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Pyrogenic carbon production in eucalypt forests under low to moderate fire severities

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ABSTRACT

Wildfires play an important role in the global carbon cycle, influencing both atmospheric carbon concentrations and terrestrial carbon storage. The production of pyrogenic carbon (PyC; the C-enriched product of incomplete combustion) is a globally significant buffering mechanism for fire-related carbon emissions. PyC production varies widely with vegetation fuel and fire characteristics, and data on the production rates for PyC for specific ecosystems, fuel components and fire severities remain scarce. This limits our understanding of the quantitative importance of PyC production, its role in the carbon budgets of fire-affected ecosystems, and our ability to modify planned fires towards maximizing this long-term carbon store. Eucalypt forests, which incur frequent wildfires and human-prescribed fires, provide an important context for understanding PyC dynamics. Here we quantify PyC production in experimental fires conducted with low- to moderate fire severities in three *Eucalyptus* forest types across southern Australia. This involved comprehensive pre and post-fire fuel inventories and quantifying all pyrogenic materials generated in eucalypt forest sites near Sydney, Melbourne, and Perth. We also estimate PyC conversion rates in the main fuel components: forest floor, understory, down wood, and overstory (comprising only tree bark as these surface fires did not affect the crowns). Our results show that, of all the carbon affected by the fire, 2.7 t C ha^{-1} (2.4 – 3.1 t C ha^{-1}) was transformed into PyC and 9.3 t C ha^{-1} (7.9 – 11.0 t C ha^{-1}) emitted to the atmosphere. This translates into an average pyrogenic carbon conversion rate of 23 % of carbon affected by fire, underscoring the relevance of PyC in carbon budgets from eucalypt forest fires. The conversion rates varied substantially among fuel components, with the bark exhibiting the highest conversion rate, at approximately 40 %, and the down wood component displaying the lowest rate at around 15 %. Intermediate conversion values were found for forest floor and understory components (20 % and 31 %, respectively). Our findings highlight the critical importance of bark in PyC production in low to moderate fires, an aspect frequently overlooked in general inventories. Given the high fire recurrence in eucalypt forests in Australia, both naturally and under human-prescribed conditions, and the expansion of eucalypt plantations in many regions around the world, our findings are relevant for fire-related carbon budget estimations at both regional and global levels and can inform the optimization of prescribed burning for reducing carbon emissions.

1. Introduction

Vegetation fires burn around 774 million hectares globally per year (Chen et al., 2023), emitting ~2.1 Pg of carbon into the atmosphere (van Wees et al., 2022). Over the longer term (i.e. decades), however, vegetation fires in fire adapted ecosystems (excluding e.g. deforestation and

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peatland fires) are widely considered as 'net zero carbon emission events' because carbon emissions from fires are normally balanced by carbon uptake by regenerating vegetation (Bowman et al., 2009; van der Werf et al., 2010). However, this zero carbon emission scenario is potentially flawed, as it does not consider the role of pyrogenic carbon as a globally significant buffering mechanism for fire-related carbon emissions (Jones et al., 2019).

During wildland fires, a fraction of the organic carbon contained in the burning vegetation and soils is not emitted into the atmosphere as gases or aerosols but transformed into pyrogenic organic matter, commonly known as pyrogenic carbon (PyC). PyC is enriched in carbon compared to its unburnt precursors and it has an overall enhanced resistance to environmental degradation, which makes it a potentially important long-term carbon store (Coppola et al., 2022). It is, however, important to recognize that PyC comprises a range of organic materials, with some of them being susceptible to bio- or photodegradation at relatively short temporal scales (Bostick et al., 2021).

The importance of PyC in the carbon cycle is increasingly recognized, but data on the production rates for PyC for specific ecosystems, fuel components and fire severities remain scarce. This limits our understanding of the quantitative importance of PyC production, its role in the carbon budgets of fire-affected ecosystems, and our ability to inform planned fires towards maximizing the PyC production and thus long-term carbon store. Its exclusion in models can lead to substantial inaccuracies in estimations of carbon fluxes and storage (Bowring et al., 2022; Santin et al., 2020; Wei et al., 2018).

Globally, fires are estimated to produce 128 ± 84 Tg of PyC per year, with varying overall production rates across regions (Jones et al., 2019). Previous studies have reported conversion rates of fire-affected carbon to PyC that range from 27 % in boreal forests (Santín et al., 2015), 16 % in savannas (Saiz et al., 2014), and 2.7 % in mixed-conifer forests in California (Miesel et al., 2018). For a given ecosystem, PyC production rates are primarily governed by fire characteristics and fuel properties. The specific characteristics of a given fire event determine the quantity of fuel consumed, the PyC produced and the immediate impact on landscape carbon stocks and fluxes (DeLuca et al., 2020; Jenkins et al., 2016; Miesel et al., 2018). Factors related to burning conditions, such as fire intensity, residence time and oxygen availability, ultimately determine PyC production (Michelotti and Miesel, 2015; Santín et al., 2017, 2016). Low severity fires are generally considered to be associated with lower combustion completeness and consequently higher relative PyC production per affected fuel, in contrast to higher severity fires that usually translate into greater fuel consumption completeness and greater carbon mass losses (Doerr et al., 2018; Maestrini et al., 2017; Miesel et al., 2018). This general pattern, however, may not always be applicable. For example, in wildfires in mixed-conifer forests in California, Maestrini et al. (2017) did not find differences in PyC production between different fire severity classes. They did find that PyC was distributed differently among fuel components, with the highest PyC values produced in high-severity fires for coarse woody debris and standing trees and the lowest for the forest floor.

Both extrinsic fuel properties, such as spatial arrangement and loads (Brewer et al., 2013; Price et al., 2022), and intrinsic properties like the chemical composition and density of fuels, affect PyC production (Hollis et al., 2011). For instance, coarser woody fuels generally yield more PyC compared to fine non-woody fuels (Jones et al., 2019; Santín et al., 2015). This is primarily due to their lower surface area to volume ratio, which limits access to oxygen, and their higher lignin content (Czimczik et al., 2003, 2002), limiting combustion completeness.

Accurate quantification of PyC production is needed to include wildfire PyC into carbon budget and flux models (DeLuca et al., 2020; Santín et al., 2016). Inventories targeting regions and ecosystems with high fire activity are of particular interest. A notable example is the temperate region of southern Australia, dominated by eucalypt forests with substantial fuel stocks that burn frequently (with typical fire intervals of 5–20 years, up to 100 years in tall forests) (Murphy et al., 2013). Fires have historically affected around 2 % of this region annually, but extreme conditions such as the ones experienced during the 2019–2020 'Black Summer' resulted in an unprecedented 23 % of temperate broadleaf and mixed forests being burned (Boer et al., 2020; Bowman et al., 2021). Large fire events are becoming more frequent under a warming climate (Abram et al., 2021; Cunningham et al., 2024). The increasing fire frequency in eucalypt forests (Fairman et al., 2016), combined with strong human influences on fire regimes (fire suppression and prescribed fires), influence the rate and completeness at which fuels burn, contributing to uncertainties in PyC production. Prescribed fires, estimated to annually burn 3071 ± 732 km^2 at low severity in south-eastern Australia alone (Canadell et al., 2021), have been examined in several PyC production inventories (Aponte et al., 2014; Bennett et al., 2017; Jenkins et al., 2016; Krishnaraj et al., 2016; Volkova and Weston, 2013). The PyC conversion rates reported in these studies vary substantially, ranging from 12.5 % in Jenkins et al. (2016), to 3.1 % in Krishnaraj et al. (2016), and 0.76 % in Aponte et al. (2014) (based on conversion rates extracted from the database in Jones et al. 2019).

In addition to their natural prevalence in Australian forests, eucalypts are among the most widely planted trees globally, covering extensive areas worldwide (approximately 22.3 Mha; Zhang and Wang, 2021). Eucalypt plantations are expanding in many regions (Hirsch et al., 2020; López-Sánchez et al., 2021). Given their high susceptibility to wildfires, quantifying PyC production rates in eucalyptus forests could have significant implications for global PyC estimations.

In this study, we conducted comprehensive pre- and post-fire inventories of all forest fuels and quantified all pyrogenic materials generated in three representative dry eucalypt forests across Australia, burned by low- to moderate-severity experimental fires. These severities represent conditions commonly experienced in prescribed fires and some surface wildfires in native eucalypt forests in Australia. The study sites included two mixed-species eucalypt forests in the temperate south, Warragamba (near Sydney) and Britannia (near Melbourne), and a jarrah forest in western Australia, Yackelup (near Perth). Our aims were to (i) quantify PyC conversion rates across different eucalypt forests subjected to low-moderate fire severities, (ii) explore differences in PyC production among fuel components, including the forest floor, understory, downed wood, and bark, and (iii) assess the potential links between PyC production in these fuel components and specific fuel characteristics.

2. Materials and methods

2.1. Study sites and experimental fires

The research was conducted in three eucalypt forests in Australia subjected to experimental fires. These fires, reaching low to moderate fire severities, were designed to simulate prescribed fires and moderate severity wildfires. Site and fire characteristics are described below, summarized in Table 1, and illustrated in Fig. 1. The fire severity classification follows that developed by Chafer et al. (2004) for SE-Australian eucalypt forest: low severity, when only ground fuels and the lowest shrubs are burned; moderate severity, when all ground and shrub vegetation consumed by fire; and high to extreme severities when the tree canopy is affected.

'**Warragamba**', west of Sydney, SE Australia. The climate is humid temperate, with moist summers and cool winters and annual rainfall of 900–1000 mm. Soils are characterized by a thin upper organic-mineral layer of 0.5–1.5 cm, covered by a litter layer of approximately 6 cm in depth. The tree types are mainly ironbark (*Eucalyptus fibrosa*), stringybarks (*Eucalyptus eugenioides, Eucalyptus oblonga*), and with some scribbly gum (*Eucalyptus sclerophylla*). The understory comprises *Banksia sp., Leptospernum sp., Acacia sp.* and *Petrophile sp.*

The fire (September 23, 2014) resulted in a predominantly moderate burn severity across the 21 ha burned area, although some sampling points within the experimental plot experienced high burn severity.

Table 1
Characteristics of sites and experimental fires. Fire severity classification according to Chafer et al. (2004).

	Site characteristics			Fire characteristics					
Site name	Location	Forest type & dominant species	Tree density (tree ha^{-1})	Fire severity	Air temperature (°C)	Relative humidity (%)	Wind speed (m s^{-1})	Litter moisture (%)	Previous burn year
Warragamba (23–09–2014)	SE Australia W of Sydney, 33° 52´16″ S 150° 36′ 04″ E	Humid temperate. *E. fibrosa* (ironbark), *E. eugenioides* and *E. oblonga* (stringybark), *E. sclerophylla* (scribbly gum)	300	Moderate	20	50	< 0.4	9.1	2001 (some charred bark remaining)
Britannia (18–04–2016)	SE Australia, E of Melbourne 37° 47´36″ S 145° 39′ 27″ E	Temperate. *E. sieberi* (silver-top ash), *E. radiata* (narrow-leaved peppermint), *E. baxteri* (brown stringybark)	800	Low	26	49	1	10	2009 (no sign of charred bark)
Yackelup (4–04–2017)	SW Australia, S of Perth 34° 11´36″ S 116 ° 32′ 11″ E	Mediterranean. *E. marginata* (jarrah), *C. calophylla* (marri)	867	Low to moderate	24	52	0.8	10.2	2000 (negligible char remaining)

Fig. 1. Photographs of each of the three experimental fire sites, during the fire (upper row) and immediately after the fire (lower row).

Most ground and understory fuels were consumed while the canopy remained largely unaffected (Fig. 1). The last wildfire affecting this site occurred in 2001 and was of high severity with some charred bark still present on numerous trees at the time of the experimental fire, but without any visible trace of charring on down wood or litter.

Wesburn '**Britannia**', east of Melbourne, SE Australia. The climate is temperate, with an average annual precipitation of 1143 mm. The soil here exhibits a thin upper organic-mineral layer, covered by a litter layer of around 3 cm depth with some grass cover. The forest is predominantly composed of silver-top ash (*Eucalyptus sieberi*), narrow-leaved peppermint (*Eucalyptus radiata*), and brown stringybark (*Eucalyptus baxteri*) trees. The understory dominants were prickly bush pea (*Pultenaea juniperiana*), bracken fern (*Pteridium esculentum*) and tussock grasses.

The area was subjected to a low intensity prescribed fire (268 ha), but the study site was burnt at somewhat higher intensity for experimental purposes (April 18, 2016). The severity of the experimental fire was nevertheless low; the litter layer was not completely consumed, and the upper organic-mineral horizon remained unaffected (Fig. 1). The tree canopy was also unaffected. The most recent prescribed fire in 2009 did not leave signs of charred bark or down wood by the time of the experimental fire.

'**Yackelup**', east of Manjimup and south of Perth, SW Australia. The climate here is Mediterranean, with an annual average precipitation of 981 mm. The soil is characterized by a patchy thin upper organic-mineral layer of 0.5–1 cm, with a litter layer of 1.5–2 cm depth. The forest is a typical 'jarrah' forest of south-west Australia, dominated by jarrah (*Eucalyptus marginata*) with occasional marri (*Corymbia calophylla*) trees. The understory vegetation was sparse and short (<1 m), with *Bossieae ornata, Leucopogon propinqus, Hakea lissocarpha, Boronia viminea*, and *Hibbertia amplexicaulis*.

The experimental fire (April 4, 2017) resulted in the complete combustion of the litter layer and the sparse understory, classified as low to moderate severity across the 0.3 ha burned area (Fig. 1). Negligible signs of charred bark remained from a previous prescribed fire in 2000.

2.2. *Experimental design and sampling*

An experimental plot was chosen at each of the three sites to represent relatively homogeneous areas in terms of terrain, fuel load and forest structure. Prior to the fires, three parallel transects of 30 m length were established in line with the anticipated fire propagation. The distance between each transect was 30 m at Warragamba, and 15 m at Britannia and Yackelup, based on the availability of homogeneous terrain and fuel distribution. Along each transect, sampling points were established at intervals of 3 m, resulting in a total of 30 points (3 ×10) along the transects. In addition, two parallel 'control' transects were established between the three experimental transects. The experimental plots were always located some distance from the perimeter of the fire (at least 10 m away in Yackelup, the smallest fire) to avoid edge effects.

Before each fire, a detailed inventory of all fuel components expected to be affected by fires was conducted following the procedure described in Santín et al. (2015). The inventory included (a) the forest floor, comprising the combination of the litter layer and the upper organo-mineral soil layer, (b) down wood, (c) understory and (d) overstory. The overstory component only comprised the bark of the standing trees as the canopy fuels were not affected by these fires. After each fire, the inventory of fuels was repeated, categorizing the remaining materials into uncharred and charred (i.e. blackened) fuels. Pyrogenic organic matter was identified as the whole range of blackened fuel materials remaining *in-situ* immediately after the fire (Santín et al., 2015). These pyrogenic organic components included ash, charcoal fragments, and charred parts in woody materials such as down dead wood or standing bark. Fig. 2 shows pre-fire and post-fire details of measurements for each component. It is worth noting that the pyrogenic matter emitted as aerosols and transported off-site was not considered in this study; this fraction, however, accounts only for a very small proportion of all PyC produced during a fire (<5 %, Santín et al., 2016).

2.2.1. Forest Floor

This fuel component comprised the litter layer and the upper organo-mineral horizon of the soil, encompassing elements such as leaves, bark fragments, charcoal pieces, or small twigs measuring less than 5 mm in diameter. Woody materials exceeding 5 mm in diameter were accounted for in the down wood inventory. We observed no effect of any of the experimental fires on the mineral soil beneath the organo-mineral horizon, which was thus excluded from further consideration in this study.

Before each fire, the forest floor was destructively sampled every 3 m along each of the control transects utilizing a 20 × 20 cm sampling square (n = 20) (Fig. 2a). At each point, the entire layers of litter and organo-mineral horizon were collected separately, and the depth of each layer was recorded at each of the four corners of the sampling square. At the Yackelup site, the mass of gravel was discounted from the total organo-mineral soil mass due to its notable proportion in some of the samples here (comprising 20 % of mass content on average).

After the fire, a similar procedure was employed to sample the charred (i.e. ash) layer and the uncharred layer underneath. This was also done using a 20 × 20 cm sampling square at 10 points along each of the three transects (n = 30) (Fig. 2b). At Warragamba and Yackelup all the forest floor components were fully affected by fire (i.e. no unburnt litter layer left), so the resultant "ash layer" was meticulously collected and accounted for in the PyC stock. At Britannia, the litter layer only partially burned, while the organo-mineral layer remained unaffected. Therefore, the charred (ash) and uncharred materials from the litter layer were sampled separately here.

The collected charred layer (ash) also includes input materials from the burning of aboveground vegetation (Bodí et al., 2014). To provide some estimate of the quantity of this input, particle traps were used to capture aboveground contributions during the fire events (Forbes et al., 2006). Thus, aluminum trays (30 ×20 cm) filled with water were positioned along the experimental plot at the ground level (their number ranging between 21 and 30 trays per site). After the fire, the contents were collected, separated into charred and uncharred materials, and respective materials from each tray combined to generate one composite sample per transect. This input of aboveground material, assumed to originate completely from understory biomass given that tree canopy remined unaffected at all sites, was then discounted from the post-fire forest floor component.

2.2.2. Understory

Understory vegetation comprised grasses, all shrubs, suspended

Fig. 2. Field sampling and measurements: a. sampling of pre-fire litter; b. sampling of ashes; c. quantification of down wood with the line intercept method before the fire; d. production of charcoal from a large down wood piece at Yackelup; e. nail used to re-locate tree circumference measurement; f. measurement of post-fire tree circumference.

fuels, trees with heights below 1.3 m, tree stumps, and grasses. Fuel loads were categorized based on a visual rank system for biomass density (Gould et al., 2011), ranks spanning low-, medium-, high-, and very high density. The understory biomass was destructively harvested before the fire within 1 × 1 m squares at every sampling point along an additional 30 m control transect outside of and perpendicular to the experimental plot, to avoid affecting fire behavior within the plot. The collected components were then classified according to two diameters classes, < 1 cm represented by leaves and thin twigs and > 1 cm by thicker branches (0.5 cm in the case of Yackelup), and weighed separately for each 1 × 1 m plot to determine their mass.

The fuel class ranking system, tailored specifically for each site, was used to non-destructively estimate the pre-fire understory fuel loads at each site along the experimental transects, using 1 × 1 m squares (n = 30). After the fire, the remaining standing fuels in these 1 × 1 m plots, were destructively sampled and categorized by diameter classes. At Warragamba, the PyC produced from the understory was quantified using the charred content collected in the particle traps described in the previous section. However, at Britannia and Yackelup, the PyC produced and collected in the traps was too low to be accurately determined. In Britannia, this was likely due to the understory being only slightly charred, with only very fine fuels having been consumed, and at Yackelup due to the lack of significant understory fuel before the fire. Hence, the particle trap data was only used at Warragamba to estimate PyC production from understory vegetation, whereas for Britannia and Yackelup, PyC production from understory was considered negligible and what may have been produced was accounted for within forest floor PyC.

2.2.3. Down wood

Down wood comprised dead twigs, limbs, branches, and logs on the ground with a diameter > 0.5 cm as per Alexander et al. (2004). The line intersection method (LIM) was used to calculate down wood mass and C loads (t ha^{-1}) (Van Wagner, 1982), which involved quantifying the contribution of each individual piece of down wood intercepting the three experimental transects (totaling 90 m per site) (Fig. 2c). For each piece, the diameter was measured, and the degree of decay was recorded, categorized as either as sound, rotten, or half-rotten.

The overall down wood load was determined as the sum of the individual contribution of each piece that intercepted the transect, using the following equation (Van Wagner, 1982):

$$W = \frac{\pi^2 G\sec(h)D^2}{8L}$$

W = down wood loads (t ha^{-1}), G = specific gravity (g cm^{-3}), h = tilt angle from the ground (degrees), D = diameter measured (cm), and L = length of transects (i.e. total length 90 m here). The tilt angle (h) was assumed 10º when the piece was noted as elevated. Specific gravity was adjusted based on the degree of decay of each individual piece (sound, half-rotten, and rotten). For Warragamba and Britannia, we used specific gravity values published by Aponte et al. (2014), given they were based on comparable eucalypt forest types in southeastern Australia. They were: 0.464 g cm^{-3} for sound pieces and 0.352 g cm^{-3} for rotten, and a median value of 0.408 g cm^{-3} for half-rotten pieces. For Yackelup, given the relatively high wood density of the dominant jarrah and marri species there, we measured wood density by water displacement in the laboratory for samples we took, with values for sound (0.670 g cm^{-3}), half-rotten (0.620 g cm^{-3}), and rotten (0.532 g cm^{-3}).

After the fire, the LIM was repeated in exactly the same places. For each down wood piece, the diameter and the charring depth at opposing sides were measured, from which an average charring depth was derived per piece. For each piece, the total charred material mass was calculated as the difference between the total estimated load of the piece and the unburnt mass remaining after charring. Charred mass values were multiplied by a conservative correction factor of 0.4 to adjust for mass loss from the wood associated with charring (Donato et al., 2009).

At Yackelup, a considerable number of large down wood pieces (>7 cm diameter up to 45 cm, with an average diameter of 10.7 cm) were found to be distributed across the experimental plot, as typically documented for jarrah forests due to the slow decay rates and high persistence of jarrah wood (Whitford and McCaw, 2019). While most of these big pieces remain unaffected by fire, those that are affected can initiate a smoldering process that can last for days and may result in partial or complete combustion of the wood piece. When this happens, parts of the wood piece are completely combusted and therefore transformed into mineral residues, while parts are converted into woody charcoal (Fig. 2d). Given their substantial contribution in mass and potentially PyC production at this site, the large down wood pieces were measured separately (n = 52). This additional analysis included mapping all the large down wood pieces and measuring their pre-fire diameters (considering both maximum and minimum diameter when asymmetrical) and lengths. After the fire, each piece was identified again, and the percentage of wood affected by the fire was visually estimated and the produced charcoal was weighed. For calculations, a cylindrical shape was assumed, and the specific gravity values applied as either sound, rotten or half-rotten.

2.2.4. Overstory: bark

The overstory component comprised small (< 10 cm diameter at breast height; DBH) and large trees (> 10 cm at DBH). Tree density was determined by counting the number of trees present within each experimental plot. The three experimental fires had minimal impact on small trees, resulting in only slight scorching, but no significant charring, and thus considered irrelevant in the PyC inventories. For large trees, charring was exclusively observed on bark (Fig. 2f) and canopies remained unaffected. Therefore, the primary source of PyC production within the overstory component was the bark.

Bark loss during fire and the quantification of PyC produced on tree bark were estimated by focusing on the surface area of bark affected by the fire. Before the fire, tree circumference was measured at breast height with a tape measure. Nails were placed at the north, east, south, and west points in the tree just below the tape to allow exact relocation of the measurement position after the fire (Fig. 2e & f). Bark thickness was measured at four points close to the nails using the sharpened pin end of a caliper. In addition, the tree species and its condition (live or dead) was recorded. After the fire, we recorded the height up to which charring occurred, the proportion (%) of bark surface that was charred, and the depth of charring, measured at four points close to the nails with a caliper. Bark loss and charred bark volumes were calculated considering bark thickness, depth of charring, surface area charred (based on height of charring, tree circumference and % area charred). PyC production was further explored according to the type of bark found at the sites—stringybark, ironbark, and scribbly gum —due to their differing response to burning. Given that at Warragamba charring from the previous 2001 fire was still present before our burn for most trees, this allowed calculation of re-combustion of previous PyC. We estimated pre-fire char loads in bark here based on the same method applied post-fire. Charred and uncharred bark mass per tree before and after the fire was calculated as the product of the respective bark volume and the bark density. Density estimates for charred bark (0.150 g cm^{-3}) and uncharred bark (0.271 g cm^{-3}) were based on laboratory measurements made on samples taken at Warragamba. Finally, estimations of the total pre- and postfire- uncharred bark and charred (PyC) bark loads (t ha^{-1}) were derived by extrapolating the sums of the loads derived per tree to the tree density per ha.

The following assumptions and simplifications were made in our estimations: bark and char depths at DBH points, as well as circumference at breast height were taken as being representative of the trees up to their charred heights. This was considered reasonable given the relatively uniform shape of trees up to the maximum charring heights. Similar to the canopy fuels, bark loads above the maximum charring height of each tree were not considered given they were not for part of the fuel loads in the burns examined here. In addition, trees fallen during or immediately after the fire were not considered in the total post-fire PyC quantification.

2.3. Quantification of C stocks in fuels

For each fuel component, we calculated the mass and carbon loads (t ha^{-1}) present in both uncharred and charred materials before and after the fire. Then, we calculated the "carbon affected by the fire" (CA) as the sum of the C converted into pyrogenic carbon (PyC) + the C lost (interpreted as emissions to the atmosphere and calculated as the difference between the C in pre-fire fuel minus the C in the uncharred post-fire fuel plus the PyC) (Santin et al., 2015). The conversion rate of carbon affected by the fire and transformed into pyrogenic carbon was also determined as the proportion of PyC produced from the carbon affected (PyC/CA).

These calculations were based on either the direct quantification of fuel mass consumed and PyC produced, or estimations based on alterations in the volume of woody and bark materials pre- and post-fire, and using the dry mass and the carbon content determined for each of these components. The carbon content in post-fire uncharred fuels was assumed to be the same as in pre-fire fuels (see Table 2). For the analysis, representative samples of charred and uncharred fuels collected during the pre-fire and post-fire inventories were oven-dried at 65°C until constant weight and analyzed for total carbon content by combustion analysis (ANCA GSL elemental analyzer interfaced with a Sercon 20/20 mass spectrometer). The presence of inorganic carbonates was tested using hydrochloric acid. No reaction was found for any samples, confirming the absence of inorganic carbon.

2.4. Statistical analyses

All statistical analyses were conducted using R v.4.3.0 (R Core Team, 2023). Kendall correlations were employed to examine the relationships between PyC production, diameter, and charring depth of down wood pieces. Given the non-normal distribution of the data, a Kruskal-Wallis test ($p < 0.05$) was subsequently performed to investigate significant differences among sites in terms of charring depth, post-fire diameters, and PyC produced in each piece.

For the analysis of bark data, a perMANOVA test (999 permutations) was used to determine whether tree bark response to fire differed among sites and bark types. Then, the Kruskal-Wallis test ($p < 0.05$, with effect size checked) followed by pairwise comparisons was employed to identify significant differences among sites for PyC production, pre-fire bark depth, char height, and char depth in the bark, distinguishing between different types of bark. Additionally, differences in old and new PyC production in bark in Warragamba were evaluated by distinguishing between bark types before and after the fire using the same statistical approach.

3. Results

The average total PyC production for the three eucalypt forest burns was 2.7 t C ha^{-1} (Table 3). Britannia exhibited the highest PyC production with 3.1 t C ha^{-1}, followed by Yackelup and Warragamba, which showed similar values of 2.4 and 2.6 t C ha^{-1}, respectively. Carbon loss to the atmosphere averaged 9.4 t C ha^{-1} across the three burns, with Warragamba recording the highest loss (11 t C ha^{-1}) followed by Britannia (9.2 t C ha^{-1}) and Yackelup (7.9 t C ha^{-1}). Based on these values, the average PyC conversion rate of the fire-affected carbon (PyC/CA) was 22.6 %, with a range from 19.3 % to 25 %.

When comparing forest components, the forest floor consistently showed the highest absolute PyC production (1.1–1.9 t C ha^{-1}) and C loss (4.4–8 t C ha^{-1}) values across all cases. The bark component showed, however, the highest PyC conversion rates among all components at the three sites (33–53 %). For a complete breakdown of pre-fire and post-fire mass and C loads of all components see SI, Table S1.

An overview of fuel C stocks and PyC produced for each fuel component at the three study sites is given in Fig. 3. The effect of the fires on C stocks as well as on PyC production are described for each fuel component in separate sections below.

3.1. Forest floor

The highest pre-fire C load was recorded at Britannia (11.09 t C ha^{-1}), and most of it was not affected by the low-severity fire, with only part of the surface litter burnt. In contrast, at Warragamba and Yackelup, the entire litter and the organo-mineral soil horizon were consumed. In absolute terms, Warragamba had the lowest PyC production (1.14 t C ha^{-1}), while Yackelup showed the highest (1.91 t C ha^{-1}). The highest absolute C loss from the forest floor was observed at Warragamba (7.95 t C ha^{-1}). These values at Warragamba resulted in the lowest PyC conversion rate (12.6 %). Britannia, with intermediate values of PyC production (1.36 t C ha^{-1}) and the lowest C loss, exhibited the highest PyC production rate at 23.7 %.

3.2. Understory

Understory C loads differed substantially among the sites. Warragamba had the highest pre-fire C loads (2.35 t C ha^{-1}), compared to Britannia (0.61 t C ha^{-1}) and Yackelup (0.24 t C ha^{-1}). The substantial C load at Warragamba resulted in high absolute PyC production (0.67 t C ha^{-1}) and C loss to the atmosphere (1.49 t C ha^{-1}), and a PyC conversion rate of 31.1 %. Conversely, the low pre-fire understory C

Table 2
Average and standard deviation carbon concentration (%) in pre-fire and post-fire fuels for samples from each site. Number of samples in brackets. Pre-charred denotes material (bark) charred in a previous fire at Warragamba in 2001.

			Forest floor			Understory	Down wood	Bark
			Litter	Organo-min. horizon	Particle traps			
Warragamba	Before fire	not charred	48.8 ± 0.3(3)	15.3 ± 4.7(9)		47.6 ± 0.7(5)	46.0 ± 0.2(3)	46.7 ± 0.1(3)
		pre-charred						64.2 (1)
	After fire	not charred			47.6 ± 0.7(5)			
		charred	28.7 ± 11.1(23)		72.8 ± 3.0(5)	71.2 ± 3.9 (6)	71.2 ± 3.9(6)	62.3 ± 1.7(6)
Britannia	Before fire	not charred	46.2 ± 0.6(3)	31.5 ± 1.8(3)		45.4 ± 0.3(3)	45.4 (1)	47.3 ± 0.9(3)
		pre-charred						
	After fire	not charred	33.5 ± 5.5(3)		45.4 ± 0.3(3)			
		charred	40.1 ± 9.4(6)		63.4 ± 3.7(3)	72.5 (1)	72.5 (1)	62.6 ± 4.6(3)
Yackelup	Before fire	not charred	47.9 ± 3.9(4)	34.8 ± 3.0(4)		46.4 ± 0.1(2)	46.3 (1)	47.7 ± 0.4(2)
		pre-charred						
	After fire	not charred			46.4 ± 0.1(2)			
		charred	39.4 ± 8.4(6)		64.1 ± 2.9(3)	71.8(1)	71.8/78.6 ± 2.3(6)*	66.2 ± 2.6(4)

* 71.8 % is the C concentration in char, 78.6 % is the C concentration of charcoal in large down wood pieces at Yackelup.

Table 3
Pre-fire and post-fire C loads of all components of the three sites. PyC/CA is the conversion rate of C of fire-affected fuel (sum of PyC and C lost to the atmosphere) to PyC. The total represents the sum values of all components, and the calculation of PyC/CA with the final values.

		Pre-fire		Post-fire			
		Uncharred C ($t\ C\ ha^{-1}$)	PyC ($t\ C\ ha^{-1}$)	Uncharred C ($t\ C\ ha^{-1}$)	PyC ($t\ C\ ha^{-1}$)	C lost ($t\ C\ ha^{-1}$)	PyC/CA (%)
Warragamba	Forest floor	9.10		0.00	1.14	7.95	12.56
	Understory	2.35		0.19	0.67	1.49	31.09
	Down wood	1.82		0.44	0.37	1.01	26.64
	Bark	1.52	0.37	0.84	0.46	0.59	43.93
	Total				*2.64*	*11.04*	***19.31***
Britannia	Forest floor	11.09		5.34	1.36	4.39	23.70
	Understory	0.61		0.48	n.d.	< 0.13	n.d.
	Down wood	4.17		2.33	0.15	1.68	8.22
	Bark	8.69		4.02	1.55	3.12	33.24
	Total				*3.06*	*9.19*	***25.01***
Yackelup	Forest floor	8.38		0.00	1.91	6.47	22.82
	Understory	0.24		0.13	n.d.	< 0.11	n.d.
	Down wood	18.10		16.85	0.14	1.11	11.43
	Bark	4.34		3.68	0.35	0.31	53.05
	Total				*2.41*	*7.89*	***23.38***
	Mean total values				**2.71**	**9.37**	**22.57**

n.d. not determined.

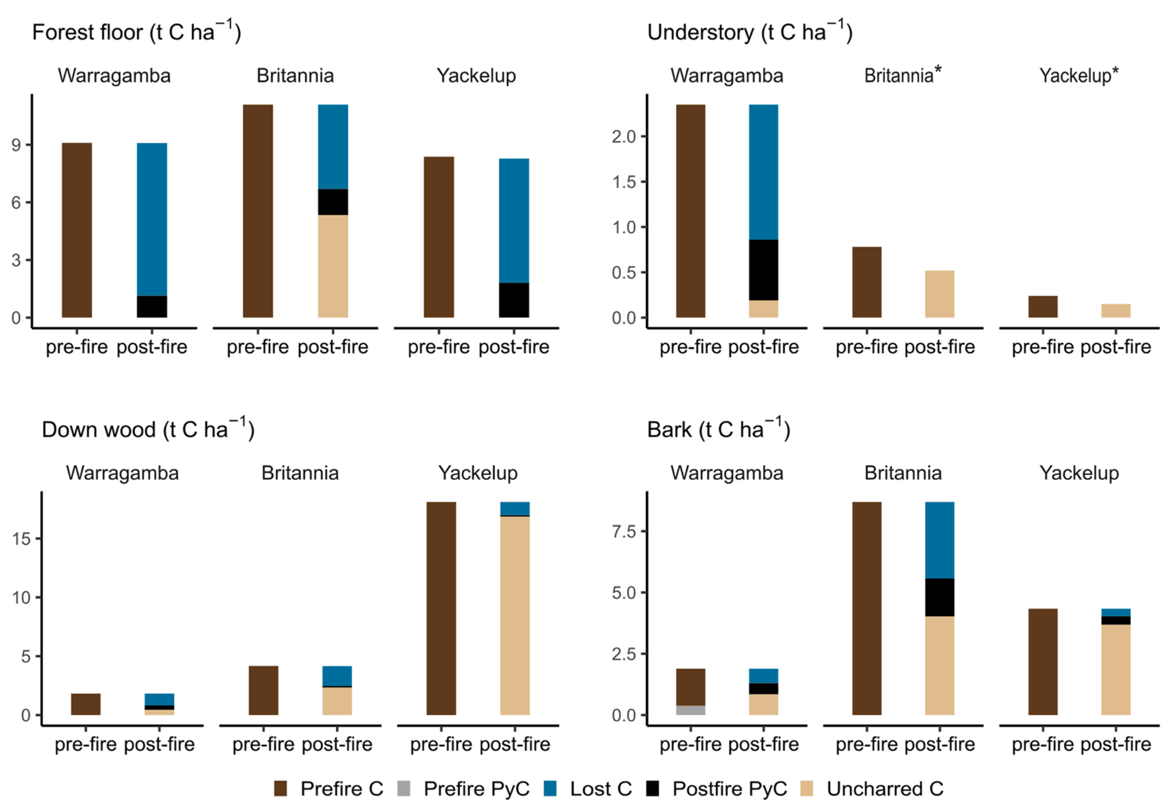

Fig. 3. Fire-affected fuel C stocks, and C transformations and losses per fuel component at each site. *PyC and loss C figures were not estimated.

load at Yackelup site did not allow accurate quantification of PyC production there, while at Britannia, only slight surface charring was observed on shrubs, which was negligible in terms of PyC mass.

3.3. Down wood

Down wood fuels showed notable differences in pre-fire C loads among the sites, with Yackelup having much more fuel than the other two sites: 18.10 $t\ C\ ha^{-1}$ compared to 4.17 $t\ C\ ha^{-1}$ at Britannia and 1.82 $t\ C\ ha^{-1}$ at Warragamba. A large part of the pre-fire C in Yackelup remained uncharred after the fire, resulting in the lowest PyC production (0.14 $t\ C\ ha^{-1}$) among sites. In contrast, Warragamba, despite having the lowest pre-fire C load, showed the highest PyC production (0.37 $t\ C\ ha^{-1}$) and the lowest C loss (1.01 $t\ C\ ha^{-1}$). This led to the highest PyC conversion rate at Warragamba, over 2-fold that of the other two sites (26.6 % compared to <12 %, respectively).

The fires resulted in similar overall mass loss across the sites (43 % at Warragamba, 38 % at Britannia, and 38 % at Yackelup, data not shown), but differed in terms of reductions in piece count and size. At Yackelup and Britannia, down wood with smaller diameters (0–0.9 cm) was primarily consumed, reducing substantially the number of pieces from 153 to 61 at Britannia and from 161 to 31 at Yackelup. In contrast, at Warragamba, larger diameter pieces (1–2.9 cm) were more abundant pre-fire and experienced greater consumption, reducing their number from 161 pre-fire to 68 post-fire (SI, Fig. A1). At Warragamba, PyC production was positively correlated with down wood diameter (Kendall's rank correlation tau, $t = 0.729$, $p < 0.001$) and charring depth ($t = 0.871$, $p < 0.001$) (SI, Table S2). The average charring depth was significantly higher at Warragamba (0.44 cm ± 0.3), compared to Yackelup (0.20 cm ± 0.27) and Britannia (0.07 cm ± 0.06) (Kruskal-Wallis, $p < 0.05$).

At Yackelup, in addition to the general down wood estimation conducted using the same methodology at the three sites, all large down wood pieces were mapped and measured (see Section 2.2.3). This estimation of large down wood yielded a pre-fire C load of 8.27 t C ha^{-1}. Of the 53 pieces counted in the entire plot, 3 were counted with the line intercept method, none of which produced PyC. 33 of the 53 pieces exhibited some charring after the fire. PyC production from these large down wood pieces was 0.23 t C ha^{-1}, twice that of the PyC produced in the general down wood pool determined with the line intercept method. With higher C loss registered in this pool (1.91 t C ha^{-1} compared to 1.11 t C ha^{-1}), the PyC conversion rate was 10.7 %, similar to the conversion rate calculated for the general down wood pool measured with the line intercept method (11.4 %) (SI, Table S1).

3.4. Overstory: Bark

Estimated pre-fire C loads in bark did not account for all the bark on the trees but only up to the height affected by fire through charring (see Section 2.2.4). Britannia exhibited the highest pre-fire C load (8.69 t C ha^{-1}) compared to Yackelup (4.34 t C ha^{-1}) and Warragamba (1.52 t C ha^{-1}). Related to the pre-fire C affected, PyC production was the highest at Britannia, with 1.55 t C ha^{-1}, compared to 0.46 t C ha^{-1} at Warragamba and 0.35 t C ha^{-1} at Yackelup. Concerning C loss to the atmosphere, Britannia once again showed the highest values with 3.12 t C ha^{-1}, compared to 0.59 t C ha^{-1} at Warragamba and 0.31 t C ha^{-1} at Yackelup. Concomitant to of this high C loss, Britannia exhibited the lowest PyC conversion rate of 33.2 %, while Yackelup exhibited the highest values with 53.1 %, and Warragamba intermediate values of 44 %.

Bark types responded statistically different at each site affecting the charring and PyC production (SI, Table S3). At Britannia, the majority of PyC production was concentrated particularly in stringybark trees (Fig. 4). Stringybark trees showed statistically higher bark depth before the fire, and statistically higher charring height and production of charred bark (Fig. 4, Table S4). The bark in many of the stringybark trees in Britannia carried the flames quite high up the trees and sustained burning into the night, well past the time the surface fire had extinguished (SI, Fig. S2). At Warragamba, ironbark trees had significantly higher pre-fire bark depth compared to stringybark, and exhibited more charred bark (Fig. 4).

Additionally, at Warragamba, the presence of PyC from the previous fire allowed for the estimation of PyC re-combustion during the new fire. The residual PyC before the experimental fire was 0.37 t C ha^{-1} . Based on estimations of bark diameter consumption, 0.28 t C ha^{-1} of the pre-fire PyC in bark remained after the fire, while 32 % of the initial PyC was estimated to have been removed by the experimental fire (0.09 t C ha^{-1}). The new PyC produced (0.46 t C ha^{-1}) was distributed between ironbark and stringybark trees without significant differences between them (Kruskal-Wallis, $p > 0.05$) (Fig. 5, SI Table S5).

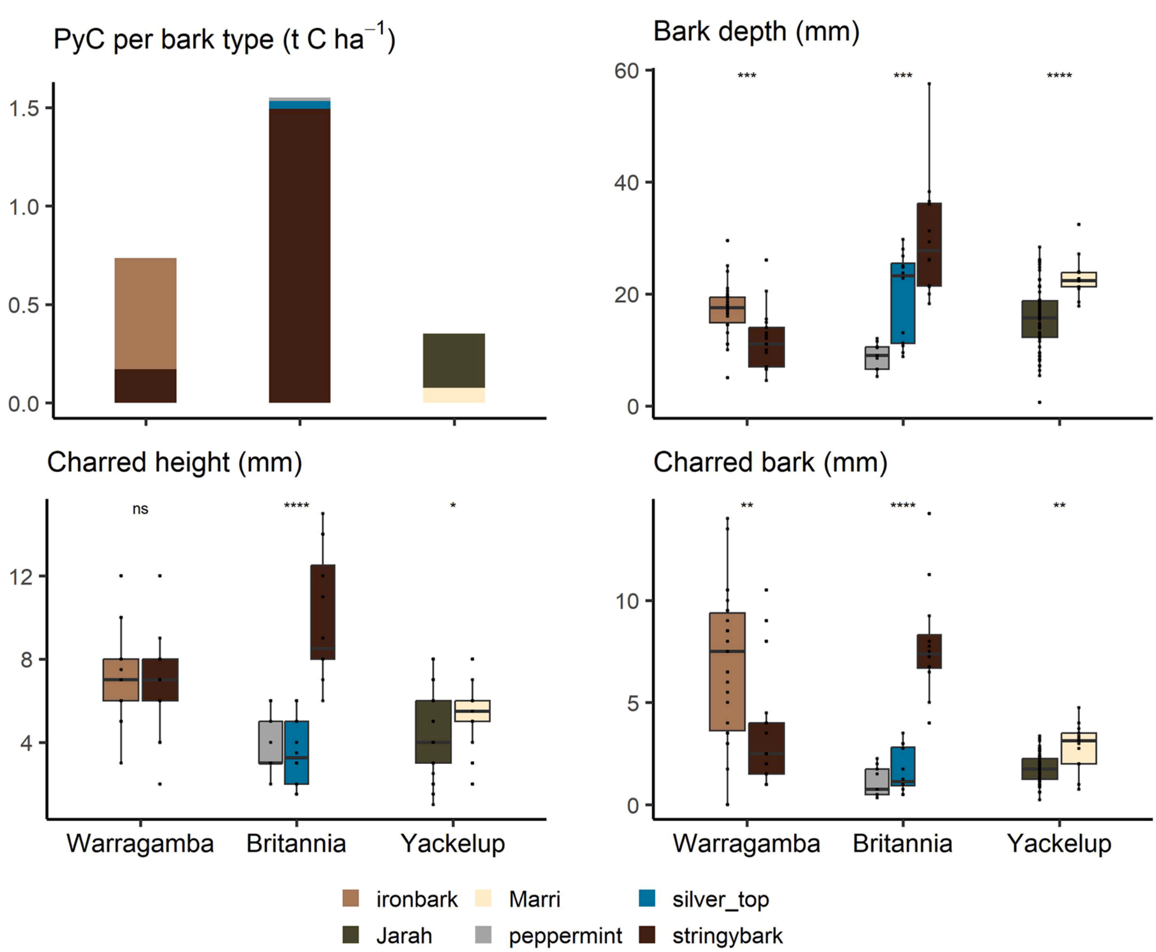

Fig. 4. Pyrogenic Carbon produced per bark type, bark depth, charred height, and charred bark at each site (Kruskal-Wallis, '***' $p < 0.001$; '**' $p < 0.01$; '*' $p < 0.05$; 'ns' not significant).

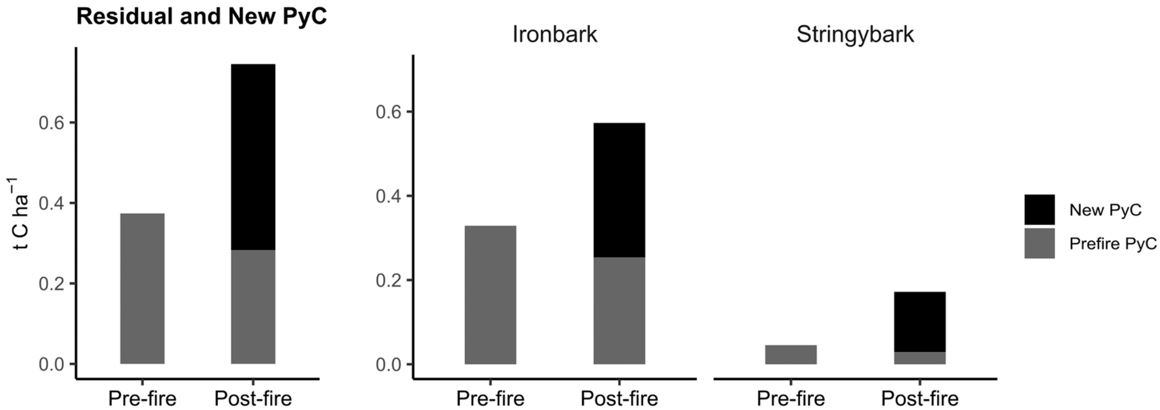

Fig. 5. Bark PyC at Warragamba. Left panel: residual PyC from the 2001 fire, and loss of residual PyC and new PyC production in the experimental fire. Right panel: PyC differentiated by the two main bark types, ironbark and stringybark.

Tree density and tree-impacts by fire varied among the three eucalypt forest sites. At Warragamba, the density was 300 trees per ha, with all trees in the plot showing some charring by the experimental fire. At Britannia, just over half of the trees showed some charring, equating to 441 of the 800 trees per ha. At Yackelup, with a density of 867 trees per ha, all trees were affected by the fire. While no tree fell at Warragamba immediately after the fire, three trees fell each at Britannia and Yackelup. Whilst it was not possible to account for these trees accurately in terms of mass loss and PyC produced using the experimental design of this study, we sampled the charcoal produced after three days of smoldering combustion for one downed tree at Yackelup (Fig. 1). The combustion resulted in 25 kg of charcoal produced from the wood. Given that pre-fire mass of these previously standing and likely hollow trees was not known, and combustion continued in some downed trees past the immediate post-fire sampling, this exploratory finding was not incorporated in the data analysis.

4. Discussion

The experimental fires conducted in the three eucalypt forests across southern Australia resulted in similar PyC conversion rates, despite variations in fuel loads and fuel consumption associated with the range of low-moderate fire severities. The average conversion rate of PyC per carbon affected (PyC/CA) of 23 % found in this study is similar to the 28 % identified in a stand-replacing boreal crown fire in Canada (Santín et al., 2015), despite the substantially higher fire intensity of the later. The overall PyC production of 2.7 t C ha^{-1} observed in our study aligns with the 2.1 t C ha^{-1} previously reported by Jenkins et al. (2016) for a series of prescribed fires in lowland temperate eucalypt forest in Australia, which considered forest floor and coarse woody debris, but not bark. In contrast, our values are substantially higher than the 0.31 t C ha^{-1} measured by Krishnaraj et al. (2016) for forest floor PyC, and the 0.25 t C ha^{-1} measured by Aponte et al. (2014) for coarse wood debris, both in south-east Australian eucalypt forests.

Fire severity patterns and their associated fuel combustion completeness affected the PyC production within the individual forest fuel compartment. Warragamba, experiencing the highest severity (i.e. moderate), showed complete combustion of the entire forest floor and understory, and even partial consumption of old PyC present in bark (produced in a 2001 fire), whose chemical characteristics make it more thermally resistant than unburnt biomass (Doerr et al., 2018). At Yackelup, the low-moderate severity fire also affected the forest floor and understory but involved limited burning of the high loads of down wood. The low severity fire in Britannia involved only partial burning of the forest floor, and minimal scorching of the understory; however, the high bark PyC load associated with the high tree density (Table 1) and abundance of stringybark contributed to the largest PyC production amongst the sites investigated (Table 3). Thus, it is clear that, apart from fire severity effects, site-specific characteristics also controlled PyC conversion rates for fuel components. The structure (spatial distribution, species) and loads of fuels varied among forest sites, affecting fire behavior and fuel consumption (Burrows and McCaw, 2013; Burrows et al., 2001), and consequently, resulting in different PyC production rates across forest components at each site (Huang et al., 2018; Jenkins et al., 2016).

The forest floor contributed with a large proportion to the pre-fire fuel loads across each of the sites and produced the highest amount of PyC (with the exception of the bark PyC at Britannia). However, a high pre-fire load did not necessarily result in the largest PyC conversion rates. For instance, despite its substantial pre-fire forest floor fuel load, Warragamba exhibited the lowest PyC conversion rate (12.6 %), which could be attributed to a high combustion completeness associated with the moderate fire severity. Conversely, the lowest fire severity and thus lowest combustion completeness resulted in the highest PyC conversion rate (23.7 %, Britannia). On average, PyC conversion rates for the forest floor affected by the low to moderate fire severities examined here were around 20 %, consistent with values in prescribed fires reported by Jenkins et al. (2016) for fine litter (< 25 mm diameter) and ground cover biomass (24 %), but notably higher than the 8 % calculated for litter fuels (< 25 mm diameter) in Krishnaraj et al. (2016). Forest floor PyC conversion rates in the current study were similar to the 24.5 % for the forest floor in the high-severity boreal fire examined by Santín et al. (2015). Compared to the other fuel components, the forest floor exhibits the highest carbon loss to the atmosphere (6.28 t C ha^{-1}), even for the lowest severity fire (Table 3). This holds important implications for carbon emissions assessment, as low severity prescribed fires specifically target the reduction of this fuel component (McCaw, 2013; Nolan et al., 2022).

Regarding understory, Warragamba showed substantial fuel accumulation (2.3 t C ha^{-1}), with a high PyC/CA conversion rate of 31.1 %, much higher than the 12.6 % conversion rate observed for the fine fuels in the forest floor. In contrast, the minimal impact on the understory in Britannia (barely scorched), reflects the common variation in understory fuel consumption in eucalypt forests after low-severity fires (Nolan et al., 2022), ranging from 0.4 % to 51 % mass consumption as reported by Volkova and Weston (2013). In our study, the low intensity of the surface fire was too low to ignite the standing fuels in the understory strata (Knapp et al., 2005). Estimating PyC produced in this fuel component with the help of particle traps proved challenging, especially where inputs where low due to a limited fire impact (Britannia) or where understory loads were very low as is typical for the Yackelup jarrah forest (Gould et al., 2011). Apart from the low yields at these sites, particle traps are also problematic for precise PyC quantification as they may include undesired components from other sources (Forbes et al., 2006).

In our study, materials collected in trays also contained small pieces of bark at the high tree density sites (Britannia and Yackelup), which would have led, if used, to an overestimation of the almost negligible PyC from understory fuels. Therefore, methodologies for understory fuels need to be improved to accurately measure PyC production, particularly where fuel loads or fire severity are low.

Down wood PyC conversion rates at Warragamba were particularly high at 26.6 %, contrasting with the lower rates of 8.2 % observed at Britannia and 11.4 % at Yackelup, where the lower fire severity may not have facilitated the consumption of coarse fuels (Burrows et al., 2001; Hollis et al., 2011). However, all down wood PyC conversion rates found at our sites exceed those reported in previous studies in similar eucalypt forests under low-severity (prescribed) fires; Aponte et al. (2014) reported conversion rates of 3.1 % for coarse woody debris, while Jenkins et al. (2016) reported a rate of 7.1 % for PyC from coarse woody debris deposited on the soil surface. The consumption of down wood fuels may have been influenced by the degree of forest floor consumption, particularly in the mixed eucalypt forest of Warragamba, where the substantial heat released from the abundant finer fuels (forest floor and understory) likely contributed to significant charring and reduction in diameter of wood pieces (Fig. S1) (Hollis et al., 2011; Whitford and McCaw, 2019). In Yackelup, the distinctive structure of down wood in Jarrah forests, characterized by a higher abundance of large-diameter pieces due to their slow decay rates (Whitford and McCaw, 2019), was associated with an 'additional' down wood PyC pool of 0.23 t C ha^{-1} not accounted for with the commonly used line-intersect method. Interestingly, consistent PyC conversion rates (~11 %) for down wood regardless of wood piece size in this low-moderate severity fire were found in this site.

Bark fuel, which has often been overlooked in PyC quantifications (Santín et al., 2016), emerges as a critical component in this study. Despite its known role as significant contributor to C loss and emissions in Australian forest fires (Volkova and Weston, 2019), this is the first study to our knowledge that quantifies PyC production from bark in eucalypt forests in Australia. The bark component exhibited the highest conversion rates compared to other forest components, ranging between 33 % and 53 %. However, PyC production in bark in absolute terms strongly varied among sites, with Britannia exhibiting by far the highest PyC production values (1.6 t C ha^{-1}), comparable to those of the forest floor (Table 3). Despite the low severity fire at Britannia resulting in minimal conversion of fine and down woody fuels into pyrogenic materials, the combustion of bark fuel was surprisingly high. The bark of the stringybark trees in Britannia burned slowly and deeply (average depth of 7.9 mm; Table S4) and reached considerable heights (up to 10 m). Stringybark, the most flammable type of eucalypt bark (Gill and Moore, 1996; Penman et al., 2017), is characterized by high thickness (30 mm on average in Britannia; Table S4), loosely held, and being highly fibrous. These physical characteristics make it easy to ignite and sustain combustion, facilitating the vertical spread of fire to the tree canopy (Gould et al., 2011; Uhelski and Miesel, 2017). Bark chemical characteristics may further influence its combustibility and PyC production (Grootemaat et al., 2017).

Jarrah bark at Yackelup, classified as stringybark type (McCaw et al., 2012), exhibited the highest PyC conversion rate. In contrast, Warragamba, with a lower fuel load of stringybark, both ironbark and stringybark produced similar amounts of PyC during the moderate-severity experimental fire. This occurred despite ironbark having greater density and being more difficult to ignite compared to stringybark (Hines et al., 2010). The relatively thick bark of many fire-tolerant eucalypt species prevents damaging vascular tissue (Gill and Ashton, 1968; Pausas and Keeley, 2017). Not only the bark type, but also bark thickness, were critical factors influencing the height and depth of charring, and thus bark PyC production. This has been also observed in coniferous species in Californian mixed-conifer forest by Maestrini et al. (2017).

The presence of charred bark from a previous fire in Warragamba trees provided insight into the re-combustion of residual bark PyC. To our knowledge, this is also the first study to quantify the PyC removal process under natural conditions in eucalypt forests. Approximately 32 % of the preexisting PyC was combusted during the fire, while a significant portion of residual PyC remained, contributing to an overall increase in PyC stocks in surviving trees. In environments with short fire-return intervals, such as in dry sclerophyll eucalypt forests, re-combustion of fuels is a loss mechanism that governs PyC storage potential (Doerr et al., 2018), as the stocks are balanced between char production and consumption. The retention of nearly 40 % of the old PyC following a moderate severity fire highlights the resilience of *in-situ* old PyC in such fire events. Previous studies have documented charred bark remaining in stringybark trees more than 30 years, attributed this persistence to its resistance to environmental degradation (Penman et al., 2017). Over time, however, bark and any PyC it contains will gradually redistribute and accumulate on the ground. This PyC will be incorporated into the forest floor litter where it can be mineralized by microorganisms or consumed in subsequent fires (Aponte et al., 2014; Wiechmann et al., 2015), buried in the mineral soil through bioturbation, which protects it from future fires (Richards et al., 2011), or transported off site via water or wind erosion, which can lead to its burial elsewhere and thus acting a longer-term carbon sink (Girona-García et al., 2024).

Additionally, the smoldering and glowing combustion of entire trees observed in the study, even triggered by the low-moderate severity fires, emerged as an unquantified but potentially significant contributor to PyC estimations and C emissions. In our study, for instance, while PyC production from bark per tree ranged from 0.4 to 1.6 t C ha^{-1}, a single tree at Yackelup produced 25 kg of charcoal over nearly 6 m after slow combustion (Fig. 2d). In addition to this understudied phenomenon, extremely dry conditions can dramatically increase the combustion of belowground fuels such as root biomass and soil organic matter. Belowground fuels are often overlooked in fire planning as they do not contribute to the flaming front. These events may have the potential to significantly distort PyC quantifications and necessitate careful consideration in future carbon inventories.

In our study, we focus on the immediate PyC production during a fire and report this in conjunction with direct carbon losses from combustion. However, given that carbon losses triggered by fire continue through degradation of dead biomass and soil respiration in the post-fire period, which in turn are affected by fire severity (e.g. Kelly et al., 2024; Miesel et al., 2018), the role of PyC production and its link to fire severity should also consider the post-fire recovery period when examining the effects of fire on the carbon budget of fire-prone ecosystems.

With the projected increase in wildfire severity and frequency due to climate change in Australian eucalypt forests (and many forest biomes globally; Jones et al., 2022), the resilience of eucalypt forests is expected to decline (Bowman et al., 2020; Fairman et al., 2016). Prescribed fires, with their PyC production, their lower carbon emissions compared to wildfires, and their ability to also reduce other environmental impacts of extreme wildfires, may provide an opportunity to counteract to some degree this predicted loss of the eucalypt forest carbon pool. In fact, traditional burning patterns of Aboriginal Australians may have historically assisted in buffering carbon pools during previous periods of climate variability (Gammage, 2011). In addition, prescribed fire can be also a key tool to manage fire-risk in eucalypt plantations, which are in expansion in many regions around the world outside of the natural distribution range of these species (Hirsch et al., 2020; López-Sánchez et al., 2021). To enhance forest resilience, understanding how frequent but small-size prescribed fires interact with large, high-severity wildfires is crucial for predicting fuel burning behavior and PyC re-combustion dynamics. We thus highlight here the need for further research into PyC production under differing fire behaviors and vegetation cover types in order to fully understand how prescribed fire could be best applied in forest management to minimize carbon loss and maximize longer-term carbon storage.

5. Conclusions

Given the extent of fire-affected eucalypt forests in southern Australia and the global expansion of eucalypt plantations, our findings have significant implications for the global carbon balance, as approximately one quarter of the carbon affected by fire is transformed into PyC rather than emitted to the atmosphere. Despite variations in fuel loads and consumption across the forests subjected to low to moderate fire severities, all fires resulted in similar PyC conversion rates, ranging from 19 % to 25 %, with PyC production values of 2.4–3.1 t C ha^{-1}.

Our study highlights the need for a comprehensive quantification of PyC production across different fire behaviors and fuel components. Bark emerges as a critical component to be quantified in the inventories, as it plays an important role in PyC production in eucalypt forests during low to moderate severity fires. In particular, stringybark trees increase forest flammability while also contribute significantly to PyC production in low severity fires. Furthermore, under these fire conditions, an elevated proportion of charred bark from previous fires is retained after a new fire (~32 %), ensuring the persistence of PyC over time under frequent, low to moderate severity fires.

Climate change projections urge the need for more detailed inventories of PyC production rates for specific ecosystems, fuel components and fire severities in order to maximize long-term carbon storage and enhance forest resilience through forest and plantation management.

CRediT authorship contribution statement

Doerr Stefan H.: Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Santin Cristina:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **García-Carmona Minerva:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Cawson Jane:** Writing – review & editing, Resources, Investigation. **McCaw W. Lachlan:** Writing – review & editing, Resources, Investigation. **Knowles Louisa:** Formal analysis, Data curation. **Duff Thomas:** Writing – review & editing, Resources, Investigation. **Chafer Chris J.:** Writing – review & editing, Resources, Investigation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.122590.

Data availability

Data will be made available on request.

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