

Article

Long-Term Response of Fuel to Mechanical Mastication in South-Eastern Australia

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Abstract: Mechanical mastication is a fuel management strategy that modifies vegetation structure to reduce the impact of wildfire. Although past research has quantified immediate changes to fuel post-mastication, few studies consider longer-term fuel trajectories and climatic drivers of this change. Our study sought to quantify changes to fuel loads and structure over time following mastication and as a function of landscape aridity. Measurements were made at 63 sites in Victoria, Australia. All sites had been masticated within the previous 9 years to remove over-abundant shrubs and small trees. We used generalised additive models to explore trends over time and along an aridity gradient. Surface fuel loads were highest immediately post-mastication and in the most arid sites. The surface fine fuel load declined over time, whereas the surface coarse fuel load remained high; these trends occurred irrespective of landscape aridity. Standing fuel (understorey and midstorey vegetation) regenerated consistently, but shrub cover was still substantially low at 9 years post-mastication. Fire managers need to consider the trade-off between a persistently higher surface coarse fuel load and reduced shrub cover to evaluate the efficacy of mastication for fuel management. Coarse fuel may increase soil heating and smoke emissions, but less shrub cover will likely moderate fire behaviour.

Keywords: aridity; coarse fraction; fuel management; mulching; surface fuel load; shrub encroachment; weeds; wildfire risk



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1. Introduction

Fire managers modify fuel load and structure to reduce the risk presented by wildfire on social, economic and environmental values in landscapes [1,2]. Live and dead vegetation act as fuel in a wildfire. Methods for modifying vegetative fuel focus on reducing the total amount or altering its structure and arrangement, with the purpose of modifying potential fire behaviour [3]. Prescribed burning is the most widely applied treatment globally [4], however there are challenges with prescribed burning such as fire escapes [5], smoke impact on human health [6] and limited windows for safe application [7]. These challenges have led people to seek alternatives, particularly at the urban-wildland interface.

Mechanical mastication is one such alternative for the treatment of fuel. The mastication process uses heavy machinery to grind, chip or shred standing fuel (commonly understorey and midstorey vegetation) and deposit it on the forest floor [8]. Mastication aims to disrupt the vertical continuity of fuel through the forest profile (i.e., from the surface to canopy), thereby reducing fire intensity, flame heights and reducing the potential for crown fire [9–12]. However, the relocation of standing fuel to the ground results in larger amounts of fine (<6 mm diameter) and coarse (≥6 and ≤25 mm diameter) dead fuel particles on the forest floor. These can form a deep-surface fuel bed [10,13,14], with implications for increasing flaming and smouldering durations [15,16].

We need to understand how mastication changes fuel properties over short and longer timeframes to evaluate its effectiveness as a fuel treatment. Despite a growing body of literature about mastication, there are few studies that quantify longer-term fuel trajectories post-treatment and the effect of environmental factors [14]. Furthermore, the results are typically contradictory among these few studies. For example, while most studies report declining surface fine fuel loads over time, the time to reach pre-treatment fuel levels varies between studies (e.g., within 4 years [15] to 8–16 years [17–19]). Similarly, surface coarse loads decrease quickly in some studies and slowly in others, e.g., 4 vs. 16 years [15,17], or can persist and remain unchanged, e.g., for up to ten years [8,19]. There has been little explanation as to why the results are different between studies beyond the suggestion that the species being targeted for mastication could be a factor [8,14]. An alternative explanation could be the effect of differences in abiotic factors between study sites (such as humidity, temperature, and rainfall), which may affect rates of decomposition [20–22]. Indeed, two of the only studies that link post-mastication fuel trajectories to environmental factors, report a significant effect, i.e., masticated surface fuel loads reduce with increasing precipitation and elevation over time [8,23], which is consistent with natural surface fuel loads [22].

Similar differences exist in studies examining the recovery of standing fuel at masticated sites. Understorey shrub density and cover in pine forests return to pre-treatment levels after 4 years [23–25] whilst in shrublands, shrub density and cover can remain low for up to 15 years post-treatment [12,18,26,27]. Rates of vegetative growth can vary across small and large spatial scales (e.g., 100–1000 m vs. 10–100 km [28,29]) as a function of environmental factors such as precipitation, radiation and temperature. Globally, it would be more useful to identify universal predictors of vegetation recovery post-mastication by directing attention towards understanding links between environmental variables and vegetation growth, rather than focusing on changes in specific vegetation types (i.e., coniferous forest vs. shrubland).

Aridity is an environmental variable with the potential to explain spatial variations in fuel across landscapes and rates of change following fuel treatments. Aridity represents the long-term balance between rainfall and net radiation [30], with increasing aridity-index values associated with increasing dryness and further unpredictability of rainfall events [30,31]. Regionally, aridity provides an indication of plant community structure with increasing aridity associated with decreasing shrub size (shorter with smaller canopies) [31,32] and decreasing surface litter decomposition rates [33]. Different vegetation recovery rates are also observed along aridity gradients as water availability limits a plant's survival and competitive ability [34]. This means that aridity could be a useful indicator for post-mastication fuel changes. The aridity index can be modelled at local scales (e.g., spatial resolution 20 m where topographic position also influences the rainfall-radiation balance [30]). This fine-scale resolution makes the aridity index particularly suited to understanding site-level changes in masticated fuel overtime, as mastication typically occurs at small scales (e.g., <1 ha). In contrast, climate data are usually modelled at larger resolutions (e.g., precipitation modelled at a 1 km resolution [35]) making them less suited for capturing conditions at masticated sites.

Australia has some of the most flammable ecosystems in the world, making it important to understand the effectiveness of fuel reduction strategies [36]. Quantifying the relationship between environmental drivers (e.g., landscape aridity) and fuel changes following mastication will allow us to build models of post-mastication fuel recovery that are applicable across multiple ecosystems. This information will enable us to fully evaluate the effectiveness of mastication against other fuel management strategies [37,38] and its potential to alter wildfire behaviour and risk [14]. Yet, there is relatively little known about the long-term efficacy of mastication in south-east Australian ecosystems as existing studies focus on shorter time periods post-mastication (e.g., 4 years) [12,15]. The aim of our study was to quantify the longer-term (9 years) effect of mastication on fuel across an aridity gradient. Specifically, our research asks the following questions:

1. How does fuel load and structure change overtime following mastication?
2. Do these fuel trajectories vary as a function of landscape aridity?

2. Materials and Methods

2.1. Study Sites

A total of 54 masticated study sites were selected across Victoria, south-eastern Australia (Figure 1) and spanned 584 km east–west (140.99 °E to 147.56 °E), 221 km north–south (36.92 °S to 38.91 °S), and 390 m in altitude (1–391 m asl [39]). Victoria has a temperate climate with cold winters and warm to hot dry summers [40] with the average annual rainfall across the sites ranging from 566–1185 mm year⁻¹ [35]. Sites were located across a range of ecosystems including dry and lowland forests, woodlands (heathy, herb-rich, hills-herb rich, grassy, plains, sedgy riparian, riparian swampy and coastal scrub), heathlands, and coastal scrub grasslands [41].

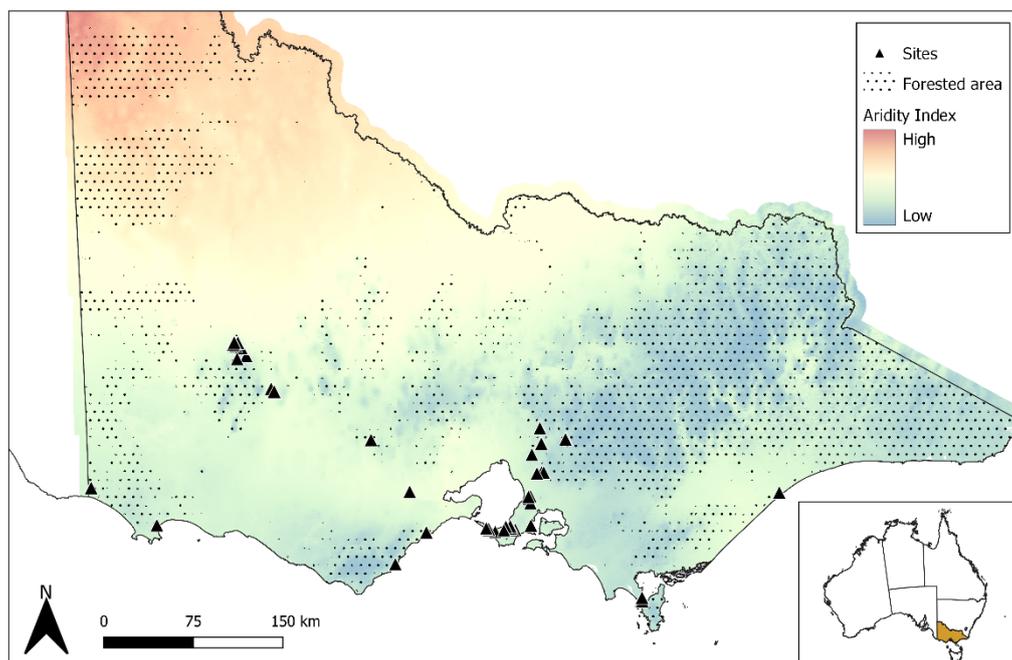


Figure 1. Locations of masticated study sites across Victoria, south-eastern Australia. Aridity index [30] is depicted on a colour scale with the most arid areas in red and least arid areas in blue. Forested area in Victoria is depicted with dots.

All sites supported a dense coverage of native and/or exotic species prior to mastication. Native species included *Acacia longifolia*, *Acacia paradoxa*, *Kunzea leptospermoides*, *Leptospermum laevigatum*, *Pittosporum undulatum*, and exotic species included *Chrysanthemoides monilifera*, *Coprosma robusta*, *Cotoneaster glaucophyllus*, *Pinus radiata*, *Polygala myrtifolia*, and *Rhamnus alaternus*. All species are considered ‘invasive’ at the sites, are highly competitive and have the ability to form dense woody thickets. All the species grow as either tall shrubs (>2 m) or low trees (<10 m), with the exception of *P. undulatum* and *P. radiata*, which grow as mid-height (10–30 m) and large trees (>30 m), respectively [42–45]. All species regenerate primarily by seed, although most can resprout from cut stems (exceptions include *L. laevigatum* where resprouting is occasional, and *P. myrtifolia* and *P. radiata* where resprouting is rare) [42–44].

Sites were selected in close consultation with fire managers to encompass a broad range of times since mastication (from 2 months to 9 years), facilitating a space-for-time approach (Figure 2). Sites were required to have no post-treatment prescribed burning or annual slashing and mowing, as these treatments further alter fuels.



Figure 2. Image of post-masticated sites in Wilsons Promontory National Park, Victoria after; (A) 6 months, (B) 2.4 years, and (C) 8.8 years. The foreground depicts a masticated site whilst the background shows a dense thicket of *Leptospermum laevigatum* (a native shrub-encroaching species) in an un-masticated area. Height pole is 2 m in height.

Skid steers or excavators were used for mastication. There were few details available on the specific mastication attachment used at each site, owing to the numerous contractors that had been engaged across the sites and because fire managers do not routinely collect data on machinery specifications. Machinery types therefore could not be evaluated as a factor impacting masticated fuel properties, but it should be noted as a potential source of variation between study sites.

Weed management strategies such as herbicide, hand pulling or a combination of both had been used after mastication at 27 sites (representing 38% of all sites). There was a large amount of variability in this follow-up treatment, including annual herbicide programs of either single or multiple treatments, biennial treatment, intermittent treatment, or no treatment. In all cases where herbicide was used, it was deemed to be a necessary part of the mastication treatment to prevent the masticated ‘invasive’ species from rapidly regenerating. Due to the targeted nature of the follow-up treatments (i.e., targeted to areas with more rapid regeneration), it was not possible for us to separate the effect of mastication from that of the follow-up herbicide in this observational study. Instead, we considered herbicide as a part of the mastication treatment. A controlled experiment would be needed to isolate the effect of herbicide from mastication.

2.2. Field Measurements

We established a 20×20 m (400 m^2) plot at each site, ensuring a minimum buffer distance of 10 m between the plot and any road or track to reduce edge effects. Masticated areas in Victoria are often small and narrow (0.5–10 ha), so 10 m is often the maximum buffer width that can be accommodated. Within the preselected sites, the north-west plot corner was randomly located using a random compass bearing and distance from the nearest road. Surface and standing fuel properties were measured at 25 points within the plot, evenly spaced on a 5 m grid using a point-intercept method. Measurements taken at each point include the surface fuel depth (using a fuel depth gauge [46]), maximum height of shrub fuel and the presence/absence of standing fuel (fine or coarse) at 10 cm height increments on a 2 m height pole. These point measurements were summarised into means (for fuel depth and shrub height) or percentage cover values for each plot (Table 1).

Table 1. Summary of the fuel property measurements taken in the study.

Fuel Property	Definition
<i>25 grid point measurements</i>	
Surface fuel cover, %	Percentage cover of surface fuels determined as a proportion of the total 25 measurements where surface fuels were present (number of points present/25 × 100) [47].
Surface fuel depth, mm	Mean depth of surface fuel (leaves, bark, twigs and other masticated debris on the forest floor) where it was present. Points with no surface fuel were not included in this calculation [46].
Cover of shrub fuel, %	Percentage cover of shrub fuel determined from the proportion of the total 25 points where it was present (number of points present/25 × 100) [47]. Shrubs include vegetation exceeding 2 m in height (above the height pole) but exclude tree canopy.
Height of shrub fuel, cm	Mean height of shrub fuel. Sites where there were less than five measurements made were excluded. Shrubs include vegetation exceeding 2 m in height (above the height pole) but exclude tree canopy.
Cover of standing fuel for each 10 cm height increment (up to 2 m), %	Percentage cover of standing fine and coarse fuel as a function of height. Determined from the proportion of the total 25 points where this vegetation was present within each height increment (number hits/25 × 100) [47].
<i>Plot corner measurements</i>	
Surface fine fuel load, t ha ⁻¹	Oven-dry mass per unit area of the surface fine fuel (<6 mm); mean for the plot and converted to tonnes per hectare.
Surface coarse fuel load, t ha ⁻¹	Oven-dry mass per unit area of the surface coarse fuel (6–25 mm); mean for the plot and converted to tonnes per hectare.
Total surface fuel load, t ha ⁻¹	Oven-dry mass per unit area of surface fine and coarse fuel; mean for the plot and converted to tonnes per hectare.
Coarse fraction, %	Percentage of total surface fuel load that is coarse fuel (6–25 mm)

Surface fuel load was measured at each of the four plot corners. Surface fuel load was calculated through sampling of all dead fuel particles <25 mm in diameter (leaves, twigs and bark on the forest floor) from within a 0.1 m² circular ring. In the laboratory, surface fuel samples were sorted into fine (<6 mm diameter) and coarse (6–25 mm diameter) size classes. Fuel was oven dried at 105 °C until a constant weight was achieved (>48 h) to determine their mass per unit area. Plot corner measurements were averaged to provide a single plot value (Table 1). The average slope and aspect were also recorded for each plot.

All measurements took place from September to December 2020. These data were supplemented with similar measurements made between November and December 2018 at nine masticated sites by Grant, Duff [12]. In total, 63 plots were used in the analysis and represent a space-for-time sampling approach.

2.3. Data Analysis

We used generalised additive models (GAMs) [48] to examine the change in fuel properties following mastication. GAMs fit a smooth spline to the data which allows for the visualisation of trends in the data without making prior assumptions about the form of any trend [48]. The surface fuel-bed response variables were total load, fine load, coarse load, coarse fraction, depth and cover, and standing fuel response variables were standing fuel cover and height. Predictor variables included time since mastication and the aridity index (spatial resolution 20 m [30]), and were fit as cubic splines with both variables smoothed. We also fit GAMs based on vegetation cover as a function of standing fuel in height increments (10 cm increments up to 2 m) by age class (0–2 ($n = 30$), 2–4 ($n = 13$), 4–6 ($n = 14$), and 6–9 ($n = 6$) years since mastication). GAMs were fit as quadratic splines, using height as a smoothed predictor. Data collected from untreated sites by Grant, Duff [12] were included in this approach. For all GAMs, a penalty term based on restricted maximum likelihood (REML) criteria was applied in the fitting process to limit the complexity of the fit.

Data processing and analysis were performed using the R statistical programming language, Version 4.1.0 (R Core Team 2016) and the following packages; *Hmisc* [49], *mgcv* [48], and *tidyverse* [50].

3. Results

3.1. Changes in Surface Fuels

Surface fuel loads ranged from 1.8 to 58.6 t ha⁻¹ in masticated sites with a mean of 17.1 t ha⁻¹ (s.d. 11.7). Surface fine fuel loads ranged from 1.2 to 30.6 t ha⁻¹ with a mean of 8.0 t ha⁻¹ (s.d. 5.7), while surface coarse fuel loads ranged from 0.05 to 37.0 t ha⁻¹ with a mean of 9.0 t ha⁻¹ (s.d. 7.0) across masticated sites. Coarse particles made up approximately 45–55% of the surface fuel load during the first 5 years post-mastication (Figure 3d).

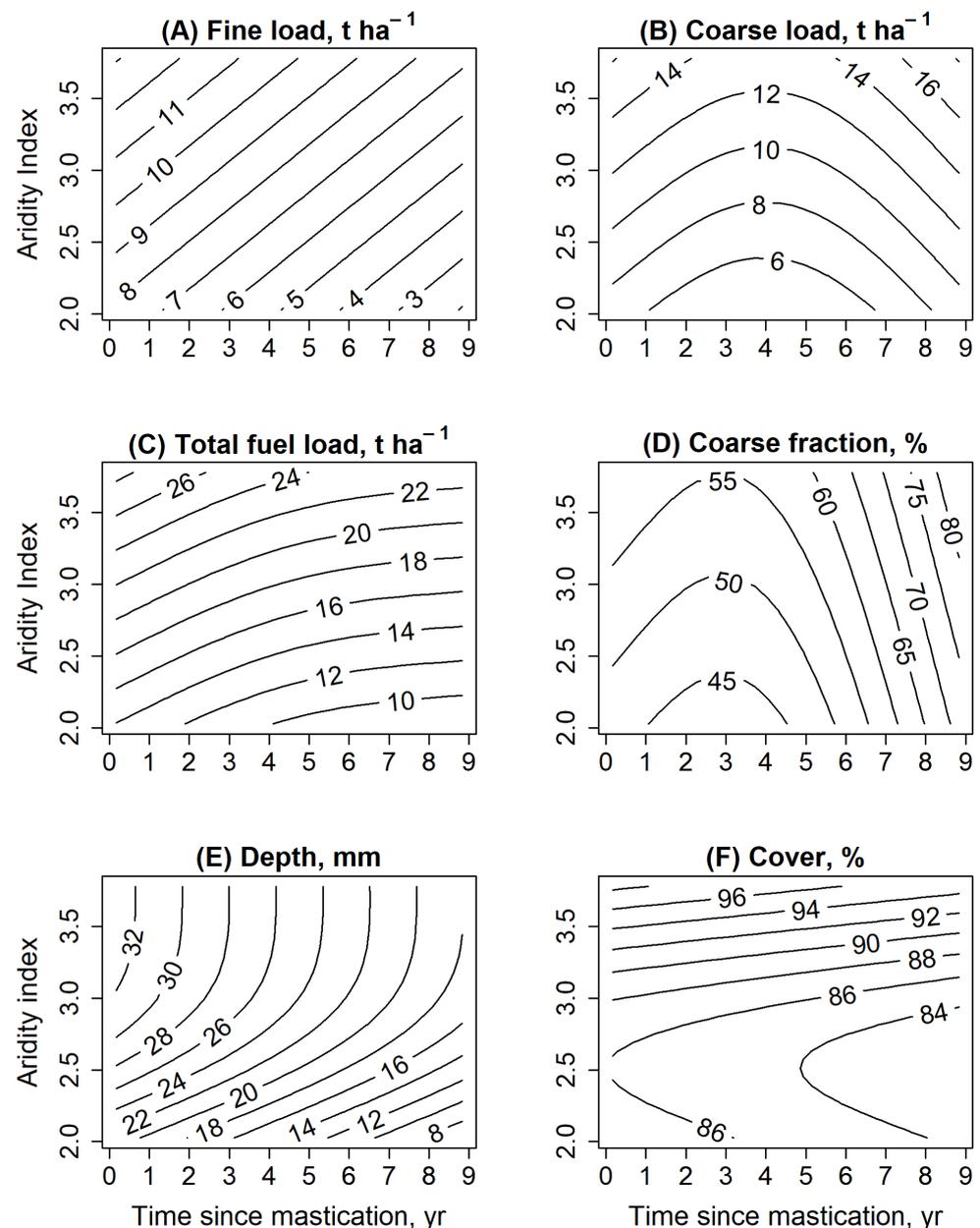


Figure 3. Contour plot showing surface fuel properties as a function of time since mastication and aridity as predicted by the GAM for: (A) fine load; (B) coarse load; (C) total load; (D) coarse fraction; (E) depth; and (F) cover. Values represent the predicted response value with units in the figure title.

Time since mastication was not a statistically significant predictor of total and coarse fuel load ($p = 0.32$ and 0.26 , respectively; Table 2) with these loads remaining constant over the 9-year timeframe (Figure 3b,c). Fine fuel load and fuel bed depth decreased markedly with time since mastication ($p = 0.03$ and $= 0.01$, respectively) (Figure 3a,e). As a result, the coarse fraction increased considerably with time since mastication ($p = 0.01$) (Figure 3e) and made up approximately 75–80% of the total surface fuel load by 9 years post-treatment. Total fuel load, coarse fuel load, fine fuel load and fuel bed depth all increased with increasing aridity ($p < 0.01$, < 0.01 , $= 0.046$, $= 0.02$, respectively) (Figure 3a–d). The coarse fraction did not vary with aridity ($p = 0.09$) and surface cover did not vary with time or aridity ($p = 0.70$ and 0.48 , respectively) (Table 2). Time since mastication and the aridity index explained 22% of the variation in surface fuel depth, 19% of the variation in coarse fraction, 18% of the variation in coarse fuel load, and 15% of the variation in total and fine fuel load (Table 2).

Table 2. Diagnostics of the GAMs fitted to the surface fuel properties with time since mastication and aridity as smoothed predictor variables. e.d.f. = effective degrees of freedom. Statistical significance denoted by * $p < 0.05$; and ** $p < 0.01$.

Model	R ² Adjusted	Deviance Explained, %	Smoothed Terms	e.d.f	p-Value
Fine fuel load, t ha ⁻¹	0.12	15.1	Time since mastication	1	0.03 *
			Aridity	1	0.046 *
Coarse fuel load, t ha ⁻¹	0.14	18.0	Time since mastication	1.7	0.26
			Aridity	1	<0.01 **
Total fuel load, t ha ⁻¹	0.12	15.3	Time since mastication	1.3	0.32
			Aridity	1	<0.01 **
Coarse fraction, %	0.15	19.3	Time since mastication	1.9	0.01 *
			Aridity	1	0.09
Depth, mm	0.19	22.1	Time since mastication	1	0.01 *
			Aridity	1.5	0.02 *
Cover, %	0.001	4.52	Time since mastication	1	0.70
			Aridity	1.5	0.48

3.2. Changes in Standing Fuel

Mastication reduced the cover of standing fuel that was taller than 60 cm (Figure 4). Fuel in the 60–100 cm height range had approximately half the amount of cover than untreated sites and this reduction was persistent for up to 9 years post mastication. Cover was approximately 15% for fuel taller than 100 cm, which is a quarter of the cover found in untreated sites (Figure 4). Regrowth was most rapid for fuel less than 50 cm tall and was approximately double the cover (85%) at 4 years compared to the cover visible within the first two years post-mastication (40%). By 9 years post-mastication cover was still marginally below pre-treatment levels (0–15%) (Figure 4).

Time since mastication was a strong predictor of height and cover for standing fuel ($p < 0.01$ for both; Table 3). Mean height increased at approximately 0.2 m per year (a total of approximately 1.6 m of growth) over the 9 years regardless of aridity ($p = 0.33$) (Figure 5a). Time since mastication contributed most to the 37% of explained variation in height (Table 3). The cover of standing fuel increased in the first 4 years after mastication to a maximum of 40% and then subsequently decreased with time (Figure 5b). Time was the strongest predictor of cover, contributing most to the 27% of explained variation in cover (Table 3). Aridity was not a strong predictor of height ($p = 0.33$) or cover ($p = 0.24$) (Table 3).

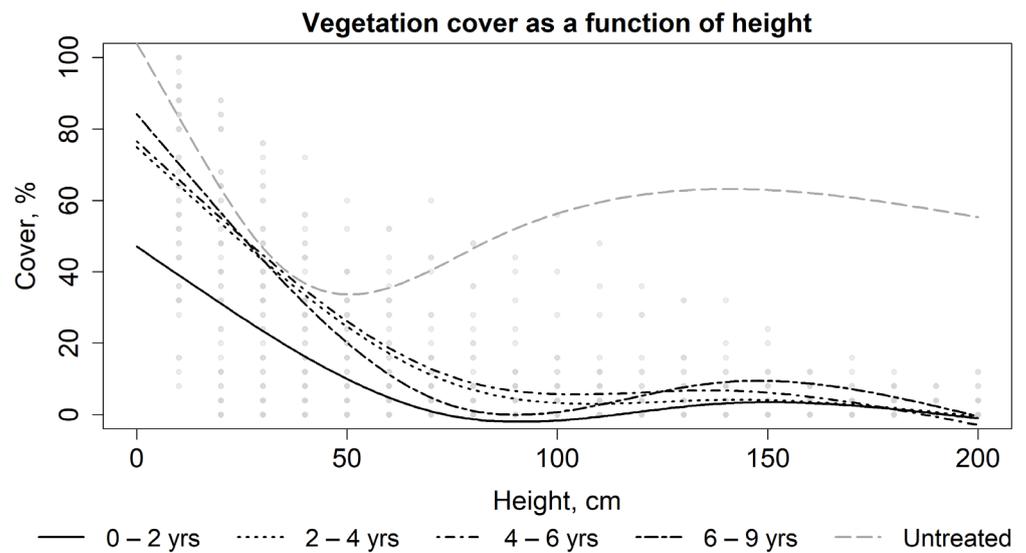


Figure 4. Smoothed lines (GAMs) to show variation in mean standing fuel cover as a function of vegetation height for different timeframes post-mastication. Grey dashed line represents untreated sites experiencing shrub encroachment measured by Grant, Duff [12]. Dots represent raw data from this study and do not include untreated site data.

Table 3. Diagnostics of the GAMs fitted to the standing fuel properties with time since mastication and aridity as smoothed predictor variables. e.d.f. = effective degrees of freedom. Statistical significance denoted by ** $p < 0.01$.

Model	R ² Adjusted	Deviance Explained, %	Smoothed Terms	e.d.f	p-Value
Cover, %	0.22	27.4	Time since mastication	3.5	<0.01 **
			Aridity	2.2	0.26
Height, m	0.32	37.2	Time since mastication	1	<0.01 **
			Elevation	1.7	0.33

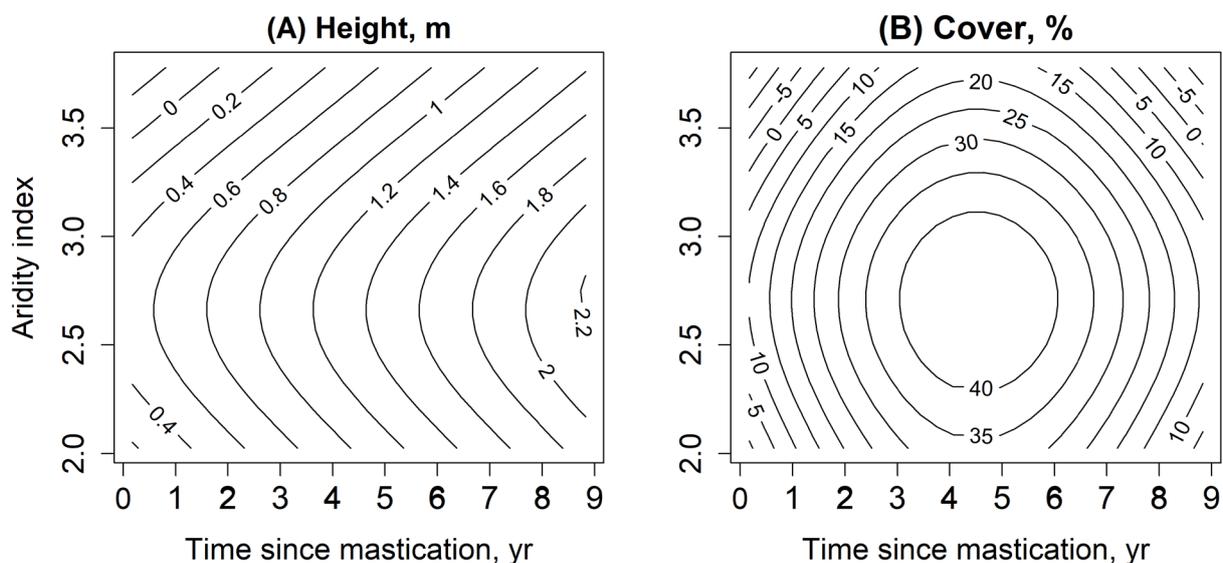


Figure 5. Contour plot showing properties of standing fuel as a function of time since mastication and aridity as predicted by the GAM for: (A) standing fuel height; and (B) standing fuel cover.

4. Discussion

Mechanical mastication is increasingly used as a fuel management technique for fire risk reduction. However, there is relatively little known about the long-term efficacy of mastication in south-east Australian ecosystems. The focus of our study has been to understand longer-term effects (9 years) of mastication on fuel load and structure, and to assess whether fuel trajectories post-mastication vary as a function of aridity. Quantifying these relationships will allow mastication to be evaluated against other fuel management strategies for wildfire risk reduction and for it to be incorporated into risk-based planning for wildfire management.

4.1. Changes in Surface Fuels

Mastication caused changes to surface fuel that persisted for at least 9 years. The total surface fuel loads (mean = 16 t ha⁻¹) measured in our plots were 62% higher than loads measured by others in comparable un-masticated sites (9.2 t ha⁻¹ [15]). Changes to surface fuel composition were also long-lasting. The initial high proportion of coarse fuel particles (45–55%) in the masticated bed is consistent with North American studies, e.g., 52% [8] and 64% [18]. These coarse particles persisted in the fuel bed throughout the 9-year timeframe. Conversely, the surface fine fuel load decreased overtime; after being initially higher than in the un-masticated sites. These trends in surface fine and coarse fuel loads with time (i.e., decreasing surface fine fuel load and persistence coarse fuel load) were also reported in American mixed-conifer and pinyon-juniper forests over an extended period (>6 years [19,51]). The continual rise of the coarse fraction over the 9 year period is presumably due to slower decomposition rates for larger masticated particles compared to their finer counterparts [52]. Mastication also removes a large portion of the vegetation that would normally contribute fine fuels to the system [23].

Surface fuels post mastication are substantially different to those present after prescribed burning. Initially, surface fine and coarse fuel loads increase after mastication, whereas the consumptive activity of fire means that these fuels are mostly removed after prescribed burns (e.g., 6.7 versus 0.6 Mg ha⁻¹ of coarse fuel and 3.6 versus 0.3 Mg ha⁻¹ of fine fuel, in masticated versus burnt sites [18]). Over time, fine fuel loads decreased post-mastication, whereas coarse fuel loads did not change. The rate of decomposition of fine fuel was higher than the rate of input from standing vegetation. Conversely, after fire, the total surface fuel load greatly diminishes (both fine and coarse) and therefore, the fuel load increases over time post-fire via contributions made from canopy and recovering standing vegetation [53]. These differences have implications for fire risk as the fuel load of the masticated surface fuel bed has ample fuel to carry a fire immediately post-mastication, unlike following a prescribed burn. This distinction between fuel treatments needs to be accounted for in fire management decision making.

The variability in surface fuel properties immediately following mastication was strongly associated with aridity. We observed that more arid environments had higher fuel loads and deeper surface fuel beds than less arid environments. This was unexpected as we assumed that more productive sites (associated with low aridity) would have relatively more woody biomass available for mastication—leading to an opposite trend to that observed. It is unclear why this was not the case. One possibility could be that arid sites promote invasive-type species to form denser stands (than those formed at mesic sites) because the low and pulsed resource availability of arid environments maximise species reproduction as compared to mesic sites which promote vertical vegetative growth [31]. Increased tree cover is associated with increased masticated surface fuel loadings [51]. Interestingly, for the variables that did change with time (coarse fraction, depth, and fine fuel load), the rate of change over time remained constant regardless of aridity—consistent with Reed, Varner [17] who found no impact of precipitation and temperature on decreased fuel loads over a 16-year period. This was contrary to our expectations. We expected the masticated surface fuel load to decrease faster in the mesic sites (consistent with Coop, Grant [23]) because microbial decomposition and invertebrate comminution rates slow with

an increasing aridity index [33]. Given that aridity and time accounted for approximately 20% of the variation in masticated surface fuels, it is likely that other important factors may have contributed to variability in surface fuels such as species' form and age, the machinery type being used and the particle size produced by the operator [8,54]. Further controlled experimentation is required to quantify the effect of these factors.

4.2. Changes in Standing Fuel

Shrub-based fuel increased consistently for the 9-year time frame considered. A similar degree of regrowth was identified in other studies, e.g., consistent growth of approx. 0.1 m per year over 8 years in chaparral [18], and 0.05 m per year over 16 years in oak woodlands, pine and mixed conifer forests [55]. This growth will also depend on the regenerative ability of species targeted for treatment. Masticated sites with species that have the capacity to resprout have been found to have a faster growth trajectory than sites dominated by seed germinating species [24,55], likely because the resprouter maintains a surviving root system which results in the fast regeneration of its aboveground biomass and subsequent competitive advantage for resources [56]. We expected growth in height to be slower at more arid sites as lower productivity is associated with fewer resprouter species [57]. However, this was not observed in our study, which is likely because most of the invasive species targeted for mastication were able to resprout, making the effects of aridity on resprouter distribution redundant. We also assumed aridity would influence growth rates, with slower growth rates and therefore slower shrub recovery in more arid sites due to reduced precipitation. However, this was not observed. Reed [55] similarly found a diminished impact of precipitation on height growth rates across varied vegetation compositions.

The cover of standing fuel changed parabolically with time since mastication across all sites. The initial increase in cover (20–40% by year four) was similar to the short-term response found in masticated Californian vegetation including chaparral, oak woodland, pine-dominated and mixed-conifer forest, e.g., 40% after 3 years [26] and 20% after 4 years [55]. After 4 years, we found that cover started to decline. This trend is likely a result of the increased competition for resources such as light and water [58]. Effects of mastication on vegetation structure were still present after 9 years (consistent with Martorano, Kane [27] in oak and chaparral over 15 years). For instance, cover for species taller than 60 cm in height was still substantially lower than that found in un-masticated, shrub-encroached sites. This is likely to moderate fire behaviour as compared to un-masticated sites, because although the vertical continuity of the vegetation profile may re-establish (through height increase), this vegetation will not be as horizontally contiguous as pre-masticated systems. This will limit flame propagation through this fuel layer [59] and make fire more controllable.

Comparisons of standing fuel regrowth between mastication and prescribed burn treatments are varied. For instance, shrub cover recovery has been found to be similar across masticated and burnt sites, e.g., 4 years post disturbance [24,60,61], but also comparatively higher after burning, e.g., 3 and 10 years post disturbance [26] and [62], respectively. This recovery is also altered by treatment seasonality. For instance, autumn mastication has been associated with a shrub cover that is lower (by 8–10%) than that found after prescribed burning (regardless of burn season); however, this difference was not evident for spring mastication [62]. Generally, there were no differences found in shrub heights between treatment type [26,60]. Vegetation response between the treatments may also depend on the regenerative ability of the vegetation at a site. For instance, mastication can favour the dense establishment of facultative seeding species at the expense of obligate seeders [61], whilst prescribed burning can favour higher densities of obligate seeders [24]. Further research should seek to better understand how the regenerative mechanisms of the dominant species at a site influence fuel trajectories overtime.

4.3. Management Implications

Fire managers should consider the fire behaviour implications of changes to surface fuel particle size following mastication. Coarse fuels (making up most of the masticated fuel bed) are typically more difficult to ignite than fine fuels, and when coupled with a re-established vegetation layer, will likely retain moisture for longer (vegetation shading and increasing particle size slows drying rates [63,64]). This means that masticated coarse surface fuel beds could be less ignitable than their non-masticated counterparts. However, when the fuels are dry and once fire enters a masticated area, the potential for increased flaming and smouldering duration in the coarse surface fuel bed [15,16] will likely deepen a wildfire's flaming zone and increase risk to human and ecological health, e.g., through prolonged smoke production and soil heating [15,65]. Faster particle breakdown before vegetation fully re-establishes may be encouraged by ensuring that fine fuel particles make up most of the initial fuel bed post-mastication. Further investigation is needed to determine appropriate fuel bed composition and the feasibility of achieving that within operational and budgetary constraints [16,66].

Mastication is likely to be most advantageous where there is a tall, dense understorey or midstorey that is difficult to treat with prescribed burning. Mastication causes a long-lasting disruption to this fuel strata, reducing flaming heights, the risk of crown fire and potentially disrupting the continuity of a fire front [9,12]. However, these effects on fire behaviour will decline overtime as the standing fuel recovers (i.e., shrubs increase in height and cover). Consequently, the benefits of mastication for fire suppression and firefighter safety decline overtime. Albeit this trend is similar to that expected after a prescribed burning treatment [60,67].

The decision to use mastication as an alternative fuel treatment will depend on whether its implementation and outcome (wildfire risk reduction) is more beneficial than other treatment strategies. Advantages of mastication include that it can be applied independently of the weather, can be used to treat fuel that is challenging to burn safely under prescribed conditions (i.e., due to the density of the shrub layer [12]), and may be more cost-effective when applied in small areas at the urban-wildland interface relative to the financial costs and fire risk associated with prescribed burning (such as escaped burns or smoke exposure [5,6]). However, it may not be a suitable replacement for the prescribed burning of large areas where the risk of damage from the prescribed burn is low (i.e., relatively low number of valued assets) and the cost of treatment per unit area is far greater for mastication. While we have demonstrated site level changes in fuel structure as a result of mastication, the ecological effects of mastication for both fauna and flora and its ability to effectively reduce wildfire risk at landscape-scales remains largely unknown in the Australian landscape. Further investigations into how mastication may modify landscape fire behaviour and the impact of wildfires on assets (human and ecological) is required at site to landscape scales through empirical and simulation studies [14,16]. The surface and standing fuel characteristics identified in this study would likely aid in such fire behaviour modelling simulations.

5. Conclusions

Mastication provides fire managers with a fuel management technique that can be used in dense shrubby fuel where it is difficult to implement prescribed burns. Changes to fuel properties following mastication are long-lasting, with a higher fraction of coarse fuel at the surface and reduced standing fuel height and cover which lasts for 9 years after treatment. Landscape aridity influences the initial differences in surface fuel properties but does not influence the trajectory of surface fuel particle decomposition or vegetation recovery following mastication. Mastication is likely to be most advantageous where there is a tall, dense understorey or midstorey that is difficult to treat with prescribed burning. Further research is needed to determine the long-term ecological effects of mastication. Investment in using mastication as an alternative fuel treatment will depend on whether

its implementation and outcome (wildfire risk reduction) is more beneficial than other treatment strategies.

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