel in high (or low) rainfall zones were 0.17 (or 0.07) and 0.31 (or 0.12) in EDS and LDS fires, respectively (Fensham 2005; Russell-Smith *et al.* 2009*a*; Yates *et al.* 2015). Previous workers have estimated that C_F for coarse fuel in high (and low) rainfall zones was 0.15 (or 0.11) and 0.36 (or 0.20) following EDS and LDS fire, respectively (Russell-Smith *et al.* 2009*a*; Yates *et al.* 2015). These workers also estimated C_F for fine fuel as 0.74–0.80 and 0.83–0.86 following EDS and LDS fire, respectively, with little differences between rainfall zones.

These C_F estimates provided a guide to constraining the FullCAM C_F parameters (Table 2) as they were estimates for pools as a whole, whereas FullCAM separately simulates different components of each of these broad categories (Fig. 1 and Supplementary Fig. S1). For example, 'fine fuel' in FullCAM includes foliage litter, grass foliage, grass litter and also twigs and bark litter of <0.6 cm diameter, with grass-based pools expected to have relatively high C_F compared with the other 'fine fuel' components because fire generally occurs when grasses are cured (senesced and dry, particularly in the high rainfall zone), with only the green base of the grass likely to remain unburnt (Meyer and Cook 2015).

Given the percentage of total fine fuel biomass that was attributable to foliage litter was predicted to be 63% ± 6% (average ± s.d.) (Supplementary Material C), it was ensured foliage litter C_F was within 5% of previous estimates for fine fuel, with branch and bark (or grass) components of fine fuel having a lower (or higher) C_F (Table 2). Similarly, given the percentage of total coarse fuel attributable to branch litter was predicted to be 80% ± 3% (average ± s.d.) (Supplementary Material C), it was ensured that C_F for branch litter was within 5% of previous estimates for coarse fuel, but with a higher C_F for bark litter applied (Table 2).

Model optimisation and testing

The highest model efficiency for prediction of AGB was found with mortality rates between 1.120 and 2.025% year^{-1}, total

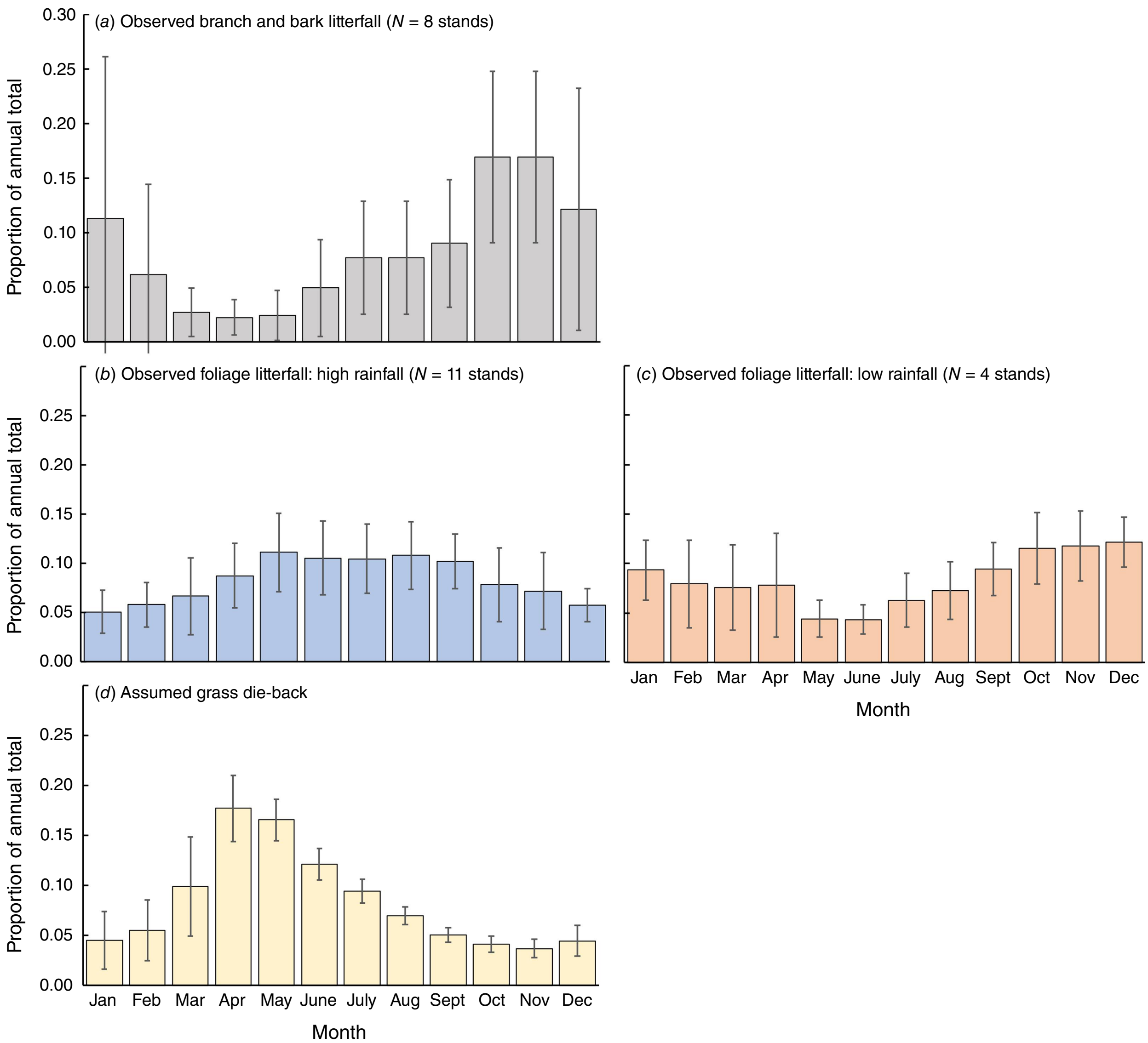

Fig. 4. Seasonal turnover (proportion of total annual turnover that occurs each month) for: (*a*) branch and bark litter as observed in either high or low rainfall zones; (*b*) foliage litter as observed in the high rainfall zone; (*c*) foliage litter as observed in the low rainfall zone, and (*d*) grass die-back as assumed in the FullCAM application in the NIR (Commonwealth of Australia 2022). Error bars represent the standard deviation across: (*a*–*c*) observations, or (*d*) years 1970–2018 in FullCAM inputs of monthly estimates of monsoonal perennial grass die-back. Source of data: Williams *et al.* (1997), McIvor (2001), Cook (2003), Cuff and Brocklehurst (2015), Yates *et al.* (2020), Commonwealth of Australia (2022).

fire impacts (= C_F + T_F) on AGB that were either very low or low for woodland or open forest vegetation types, but moderate to high for shrubland vegetation types, and T_F that varied between components of AGB, increasing in the order: stem, branch, bark and foliage (Table 3). Applying these calibrations gave model efficiencies of AGB prediction between 82 and 93%, demonstrating goodaccuracy (Fig. 5).

Consistent with Cook *et al.* (2020), mortality of AGB was higher in the vegetation from high cf. low rainfall zones (Table 3). Within the low rainfall zones, this non-fire related death rate was predicted to be higher in vegetation types dominated by relatively short-lived species (e.g. *Acacia* and *Grevillea*), consistent with calibrated mortality rates being higher in stands of Shrubland – Low rainfall (SL) and Pindan (PL) cf. Woodland – Low rainfall (WL).

When C_F and T_F parameters of AGB (Table 3) were applied in FullCAM, the model predicted that a total (= C_F + T_F) of between 0 and 25% of AGB is lost through either combustion or transfer to non-living pools, which was within the order of the 1–23% estimate for Australian savannas, albeit for fires of fairly high intensity (Cook *et al.* 2015*a*). Using Woodland – High rainfall (WH) calibration sites as a case study, it was demonstrated that the fire impact parameter values were appropriately optimised, as

Table 3. Calibrated parameters for mortality rates (defined as non-fire related death) for the different categories of savanna vegetation, assumed total impact of fire ($C_F + T_F$; C_F, combustion factor; T_F, transfer factor) on live pools of above-ground biomass (AGB), and the resulting calibrated parameters for C_F and T_F of AGB for different categories of vegetation by fire (EDS, Early Dry Season; LDS, Late Dry Season; subscripts 1, 2, 3 denote low, medium and high intensity wildfire, respectively). Different mortality, C_F, and T_F parameters were not required for the sub-categories of WH and WL vegetation types, and because there were no repeat measurements of AGB for PL vegetation types, C_F and T_F were assumed to be the same as that of SL for fire types of moderate intensities.

Vegetation category	Non-fire deaths (% year^{-1})	Fire impact level	Fire type	Total[H] impact (%)	C_F (and T_F), % impact on the live AGB pool			
					Stem	Branch	Bark	Leaf
WH[A]	2.025[F]	Low	EDS_1	0.00	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
			EDS_2	2.50	0.50 (2.00)	0.75 (1.75)	1.50 (1.00)	1.75 (0.75)
			EDS_3	5.00	1.00 (4.00)	1.50 (3.50)	3.00 (2.00)	3.50 (1.50)
			LDS_1	5.00	1.50 (3.50)	2.00 (3.00)	3.50 (1.50)	4.00 (1.00)
			LDS_2	10.0	3.00 (7.00)	4.00 (6.00)	7.00 (3.00)	8.00 (2.00)
			LDS_3	15.0	4.50 (10.5)	6.00 (9.00)	10.5 (4.50)	12.0 (3.00)
WL[B]	1.120[G]	Very low	EDS_1	0.00	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
			EDS_2	0.00	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
			EDS_3	2.50	0.25 (2.25)	0.50 (2.00)	1.50 (1.00)	1.75 (0.75)
			LDS_1	0.00	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
			LDS_2	5.00	0.55 (4.45)	1.50 (3.50)	3.50 (1.50)	4.00 (1.00)
			LDS_3	10.0	1.10 (8.90)	3.00 (7.00)	7.00 (3.00)	8.00 (2.00)
SH[C]	2.025[F]	High	EDS_1	5.00	1.00 (4.00)	1.50 (3.50)	3.00 (2.00)	3.50 (1.50)
			EDS_2	7.50	1.50 (6.00)	2.25 (5.25)	4.50 (3.00)	5.25 (2.25)
			EDS_3	10.0	2.00 (8.00)	3.00 (7.00)	6.00 (4.00)	7.00 (3.00)
			LDS_1	15.0	4.5 (10.5)	6.00 (9.00)	10.5 (4.50)	12.0 (3.00)
			LDS_2	20.0	6.00 (14.0)	8.00 (12.0)	14.0 (6.00)	16.0 (4.00)
			LDS_3	25.0	7.50 (17.5)	10.0 (15.0)	17.5 (7.50)	20.0 (5.00)
SL[D]	1.680[F]	Moderate	EDS_1	2.50	0.25 (2.25)	0.50 (2.00)	1.50 (1.00)	1.75 (7.50)
			EDS_2	5.00	0.50 (4.50)	1.00 (4.00)	3.00 (2.00)	3.50 (1.50)
			EDS_3	7.50	0.75 (6.75)	1.50 (6.00)	4.50 (3.00)	5.25 (2.25)
			LDS_1	10.0	1.10 (8.90)	3.00 (7.00)	7.00 (3.00)	8.00 (2.00)
			LDS_2	15.0	1.65 (13.4)	4.50 (10.5)	10.5 (4.50)	12.0 (3.00)
			LDS_3	20.0	2.20 (17.8)	6.00 (14.0)	14.0 (6.00)	16.0 (4.00)
PL[E]	1.680[F]	Moderate	EDS_2	5.00	0.50 (4.50)	1.00 (4.00)	3.00 (2.00)	3.50 (1.50)
			LDS_2	15.0	1.65 (13.4)	4.50 (10.5)	10.5 (4.50)	12.0 (3.00)

[A]Woodland – High rainfall.
[B]Shrubland – High rainfall.
[C]Woodland – Low rainfall.
[D]Shrubland – Low rainfall.
[E]Pindan.
[F]75% or [G]50% of the total annual mortality calculated by Cook *et al.* (2020).
[H]Total impact on live AGB pools is the sum of combustion factor (C_F) and transfer factor (T_F).

decreasing $C_F + T_F$ below the calibrated value resulted in an increasing positive bias in predicted AGB (Supplementary Fig. S15).

The relative sensitivity of different vegetation types to fire (Table 3) was generally consistent with the observed average proportion of total above-ground woody biomass that was heavy fuel (Fig. 6). There was evidence that the average proportion of total above-ground woody biomass that is heavy fuel was in turn related to the proportion of AGB that was attributable to fire-susceptible small trees and shrubs (Supplementary Material E). The relatively high total fire impact on AGB for Shrubland – High rainfall (SH) and

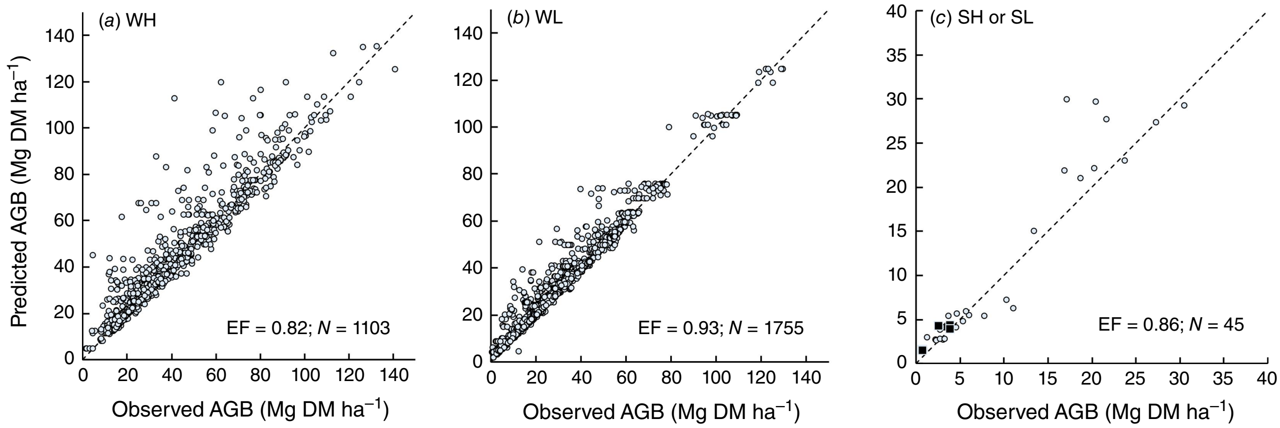

Fig. 5. Relationship between observed and predicted AGB that represented the woodland and open forest vegetation types in: (*a*) Woodland – high rainfall zones (WH); (*b*) Woodland – low rainfall zones (WL), and (*c*) shrubland vegetation types, either in high rainfall zones (circle symbols, SH) or low rainfall zones (square symbols, SL). Predictions of AGB were based on the fire intensity assumptions that provided the highest model efficiency (EF) (Table 3). Dashed line represents the one-to-one line. Axis units are Mg of dry mass (DM) per hectare.

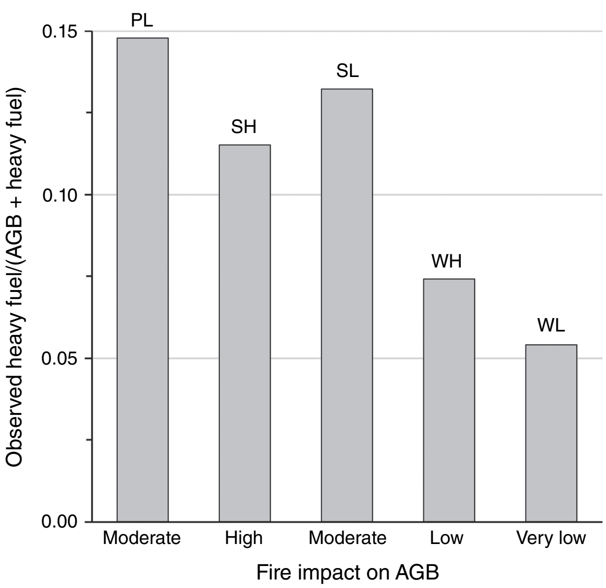

Fig. 6. Relationship between the relative impact of fire on above-ground biomass (AGB) (Table 3) and the observed proportion of total woody biomass that was heavy fuel (Fig. 7). WH, Woodland – High rainfall; SH, Shrubland – High rainfall; WL, Woodland – Low rainfall; SL, Shrubland – Low rainfall; PL, Pindan.

Pindan (PL) (and presumably also Shrubland – Low rainfall (SL)) vegetation was expected given they have a much greater proportion of shrubs or small multi-stemmed acacias (e.g. *Acacia*, *Calytrix*, etc.) compared with the other vegetation types (Supplementary Fig. S11). Shrubs have relatively small diameters, heights and bark thicknesses, which renders them more fire-sensitive than trees (Williams *et al.* 1999; Lawes *et al.* 2011; Bond *et al.* 2012). For example, in plots of SH vegetation, 94% of live stems had a stem diameter at 130cm height (D_{130}) < 20 cm cf. only 67–89% for other vegetation types (data not shown).

The calibrated total fire impact on AGB was higher for vegetation from high cf. low rainfall zones (Table 3), perhaps for two reasons. First, high rainfall zone vegetation had quite high proportions of stems that were relatively large. Across the calibration dataset (Fig. 5), the high rainfall zone vegetation category had 0.3–2.8% of live stems with D_{130} > 50 cm, whereas the percentage of stems of this size was ≤0.1% for the other categories of vegetation. Larger trees in Australian savannas are often fire-sensitive as they can burn from the inside when hollow owing to damage from termites or previous fire (Williams *et al.* 1999; Cook *et al.* 2005). Secondly, high rainfall zone vegetation has relatively high proportions of fire-sensitive non-eucalypt species relative to the less fire-sensitive eucalypt species (Bond *et al.* 2012). Although calibration sites used in the present study were not a random sample, across the calibration dataset, stands from high rainfall zones had relatively high proportions of the more fire-sensitive non-eucalypt trees such as *Callitris intratropica* (e.g. 16% of species found in $WH_{0.6}$) and *Erythrophleum chlorostachys* (e.g. 17% of species found in $WH_{0.3}$) (Supplementary Fig. S11).

The final test of model performance was the assessment of how well predicted pools of fuel matched those observed, with results again indicating model performance was good (Fig. 7). Moreover, with the calibrated parameters given in Table 3, FullCAM-predicted recovery (Supplementary Fig. S4) was consistent with observations (Russell-Smith *et al.* 2009*a*; Yates *et al.* 2015, 2020; Lynch *et al.* 2018), with increases in fuel with time since last burn being least pronounced with the coarser components (e.g. deadwood, Supplementary Fig. S17*a*) and most pronounced with the relatively fine components of litter (e.g. foliage litter, Supplementary Fig. S17*b*, *c*).

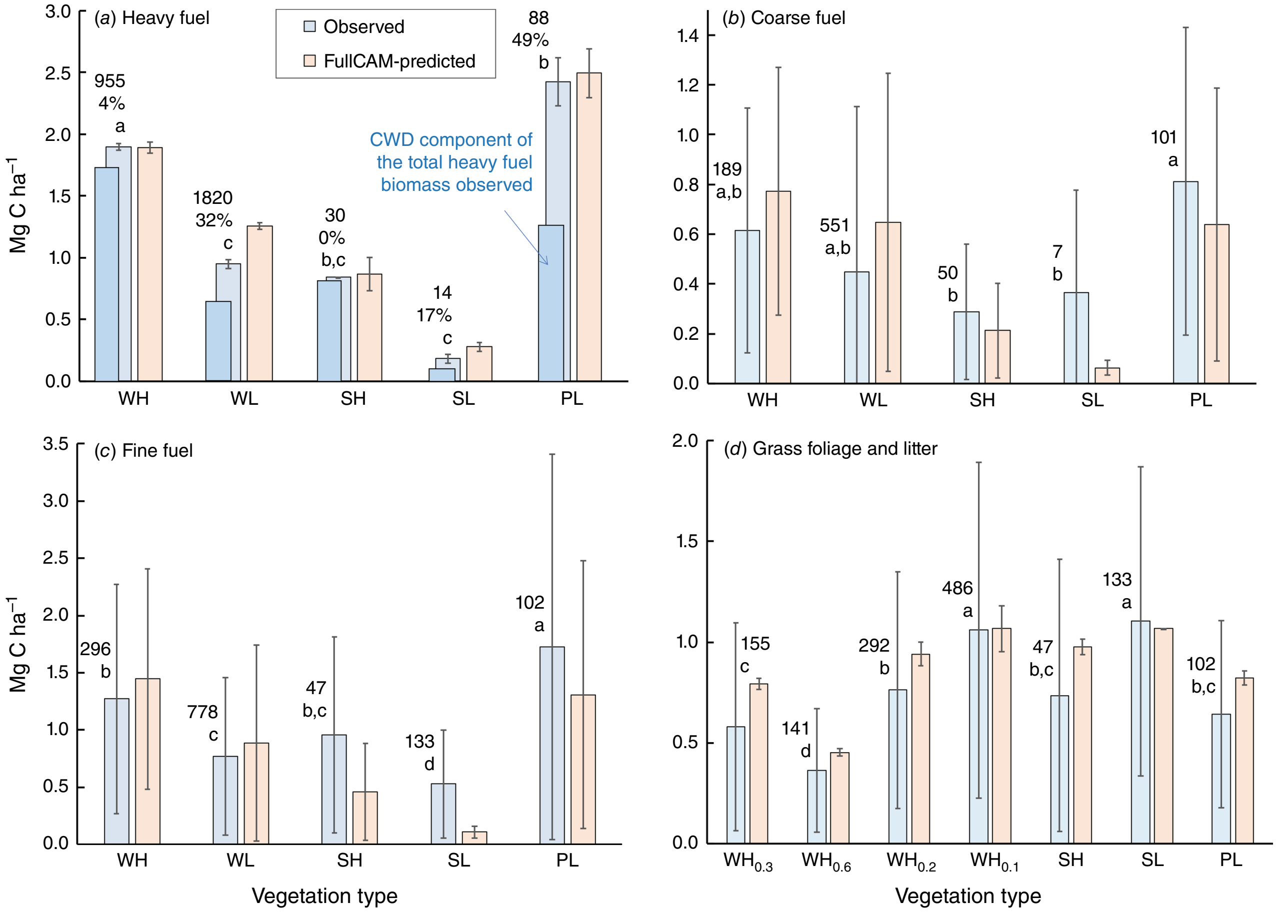

Fig. 7. Comparison between observed and predicted fuel biomass (in Mg C ha^{-1}) in: (*a*) heavy (stags and CWD), (*b*) coarse, (*c*) fine, and (*d*) grass pools, within differing categories of vegetation. Error bars represent standard errors. Numbers and percentages above the bar represent the sample size (*N*), and proportion of 'observed' heavy fuel calculated to be stags. Bars with the same letters were not statistically different according to the Tukey test at 95% confidence interval. Data source is provided in Supplementary Tables S4–S8. Vegetation type definitions are given in Table 1.

Scenarios of fire management: implications

Land managers can use planned EDS fires to reduce the frequency of high-intensity LDS fires and, to a lesser extent, overall fire frequencies (e.g. Russell-Smith *et al.* 2013). When such fire management scenarios were simulated with FullCAM using the calibrated parameters (Tables 2 and 3), on average across all vegetation types, 65% of total abatement (range 45–87%) was attributable to sequestration of CO_2-C, with the remainder being attributable to avoided emissions (Fig. 8). In regions of high (or low) rainfall, net abatement over a 25-year simulation period was between 0.06 and 0.43 (or 0.02 and 0.05) Mg CO_2-e ha^{-1} year^{-1} (Fig. 8). But even within a region, variation in this abatement was evident among vegetation types owing to differences in C_F of AGB (Table 3) and the productivities of the woody and grass components of the stand (i.e. *M* and grass cover).

The results from these analyses illustrate potential outcomes across a range of scenarios with differing baseline fire frequencies, and with assumed impacts of management reflected as changes in the relative frequencies of EDS and LDS fire. It is important to note these scenarios are hypothetical and are thus not validated, and do not relate to specific locations or situations. Cook *et al.* (2015*b*), using the individual-based FLAMES model, also investigated the impacts of changed fire management on total above-ground carbon stocks and rates of sequestration, with model parameters based on the 'Three Parks' monitoring study (Russell-Smith *et al.* 2009*b*). Although the simulations of Cook *et al.* (2015*b*) explored a greater range of fire frequencies and seasonal fire timings than those considered here, changes in carbon stocks and sequestration rates were broadly similar to our results in terms of both direction and magnitude.

Consistent with the other recent studies (Levick *et al.* 2019; Werner and Peacock 2019; Murphy *et al.* 2023), our results indicate that sequestration of carbon in live biomass is a key driver of abatement following savanna fire management, noting that predictions are highly sensitive to the assumed upper limit of AGB, or the *M* input layer.

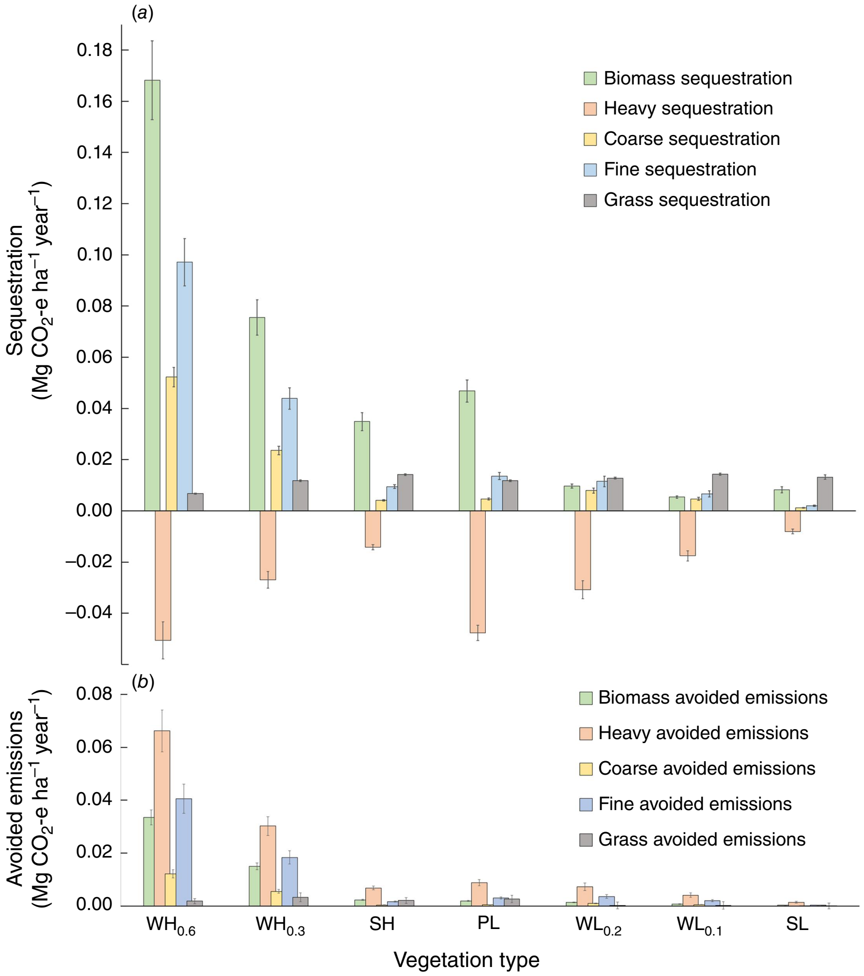

Fig. 8. Summary of the impact of changed fire regime (project compared with baseline) on annual average rates (over the 25-year baseline and project periods) of: (*a*) sequestration of CO_2-e and annual average rates (over the 25-year baseline- and project-periods) and (*b*) avoided fire-induced CO_2-e emissions, with these being attributable to five pools: total biomass of woody vegetation, namely above- and below-ground pools, heavy fuel, coarse fuel, fine fuel and grass fuel. Vegetation type definitions are given in Table 1.

Although verified for savanna vegetation (Supplementary Fig. S2), the *M* input layer remains a key source of uncertainty for any given stand, given *M* may be inaccurate depending on fine-scale spatial variability associated with position within the landscape, and hence, soil nutrients and depth (and thus, water holding capacity) (Supplementary Fig. S6). Also, not all categories of savanna vegetation were represented in the calibration of this input layer (e.g. Pindan). As outlined in Supplementary Material F, in addition to improving predictions of AGB, there are opportunities to collate additional datasets to further constrain calibration of model parameters that are currently highly uncertain owing to the paucity of available data, e.g. rates of decomposition of pools of standing dead and debris. Parameters that could not be constrained owing to negligible available data (mortality, C_F and T_F of AGB) were optimised in this study, and further work is required to verify these, and where required, constrain them to collected datasets.

As a result of this work, modelling capability has been developed to facilitate the development of a comprehensive methodology encompassing the impacts of different fire types on both avoided emissions and sequestration of carbon, thereby overcoming limitations of existing methods that only account for avoided emissions (Commonwealth of Australia 2015), only account for sequestration in dead (rather than also live) pools (Commonwealth of Australia 2018), or do not distinguish between effects of fires of different intensities (Voluntary Carbon Standard 2015). However, the scenario analysis (Fig. 8) provides only simplistic hypothetical results on abatement (both sequestration and avoided emissions) from implementation of savanna fire management. Work is currently under way to facilitate the spatial application of FullCAM at a project scale (as currently, spatial FullCAM application is limited to national-scale application via the NIR; Commonwealth of Australia 2022). This capacity will provide opportunities to work with project proponents to test FullCAM-predicted abatement implications of actual savanna fire management projects, and compare results with existing methodologies (Commonwealth of Australia 2015, 2018).

Conclusions

The compilation of vast amounts of field datasets for FullCAM calibrations undertaken here provides confidence in predicted dynamics of the composition and quantity of fuel pools in response to different types of savanna fires, resulting in substantially improved accuracy and capability of Australia's NIR (Commonwealth of Australia 2022), and hence, project-level accounting (Commonwealth of Australia 2015, 2018). The improved capability for accounting for AGB and fuel dynamics and the mosaic patterns associated with patchiness within observed fire scars has enabled biomass in these pools at the time of a fire event to be accurately estimated, thereby increasing the accuracy of emissions estimates. To further improve FullCAM and develop confidence in FullCAM predictions, it will be necessary to compare project-scale emissions derived under current and proposed methods and, over time, model-predicted sequestration with independently validated measurements. Opportunities for further progressing improvements in FullCAM-predicted fire emissions and sequestration of carbon in savanna ecosystems are outlined in Supplementary Material F.

Supplementary material

Supplementary material is available online.

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