Shoot Flammability Patterns in Urban Plants at the Wildland-Urban Interface of the Greater Sydney Region

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Thesis submitted in fulfilment of the requirements for the degree of Master of Science (Research), under the supervision of Associate Professor Brad Murray, Dr Megan Murray, Professor Jonathan Webb, and Dr Dan Krix.

October 2023
University of Technology Sydney
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This research is supported by an Australian Government Research Training Program.

Certificate of Original Authorship

I, Nicola Kate Huber-Smith, declare that this thesis is submitted in fulfilment of the requirements for the award of Master of Science (Research) – Environmental Science, in the School of Life Sciences at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are acknowledged in the thesis. I have submitted several drafts of my thesis to my supervisor with sufficient notice and have received feedback.

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The undersigned hereby states that the above student's Master's thesis meets the requirements (tick below as appropriate) for submission and is hence ready for examination:

☑ I have received and given feedback with sufficient notice on the written thesis.

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Date: 9th October 2023

Acknowledgements

Like most things in life, you need the support of others to help you reach your goals. It has become apparent to me that this is even more essential within the world of scientific research. I'd like to express my gratitude to my principal supervisor Brad Murray for helping guide me through the trials and tribulations for these two years of my Master's candidature. Your commitment to myself as your student has made the utmost difference in my professional abilities and myself as a young person entering the field of science. I cannot thank you enough.

I would like to acknowledge the dedication of my co-supervisor Dr Dan Krix, who provided consistent support to myself, especially in data analysis. Your help has been invaluable, and I am very grateful. I would also like to thank my co-supervisors Dr Megan Murray and Dr Jonathan Webb for their support. I would like to extend my gratitude to everyone who volunteered their time to proofread and edit my work prior to publication.

In order to obtain specimens to analyse throughout my studies, many people were kind enough to allow me to obtain free samples. From Andreasens Green Wholesale Nurseries, I am very grateful to managers Andrew O'Neil and Paul Jasman, and worker Rob McEwan who lent me their time in showing me around the nursery site, allowing me to sample their plants and providing their specialty knowledge. I would also like to extend special thanks to manager Richard Reilly from the nursery Trees Impact in Lake Munmorah, for being so accommodating throughout the sampling process and sharing your expertise. You have left a great impression as one of my first industry contacts and have made me excited for the creation of future collaborative work in the environmental science field.

The University of Technology Sydney's School of Life Science tech staff went out of their way in assisting me throughout my candidature. I'd like to make special thanks to Sue Fenech and

Scott Allchin who on several occasions helped me when there was broken equipment. Similarly, Andrew Tweed helped me tremendously throughout my research through dedicating his time to assisting me with sampling, lab work and the flammability experiments of my garden species. However, none of this research would have been possible without the help of Elisabeth Morley, my partner in crime throughout this degree. She assisted me in lab work, in the collection of samples from nurseries and in the field, the flammability experiments, the crazy amount of driving, as well as providing consistent emotional support which I am extremely grateful for. I'd also like to thank my family and friends outside of university which without fail acted interested in the research I was conducting and listened to any rants I had to get off my chest. Lastly, I am extremely grateful for my bearded dragon Nugget who sat by me (and on me) whilst writing my thesis and who provided me with great company and support throughout this time.

My Masters plant flammability research was supported by an Australian Government Research Training Program.

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Statement of thesis format

This thesis is structured as a conventional thesis format with five chapters. Chapter 1 provides a general introduction to wildfire research, plant flammability, the wildland-urban interface, and gaps in this field of research. There are three standalone data chapters (chapters 2, 3 and 4) within this thesis, each with their own relevant introductions and discussions. They have been created in mind of being published as separate articles to journals and thus have some repetition as to be individually comprehensible. Chapter 3 ("Shoot flammability patterns in native and exotic street tree species: Implications for wildfire spread at the wildland-urban interface") has been submitted to a journal for publication consideration as of 8th September 2023, and has been worded as such within this thesis. Chapter 5 provides a general discussion of the results and concepts that have arisen from the three data chapters, highlights the contribution this thesis makes to the plant flammability research in Australia, and provides future directs for the field.

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Thesis Abstract

This thesis is structured in a conventional thesis format. Climate change is generating shifts in natural wildfire regimes in Australia, by increasing the incidence of high wildfire risk conditions, which manifest in increases in the intensity and frequency of wildfires. With the recent devastating 2019–2020 'Black Summer' wildfires, it has become apparent that further research is needed to better understand inter-species variation in flammability in relation to mitigating wildfire risks at the wildland-urban interface (WUI). The WUI is one of the most at risk areas from the effects of wildfires, experiencing detrimental impacts to infrastructure, biodiversity, and human lives. At the WUI, often the last barrier between houses and wildland is urban plants, which include ornamental plant species in gardens and plantings of tree species along streets. In this context, the identification of low-flammability species among urban plants will provide important information for the selection of fire-resilient species that can be used in opportunistic green firebreaks to help mitigate the risks of wildfire spread at the WUI.

I assessed flammability patterns among 12 garden plant species (spring, Sept–Nov 2022) and 10 street tree species (summer, Jan-Feb 2023) common to the Greater Sydney Region. I measured shoot flammability attributes including time-to-flame (TTF), flame duration (FD), number of flame events (nF), and flame temperature (FT) for each study species on a flammability testing device built to international standards. In addition, a range of shoot traits were measured to determine relationships between shoot flammability and inter-species variation in shoot traits. I found that each study species had a unique presentation for each flammability attribute. Consequently, some species were found to have high flammability in one attribute and low flammability in another. This means no completely ideal

low-flammability species was found within these datasets. This indicates further that deeper location assessments should be conducted at the WUI to determine in what flammability attributes a site is most vulnerable to, and then plant accordingly. The flammability attributes defined in this study are the time-to-flame (TTF; how long it takes a shoot to ignite once exposed to flame), number of flame events (nF; the number of times a sample ignites in the exposure duration), flame duration (FD; the cumulative duration of which the shoot has flame throughout the exposure period) and the maximum flame temperature (FT; how hot the shoot sample burnt). A range of shoot traits were found to affect a variety of shoot flammability attribute outcomes across the three studies. These traits were leafing intensity (number of leaves in relation to number of branches), bulk density, shoot volume and fuel moisture content. Increasing leafing intensity was found to consistently increase flammability throughout all three studies, despite it not being a common measurement in previous shoot flammability studies. It is recommended that this trait be used in future research as it creates a more well-rounded representation of a shoot's architecture. Despite native plant species often being anecdotally known by laymen and professionals for having a higher flammability than exotic plant species, these studies did not find conducive evidence of this. Exotic species presented higher flammability for some attributes in some studies and native species in other attributes in other studies.

The third experimental assessment of plant flammability in this thesis asked whether differences in maximum ambient temperatures during the burning period had an impact on shoot flammability. I tested the prediction that hotter ambient temperatures would increase shoot flammability. I compared the flammability of native street trees between winter (June–Aug, 2022) and summer (Jan–Feb, 2023), and of native garden plants between spring (Sep–Nov 2022) and autumn (Mar–April 2023). This study found that increases in ambient temperatures between seasons led to increases in all four flammability attributes (TTF, FD, nF, FT). The TTF was found to be faster in all street tree species with increasing ambient temperatures, along with the garden plant species *Eucalyptus robusta*. A longer FD from a higher ambient temperature was found to be driven by the street tree *Tristaniopsis laurina.* The nF was found to increase in all street trees with higher ambient temperatures. Lastly higher ambient temperatures caused higher FT in all study species. Another analysis showed evidence of a continued effect of temperature on shoot flammability with the inclusion of traits. The significant traits were shoot mass, volume, branching intensity, and leafing intensity. These traits relate to the size and density of the plant material, and can advise people in what traits may lead to increased plant flammability at the WUI. As temperature increases the intrinsic flammability of plants, it is also advisable in future flammability research to control for the ambient temperature. As climate change lengthens the wildfire season it means plants will be exposed to hot temperatures for longer, and consequently have a higher intrinsic flammability for a longer duration again increasing the likelihood of wildfire, along with more frequent wildfire risk conditions.

The findings of this thesis provide a novel insight into the flammability of urban plants at the wildland-urban interface in eastern Australia. By identifying low flammability species, plant traits and conditions, it means that areas of low–moderate risk of wildfire can apply this information to better support their region. This can be done by implementing low-flammability species in opportunistic green firebreaks that at the WUI, that can prevent radiant heat and embers from spreading wildfire, whilst continuing to support native wildlife and biodiversity.

Chapter 1 | Introduction

1.1 Climate change and wildfires worldwide

Anthropogenic climate change is a global phenomenon that has altered temperature patterns and had biodiversity impacts across a wide range of terrestrial and aquatic ecosystems (Geyer et al., 2011; Staudt et al., 2013; Pascual et al., 2022). The likelihood of extremely high temperature weather events occurring has increased by a factor greater than 60 since 1950 (Ying et al., 2014). Such temperature increases threaten not only the health and wellbeing of people (Ebi, 2008; McMichael, 2009; Ebi et al., 2021), but also pose a significant risk to national economies (Mendelsohn & Neumann, 2004) and to biodiversity (Gill et al., 1999; Woinarski et al., 2015). The overall increase in global temperatures will lead to increases in the spread of infectious diseases (McMichael, 2009), poorer health (Ebi et al. 2021), thermal stress (Smith et al., 2016), hunger (Parry et al., 2005) and mortality in people (Bi et al., 2023), as well as in wildlife (Harris et al., 2018). We are also witnessing increases in high intensity wildfires around the world (Silveira et al., 1999; Lloret et al., 2009; Ying et al., 2014; Rossiello & Szema, 2019). This is due to climate change increasing the probability of key wildfire risk conditions including drought (Mukherjee et al., 2018), dry lightning (Canadell et al., 2021) and prolonged heatwaves (Varga et al., 2022), all of which can aid the ignition and spread of wildfires.

The increasing intensity, frequency, duration and spread of wildfires has devasted landscapes across the globe, taken the lives of people, and destroyed habitats at a rate higher than ever before (Boegelsack et al., 2018). A combination of these risk conditions led to the 2020—2021 wildfires across California in the United States, making it one of their most widespread wildfire episodes in the last century (Goss et al., 2020; Safford et al., 2022; Varga et al., 2022). Deforestation and climate-change driven drought has also made rainforests such as the Amazon and the Emas National Park in Brazil highly susceptible to wildfires, causing long-term biological harm to megafauna (Silveira et al., 1999), birds (Mestre et al., 2013) and vegetation understories (Ramos-Neto & Pivello, 2000). Many countries around the globe including the USA, Brazil, Mexico, Chile, South Africa, those around the Mediterranean, and Australia have all been identified as being at risk of ongoing hazardous weather conditions for wildfires from shifts linked to climate change (Lloret et al., 2009).

1.2 Wildfires in an Australian context

Australia is especially vulnerable to the adverse effects of climate change as we have naturally high climatic variability and is one of the most fire prone places on Earth (Moore, 2010; CSIRO & Bureau of Meteorology, 2018). Australia has a deeply intertwined history with fire, with plant species having co-evolved with natural fire regimes (Gill, 1975; Bradstock, 2008; He et al., 2011; Bradstock et al., 2012). Additionally, Indigenous Australians have used cultural fire practices to manage landscapes, cook, communicate, promote the growth of foodplants, as a tool for hunting, and in ceremonies for approximately 65,000 years (Bowman, 1998; Burrows et al., 2006; Bird et al., 2008; Jones, 2012; Pascoe, 2014; Cahir et al., 2018; McKemey et al., 2021). Due to this long relationship between fire and the Australian landscape, some trait adaptations to fire have been discovered in plants, including thickened cuticles to prevent moisture loss when exposed to heat (e.g. Proteaceae family) (Jordan et al., 2005; Ormeño et al., 2020), the reproductive process of serotiny (fire and smoke stimulating seed release e.g. Proteaceae family) (He et al., 2011), and thickened bark in areas of high fire activity (Schubert et al., 2016).

Throughout Australia fire regimes vary due to climatic and vegetation diversity. For example, wet seasons in northern Australia cause an increase in vegetation biomass, promptly followed by a dry season, which together produce an annual fire regime (Bradstock et al., 2012; Murphy et al., 2013). In contrast, in temperate eastern Australia, where dry sclerophyll forest vegetation continually grows and rainfall is more consistent, wildfires naturally occur in spring–summer (September–February) with a larger minimum wildfire interval of around five years, often producing higher intensity fires than those in northern Australia (Bradstock & Kenny, 2003; Bradstock, 2010; Australian Bureau of Meteorology, 2017; Morley, 2022). Although wildfires are an ecological event that is essential for the health of many Australian (Williams et al., 2012) and global (He et al., 2019) ecosystems, extreme wildfire events can have ecological impacts that are difficult to recover from (Dickman, 2021). An example of this in Australia is the recent 2019–20 'Black Summer' bushfires that caused approximately 24 million hectares of Australian landscape to burn (Canadell et al., 2021), burning areas that housed approximately 44% of Australia's threatened plant species (Gallagher et al., 2021), killing over 1 billion animals (Komesaroff & Kerridge, 2020), taking 33 people's lives, and destroying approximately 3,000 houses (Filkov et al., 2020; Richards, 2020).

1.3 Wildland-urban interface

The area of transition between urban developments and wildland vegetation is called the wildland-urban interface (WUI) (Radeloff et al., 2005; Stewart et al., 2007). The WUI is at a greater risk of damage from wildfires than other urban areas. This is because of the higher level of human interaction with natural wildland regions, leading to an increased risk of wildfire ignition, and the proximity of the vegetation to infrastructure allowing wildfires to spread into urban areas (Mell et al., 2010; Price & Bradstock, 2014; Michael et al., 2018). Due to the WUI experiencing high economic and social losses from wildfire events, it is a geographical region that has increasingly come to the forefront of wildfire research in recent years (Haight et al., 2004; Michael et al., 2018; Murray et al., 2018; Krix et al., 2019; Murray et al., 2020). The WUI contains two classifications of vegetation that can act as fuel for wildfire, one being natural vegetation and the other being urban vegetation such as private and public gardens, parks, and street trees (Hawthorne, 2020). There often is overlap between these two vegetation forms, such as with weed and planted populations spreading between the urban and wildland sides of the interface, and urban gardens, often retaining remnant populations of wildland plants. For this thesis, the research focuses on intentionally planted urban species within the wildland-urban interface, as these plants are pre-planned prior to wildfire events.

In response to a general lack of studies on plant flammability at the WUI, recent times have seen well-needed growth in research on the flammability of wildland vegetation at the WUI, particularly in the context of increased fire risk as a consequence of climate change in Australia and worldwide (e.g. (Bradstock & Kenny, 2003; Kauf et al., 2015; Curran et al., 2018; Krix et al., 2019; Alam et al., 2020; Morley, 2022; Murray et al., 2023). However, there is a relative paucity of scientific studies exploring the flammability of plants in urban landscapes, studies that could provide meaningful advice for the design of fire-resilient landscapes (Thacker et al., 2023). As such, there is a pressing need for further plant flammability research at the WUI that targets both native and exotic plant species. Most urban regions are a mix of native and exotic plant species, as a result of the variability in plant preferences of people throughout the years. Urban design often reflects the culture and preferences of individuals and society as a whole, and historically in Australia this is often shown in its largely European heritage (Trigger & Head, 2010). Due to the scale of exotic plantings in Australia and the rate of them in public and private gardens at the WUI they must be considered in this study to create a holistic understanding of urban plant flammability.

1.4 Plant flammability

Although plant flammability has been explored at various scales, flammability remains a difficult concept to define. Due to this, previous studies have broken down the concept of flammability in various “flammability attributes” which describe how a plant sample displays its flame response. The flammability attributes used in this thesis are the time-to-flame (TTF; how long it takes a shoot to ignite once exposed to flame), number of flame events (nF; the number of times a sample ignites in the exposure duration), flame duration (FD; the cumulative duration of which the shoot has flame throughout the exposure period) and the maximum flame temperature (FT; how hot the shoot sample burnt). These flammability attributes have successfully described how a plant may burn and the extent of their flammability potential in previous studies (Krix et al., 2019; Alam et al., 2020; Krix et al., 2022; Morley, 2022; Potts et al., 2022; Murray et al., 2023).

Urban vegetation and biodiversity are well known to provide many ecosystem services such as reducing the urban-island heat effect (Wang & Akbari, 2016; MacLeod et al., 2019), improving the physical (Turner-Skoff & Cavender, 2019) and mental health of people (Hedin et al., 2022), creating permaculture opportunities (Holmgren, 2006) and supporting biodiversity conservation (Vergnes et al., 2012; Ossola et al., 2019). A lesser discussed topic is the potential for urban vegetation to cause ecosystem disservices (Koyata et al., 2021), such as causing infrastructure damage (Mullaney et al., 2015; Lucke & Beecham, 2019), unwelcome wildlife and pests (Saldarriaga et al., 2020), and importantly the potential for urban vegetation to act as a fuel for wildfire. As people need to coexist with plants in urban areas for their range of ecosystem benefits, it’s important to determine how to minimise the potential disservices that plants bring as a fuel for wildfire. To do this, it is crucial to understand the variation in common species’ flammability, to better protect people and biodiversity at the WUI. By understanding patterns in the flammability of species in urban areas, we have the potential to mitigate the ecosystem disservice provided by urban vegetation of providing fuel for wildfire spread. In fact, urban vegetation’s relationship with wildfires could be turned into an ecosystem service. If low-flammability species are identified, then biodiversity can continue to be supported in at risk urban landscapes with less concern of fire hazards (Murray et al., 2018; Cui et al., 2019). This potential ecosystem service of low-flammability plants will allow ecological networks to flow without widespread wildland fragmentation at the WUI and support wildlife connectivity while ensuring a lower wildfire risk to homes (Knapp et al., 2021). Similarly by determining low-flammability plants, green firebreaks could be implemented to protect infrastructure from radiant heat and embers in low intensity wildfires (Curran et al., 2018; Murray et al., 2020). By identifying high-flammability species it will also inform residents and decision-making bodies on what species they may like to avoid in at risk areas.

The flammability of natural vegetation assemblages is commonly explored around the world through field surveys, e.g. (Silveira et al., 1999; Stevens-Rumann & Morgan, 2019; Shepherd et al., 2021) and GIS remote sensing technologies, e.g. (Chuvieco, 1999; Pew & Larsen, 2001; Loepfe et al., 2010; Padrão et al., 2022; Varga et al., 2022), which provide broad-scale assessments of wildfire behaviour, vegetation density and the damage that has occurred post wildfire. Missing from such assessments is consideration of the fact that not all plant species are flammable in exactly the same way, with each responding with their flammability attributes uniquely. That is, variation in flammability among species is ignored, yet previous research has shown that some species are considerably more flammable than others, while other species are much less flammable (Krix et al., 2019; Alam et al., 2020; Potts et al., 2022; Murray et al., 2023). Up until recently, most plant flammability research that has compared the relative flammability of species has primarily focused on the flammability of leaves, as both fresh fuel and leaf litter (Scarff & Westoby, 2006; Ormeño et al., 2009; Ganteaume et al., 2013; Murray et al., 2013; Molina et al., 2017; Krix et al., 2019; Ormeño et al., 2020; Ganteaume et al., 2021; Romero & Ganteaume, 2021). However, recent research indicates that leaf flammability may not effectively replicate whole plant flammability (Jaureguiberry et al., 2011; Alam et al., 2020).

In an ideal situation, assessments of whole-plant flammability would be employed to understand inter-species variation in intrinsic flammability. However, conducting whole-plant flammability assessments such as igniting a mature tree for each replicate is unfeasible in the field, which makes flammability assessments and understanding fire dynamics in whole plants across WUI landscapes challenging (Jaureguiberry et al., 2011). This difficulty can be mitigated through maintaining the plants structural integrity by using a shoot sample (i.e. a section of plant about 50 to 70 cm long that maintains a plant’s canopy architecture; e.g. Wyse et al. 2016; Alam et al. 2020). Such shoot flammability assessments worldwide have been found to provide robust estimates of whole plant flammability, and it is now standard practice to use shoot flammability assessments to determine the relative flammability of species (Jaureguiberry et al., 2011; Pérez-Harguindeguy et al., 2013; Wyse et al., 2016; Wyse et al., 2018; Alam et al., 2020; Cui et al., 2022; Potts et al., 2022). Previous research has also linked functional and physical traits of plants to their flammability, and by determining these differences between species it may lead to a deeper understanding of flammability behaviour (Schwilk, 2003; Schwilk & Caprio, 2011; Murray et al., 2013; Pérez-Harguindeguy et al., 2013; Krix & Murray, 2018; Morley, 2022; Potts et al., 2022). Therefore, the analysis of urban vegetation's traits and flammability may allow for the best determination of species whole-plant flammability potential.

1.5 Research objectives and thesis outline

In this thesis, I performed three sets of flammability experiments throughout the winter (June––August) and spring (September–November) of 2022, and the summer (January–February) and autumn (March–April) of 2023, to examine shoot flammability patterns in urban plant species. My thesis explores the flammability of two major forms of urban greenery – private gardens and street trees.

In Chapter 2, I present the results of flammability assessments of 12 ornamental species commonly planted in urban gardens in the greater Sydney region of New South Wales, Australia. This study was conducted in the spring of 2022 (September–November). These flammability assessments included six native and six exotic species. The aims addressed in this chapter were to:

i. Determine the relative ranking of the 12 garden species based on the flammability attributes ignitibility, sustainability, and combustibility.
ii. Quantify relationships between shoot flammability and a set of simple-to-measure shoot traits.
iii. Identify whether native and exotic garden species differed in their flammability or shoot traits.

In Chapter 3, I assessed flammability patterns among 10 species widely used as street trees in the Central Coast region of New South Wales, Australia. This study was conducted in the summer of 2023 (January–February). These assessments included five native and five exotic species. The aims addressed in this chapter were to:

i. Determine the relative ranking of the 10 street tree species based on the flammability attributes described above.

ii. Quantify relationships between shoot flammability and a broader suite of shoot and leaf traits.
iii. Identify whether native and exotic street tree species differed in their flammability shoot traits.

In Chapters 2 and 3 of this thesis, I performed flammability assessments during a single season when weather conditions were consistent, in as much as that ambient temperatures on days when experiments were performed were not markedly different from each other. This experimental methodology was adopted to minimise any external influences of changes in ambient temperature on measurements of plant flammability.

In Chapter 4, I tested the hypothesis that more marked seasonal differences in ambient temperature would affect patterns in shoot flammability. The prediction was that as ambient temperatures increase, there will be an associated increase in shoot flammability. I repeated the flammability assessments performed in Chapters 2 and 3, in different seasons, and compared datasets collected for street trees between winter (June–Aug, 2022) and summer (Jan–Feb, 2023); and for garden plants between spring (Sep–Nov 2022) and autumn (Mar–April 2023).

1.6 Study regions

The eastern coast of Australia is one of the most wildfire impacted regions on the continent (CSIRO & Bureau of Meteorology, 2018). In the selection of the study region of the east coast of Australia, the greater Sydney region (GSR) posed a strong candidate as it has the highest population out of the capital city regions (Australian Bureau of Statistics, 2021-22). The GSR encompasses many vulnerable stretches of the WUI on its outskirts. The region extends along the eastern coast from Wyong in the north, the Blue Mountains in the west and the Royal National Park in the south (City of Sydney, 2020; Australian Bureau of Statistics, 2021a) (Fig. 1.1). Within the defined GSR's wildland and WUI areas, there were six major wildfire events during the 2019–2020 'Black Summer' wildfire season (Australian Institute for Disaster Resilience, 2020). Four of these fires occurred west of the GSR in the Blue Mountains area, destroying over 90 homes at the WUI (Named: Ruined Castle fire, Green Valley fire, Gospers Mountain fire, and the Wollondilly Green Wattle Creek fire) (Australian Institute for Disaster Resilience, 2020). The 'Black Summer' bushfires burnt approximately 80% of the Greater Blue Mountains World Heritage Area and an estimated 143 million native animals were impacted in the region (Blue Mountains Conservation Society, 2021; Smith, 2021). Similarly, the Central Coast local government area (LGA), experienced one of the six GSR major wildfires of the 2019–2020 fire season, named the Three Mile Fire (Australian Institute for Disaster Resilience, 2020). The WUI vulnerability to wildfires in these areas in the greater Sydney region permitted for the selection the study locations.

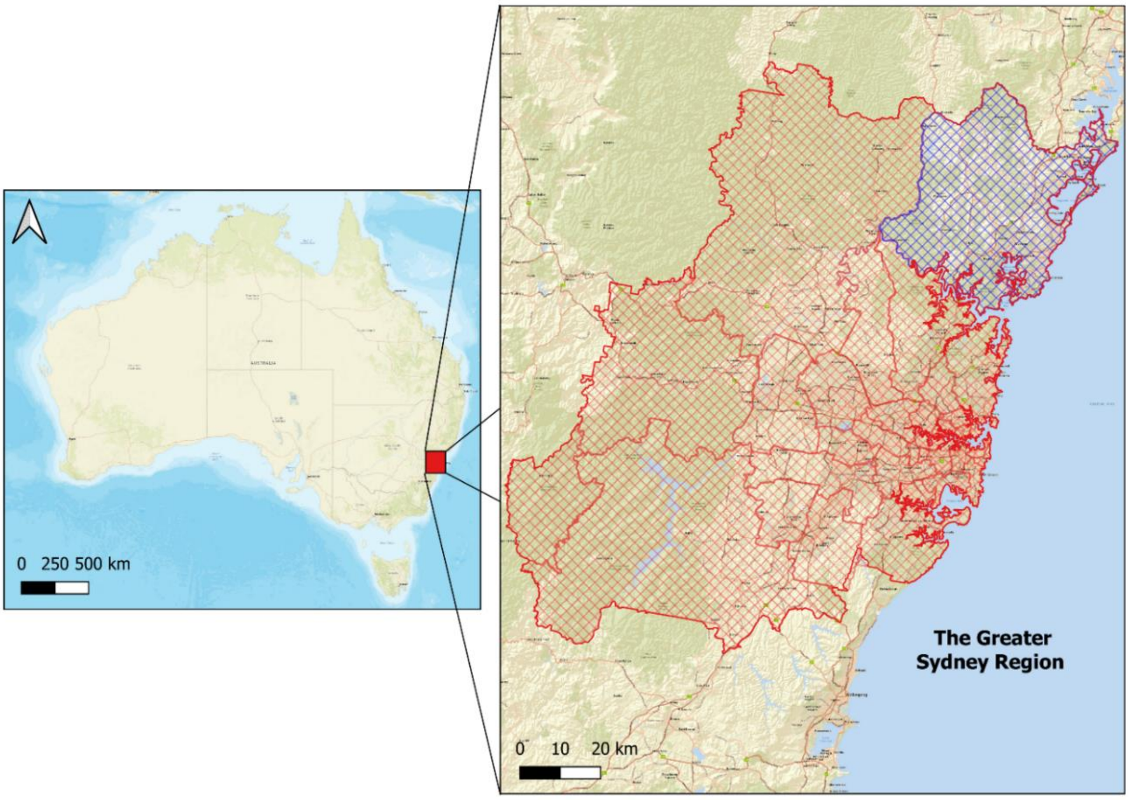


Fig. 1.1 Map of the Greater Sydney Region (red) and the Central Coast local government area in the north (blue).

Chapter 2 | Shoot flammability differences among common ornamental garden species of eastern Australia

2.1 Introduction

Australia is one of the most wildfire-prone continents in the world (Sharples et al., 2016; Australian Bureau of Meteorology, 2017; Ward et al., 2020; Abram et al., 2021). Wildfire frequency in eastern Australia is increasing as a consequence of current warming trends of temperatures in the region, further contributing to Australia's place as one of the most wildfire-impacted regions on Earth (Shi et al., 2021; Collins et al., 2022). The vegetation of eastern Australia has a long history of disturbance from wildfire events prior to the onset of recent climate change, due to its natural high rates of climate variability, droughts, and heatwaves (Perkins et al., 2015; Sharples et al., 2016; CSIRO & Bureau of Meteorology, 2018). The length of the fire season varies throughout different regions of the country, but in New South Wales, the season spans from spring to summer (September–February) (Australian Bureau of Meteorology, 2017). The dry sclerophyll forest wildfires of the east are often of high severity, and prior to recent climate change, naturally occurred every five years on average (Bradstock & Kenny, 2003; Bradstock, 2010; Morley, 2022). Although wildfires are an ecological event that is essential for the health of many Australian (Williams et al., 2012) and global (He et al., 2019) ecosystems, extreme wildfire events can cause ecological damage from which it is difficult to recover (Dickman, 2021). Eastern Australia, and the Greater Sydney region in particular, has been heavily impacted by wildfires in recent times. The region is predicted to be even more heavily impacted in the future due to worsening wildfire risk conditions (Bradstock et al., 2009; Clarke et al., 2013). An example of this was the 2019–2020 Australian 'Black Summer' wildfire season which occurred after Australia's hottest and driest year on record, and resulted in extensive social, economic, and environmental impacts (Filkov et al., 2020; Ward et al., 2020; Abram et al., 2021; Dickman, 2021). In New South Wales, this included approximately 3,151 hospitalisations (Borchers Arriagada et al., 2020), loss of 3,000 homes (Filkov et al., 2020) and over 23% of temperate southeastern Australian forests being burnt (Abram et al., 2021).

The wildland-urban interface (WUI) is the area of transition between wildland areas and low-density peri-urban communities (Murray et al., 2023). The WUI is at a greater risk of wildfires due to its proximity to surrounding wildland vegetation (Radeloff et al., 2005; Michael et al., 2018). Wildfires that spread in WUI areas often cause greater economic loss and casualties (Michael et al., 2018; Hawthorne, 2020; Murray et al., 2020), as was demonstrated by the 'Black Summer' bushfires (Abram et al. 2021; Dickman 2021). At the WUI, there are two main forms of vegetation present, wildland vegetation and urban vegetation. Wildland vegetation generally comprises the natural vegetation of the broader region both surrounding areas of urban development, as well as pockets or patches of remnant natural vegetation within urban areas. Urban vegetation within the WUI is considered in this thesis as the vegetation present within the perimeters of a town or city, that does not include patches of natural vegetation remaining in the region. Residential and public gardens are a main source of urban vegetation within suburban areas in eastern Australia (Harris et al., 2017) and make up to a third of total urban land area in western cities, often providing a majority of the vegetation present (Daniels & Kirkpatrick, 2006). Urban vegetation occurring in private gardens, for instance, might have the potential to be a line of defence in mitigating wildfire spread to homes at the WUI (Murray et al., 2018).

Globally, there is limited research on the role of gardens as a means for wildfire mitigation. The closest concept of this application is the use of green firebreaks, which is creating a plantation strip that acts as a low-flammability barrier to help protect property and areas of high biodiversity significance (Curran et al., 2018; Murray et al., 2018; Cui et al., 2019). Ideally, residential gardens could simulate the principles of a green firebreak, in a more opportunistic way compared with formal green firebreaks. For example, gardens containing low-flammability species that take a long time to ignite, burn for only a short period at low temperatures, and don't experience many flaming events on the plant, could effectively work to slow the spread of low-mid intensity wildfires. Such gardens should also avoid being planted with high-flammability species that ignite quickly, burn for long periods at high temperatures, and have numerous flaming events. Evidence shows that incrementally increasing urban green-scapes leads to large improvements in plant species richness, diversity and complexity (Mata et al., 2023). If low-flammability species could be incorporated into gardens, it could support biodiversity at the WUI rather than having to fragment vegetation vertically (e.g. not planting beneath trees) and horizontally (e.g. avoiding continuous planting) across the garden landscape as suggested under most current wildfire safety advice (MacLeod et al., 2019). At present, there is a paucity of research on the flammability of common ornamental garden species, and only one study conducted in Australia at the shoot scale (Murray et al., 2023). In section 1.4 of Chapter 1, I provide the rationale for the use of shoot flammability assessments as a robust representation of whole-plant flammability. More research is needed to assess whether comparatively low-flammability garden plant species can be identified for the purpose of opportunistic green firebreaks in residential gardens. Given that residential gardens at the wildland-urban interface often contain both native and exotic plant species, due to the Australian public varying in their plant preferences (Daniels &

Kirkpatrick, 2006; Kendal et al., 2012; Harris et al., 2017; Drew-Smythe et al., 2023), assessments of plant flammability should preferably include a mix of both native and exotic species. This will better protect properties and help public and private property owners in making informed decisions about wildfire mitigation. Because of the lack of flammability research being conducted on native and exotic species within Australia, it is more important than ever to get a better understanding of how common ornamental garden species burn to help protect properties from the increasing risk of wildfires.

The main aim of this chapter is to assess shoot flammability patterns in ornamental garden species of eastern Australia, to help inform garden design in public and private gardens that explicitly wishes to consider the flammability of plants in the context of mitigating wildfire spread risk. The specific aims of this chapter are:

1. To compare shoot flammability patterns among 12 garden species, empirically quantifying inter-species variation in flammability of six exotic and six native plant species). The principal outcome of this study will be the identification of low-flammability species that might be considered for use in opportunistic firebreaks, as well as high-flammability species that should be avoided.
2. To determine if exotic species are consistently less flammable than native species, as it is a common assumption by professionals and the public that this is the case.
3. To assess relationships between shoot flammability and six shoot traits including shoot mass, volume, bulk density, branching intensity, leafing intensity, and fuel moisture content. The identification of shoot traits underpinning inter-species patterns in shoot flammability means that predictions about the trait drivers of shoot

flammability can be extended to other species and regions in assessments of shoot flammability.

2.2 Material and methods

2.2.1 Study region and species

The study area for this research was the greater Sydney region of NSW on the eastern coast of Australia (33° 33’12”S, 151° 05’36”E) (Fig. 2.1). Greater Sydney has the highest population of any capital region in Australia, with an estimated resident population of 5,297,089 as of the June 30, 2022 (Australian Bureau of Statistics, 2021-22). The region is 12,368.2 km^2 and extends down the eastern coastline from Wyong in the north, Royal National Park in the South, and the Blue Mountains in the west (City of Sydney, 2020; Australian Bureau of Statistics, 2021b). There are over 200 national parks in NSW, with one of the largest being the Blue Mountains National Park to the west of Sydney (NSW National Parks and Wildlife Service, 2023). The Blue Mountains National Park has had wildfires naturally occur for millions of years (Hammill & Tasker, 2010; Hawthorne, 2020; Nolan et al., 2020). During the ‘Black Summer’ wildfires, the two of the largest fires (‘Gospers Mountain Fire’ and ‘Green Wattle Fire’) within the greater Sydney region were in the Blue Mountain National Park (Katoomba/Leura Rural Fire Brigade, 2020). These outer regions of the Sydney area are situated in the WUI making the communities more vulnerable to wildfires during the eastern coast fire season of spring to summer (September– February) (Australian Bureau of Meteorology, 2017). In the Greater Sydney region, spring has an average daily maximum temperature of 21°C and summer has an average daily maximum temperature of 33°C, with humidity averaging at 70–90% annually (Australian Bureau of Meteorology, 2017; 2020).

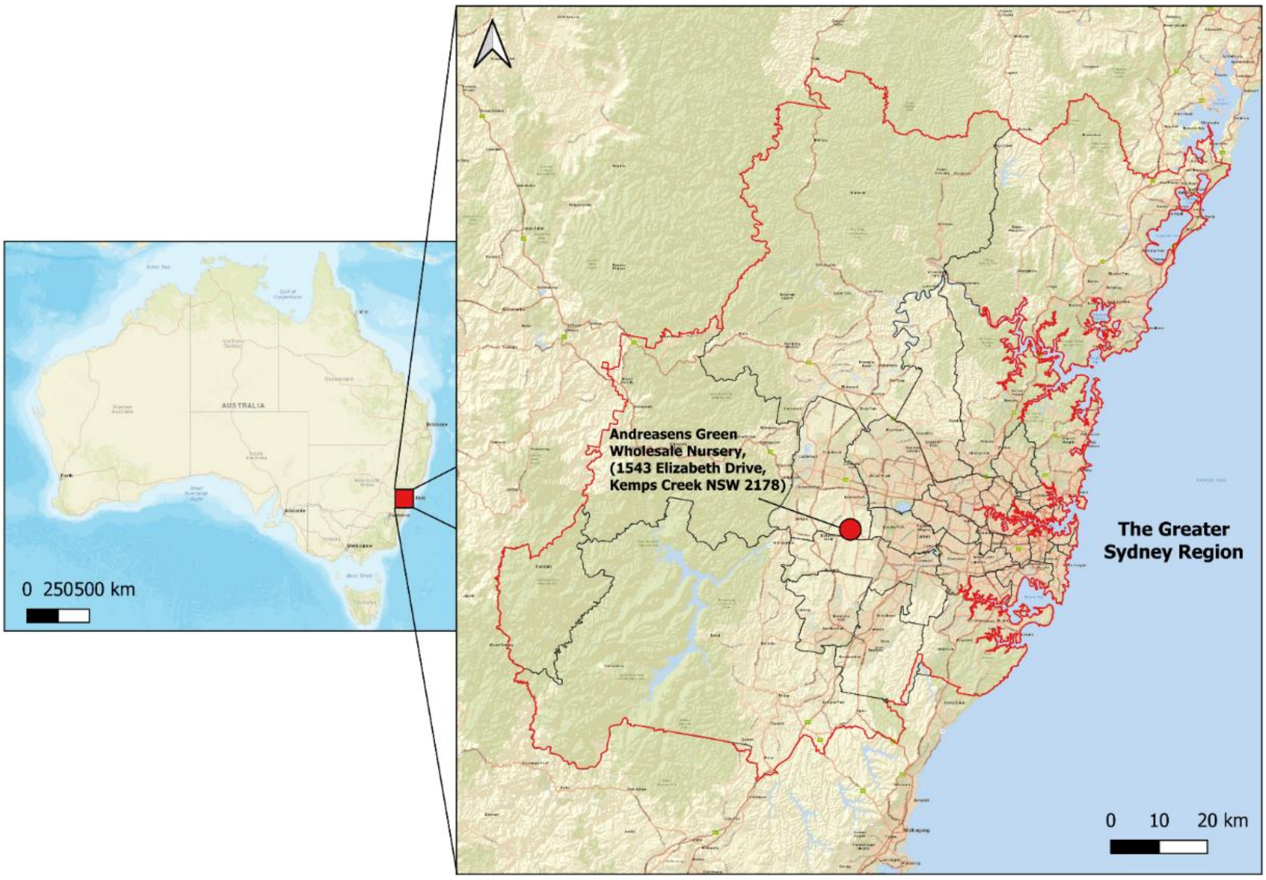


Fig. 2.1 Map of the Greater Sydney study region of New South Wales in eastern Australia. Sampling location of Andreasens Green Wholesale Nursery indicated by the red circle.

The New South Wales Government has a target of increasing the urban green grid in Sydney to 40% by 2056, planting 5 million more trees by 2030 and delivering free tree programs (Greater Cities Commission, 2018; NSW Government, 2022a; 2022b). This expanding green grid is a network of high-quality green spaces that connects urban areas to the natural landscape to boost biodiveristy, through connecting street trees, green corridors, gardens, parks etc. to larger regions of wildland and reserves (Greater Cities Commission, 2018). This means the area and plant density of public and private gardens will increase. Current composition of public and private gardens contains both native and exotic species. I consulted the large plant wholesaler in western Sydney, Andreasens Green Wholesale Nursery (1543 Elizabeth Dr, Kemps Creek NSW 2178) to determine some of their most popular ornamental stock in Sydney gardens (Fig. 2.1). Six native and six exotic common ornamental garden species of the Greater Sydney region were selected through this process (Table 2.1). The Sydney location of Andreasens nursery supplies both large-scale commercial plantation projects as well as private gardens throughout the Greater Sydney region. Seven out of the twelve study species were popular cultivars, which are selectively bred for their improved aesthetic or functional traits in the garden (Table 2.1). In other studies, these plant characteristics have been found to be strong determinants for people's plant preferences in the garden (Kendal et al., 2012; Drew-Smythe et al., 2023). This finding helps support the ratio of cultivars verses non-cultivars selected for this study in creating an accurate representation of eastern Australian gardens.

Table 2.1 The twelve ornamental garden species assessed for shoot flammability with their common name, taxonomic family and status in Australia.

Species	Common Name	Family	Status
Acmena smithii 'Minor'	Dwarf Lilly Pilly	Myrtaceae	Native (cultivar)
Callistemon viminalis 'Dawson River Weeper'	Bottlebrush	Myrtaceae	Native (cultivar)
Eucalyptus robusta	Swamp Mahogany	Myrtaceae	Native
Grevillea 'Moonlight'	Grevillea 'Moonlight'	Proteaceae	Native (cultivar)
Waterhousea floribunda 'Amaroo'	Amaroo	Myrtaceae	Native (cultivar)
Westringia fruticosa	Coastal Rosemary	Lamiaceae	Native
Cupressocyparis leylandii 'Leightons Green'	Leightons Green	Cupressaceae	Exotic (cultivar)
Fraxinus griffithii	Evergreen Ash	Oleaceae	Exotic
Gardenia augusta 'Florida'	Gardenia 'Florida'	Rubiaceae	Exotic (cultivar)
Lagerstroemia indica x *L. fauriei* 'Acoma'	Acoma Crepe Myrtle	Lythraceae	Exotic (cultivar)
Magnolia grandiflora 'Little Gem'	Magnolia 'Little Gem'	Magnoliaceae	Exotic (cultivar)
Viburnum odoratissimum	Sweet Viburnum	Adoxaceae	Exotic

2.2.2 Garden species shoot collection

Andreasens Green Wholesale Nursery in western Sydney provided access to their nursery for collecting shoots of the 12 species during the spring of 2022 (September-November). Shoot samples were collected at Andreasens Green from of healthy, and well cared for plant replicates following an internationally standardised procedure (Jaureguiberry et al., 2011; Wyse et al., 2016; Potts et al., 2022). Nine randomly selected replicate plants of each species were sampled over the spring period. This number of replicates or fewer have successfully been used in previous shoot flammability studies (Pérez-Harguindeguy et al., 2013; Wyse et al., 2016; Wyse et al., 2018; Hawthorne, 2020; Morley, 2022; Potts et al., 2022; Murray et al., 2023). Two representative 50 cm shoot samples were collected from the external, sun-exposed branches from each replicate plant. These shoots had to contain a representative distribution, and number of leaves and branches as the whole individual. One of these shoots was considered the 'trait' shoot, which allowed me to measure a variety of shoot traits that could not be taken off the shoot used in the flammability assessments. The other shoot was called the 'burn' shoot that was measured for traits and was then used in the flammability assessments. All sample shoots had healthy multiple leaves and branches, ensuring they were visually representative of the branch architecture of the species. To preserve the water content and architecture of the samples, the ends were bound in a dampened cloth and the samples were stored in plastic bags at room temperature overnight for processing the next day. Trial runs of the flammability experiment showed that no pre-burn drying procedure had to be conducted for the samples as all samples ignited within the specified timeframe of five minutes.

2.2.3 Shoot flammability and shoot trait measurements

The shoot flammability experiments were conducted using a portable bespoke device following the internationally standardised design from Jaureguiberry et al. (2011), modified to fit Australian-New Zealand standards (Wyse et al., 2016; Murray et al., 2023). Four flammability attributes were recorded whilst the flammability experiments were undertaken. This included the time a sample took to ignite after exposure to the flames (time to flame, TTF), the duration of time the shoot spent in flaming combustion (flame duration, FD), the maximum combustion heat of the shoot (flame temperature, FT), and the number of times it entered flaming combustion during its burn duration (number of flaming events, nF). The nF included the initial flaming event and each time a shoot entered flaming combustion after having stopped flaming. The observations concluded when a shoot did not enter flaming combustion again after two minutes without flames. This study concentrated on shoot flammability as a determination of whole-plant flammability as it was not feasible to burn whole replicates of the study species, as the mature individuals were often several meters tall. Current research studies have shown that shoot flammability which encompasses the leaf and branching architecture of the whole plant is a good representation of whole plant flammability, whilst being able to maintain the manageable scale of leaf flammability studies (Schwilk, 2003; Jaureguiberry et al., 2011; Wyse et al., 2016; Wyse et al., 2018; Alam et al., 2020).

The flammability device provided heat to the shoots from below a mesh grill sheet from two LPG-powered burners. The nine replicate burn shoots for each species were placed horizontally on the grill set 20 cm above the flames. The grill temperature was maintained at approximately 185°C, determined using an infrared laser thermometer (Digitech QM 7226). As soon as a shoot was placed on the BBQ grill above the flames, a timer was started to measure TTF and FD. We recorded nF for each shoot, with FD calculated as a summed value of time across all separate flaming events. The same infrared laser thermometer was used 50 cm from the shoot sample to measure the maximum temperature (FT) reached by the shoot samples generated flames (Jir-Ming & Jun-Hsien, 1996; Pérez-Harguindeguy et al., 2013; Wyse et al., 2016). The field of view of the infrared laser thermometer at this distance was approximately 1.67 cm in diameter. When large or multiple flame events occurred, the sample was quickly scanned back and forth by the thermometer to determine maximum flame temperature.

I weighed each burn shoot approximately 1–3 hours before flammability assessment using a portable scale spring balance to determine shoot mass (g), and I measured the shoot length, width and height (cm) of the sample to estimate shoot volume as an elliptical cylinder (Table 2.2). The minimum and maximum stem thickness (cm) was also measured, and the number of leaves (leafing intensity, LI; number of leaves in comparison to number of branches) and branches (branching intensity, BI) was counted on each burn shoot. Further detail in the definitions of leafing and branching of the study species can be found in Appendix A. The nine replicate trait shoots collected for each species were weighed (using a Sartorius A 120 S Analytical Balance) to determine fresh mass (g), placed in a drying oven at 80°C for 48 hours, and then weighed again to determine its dry shoot mass (g) (Table 2.2). Shoot fuel moisture content (FMC) was expressed as a percentage and calculated as the ratio of difference between air-dried and oven-dried mass to air-dried dry mass (Table 2.2). Shoot bulk density (g.cm^{-3}) was calculated as shoot air-dried mass divided by shoot volume (Table 2.2). Leaf length and width was measured on one representative leaf from each of the nine trait shoots for each species. Each trait shoot measurement was determined to be comparable to the burn shoot replicate as they were sampled from the same individual.

Table 2.2 Summary of shoot traits (middle column) related to shoot flammability in this study. The variables measured for each trait on the 'burn' shoot and 'trait' shoot are shown (first column), as well as the equipment used (last column).

Variables Measured on 'Burn' Shoot	**Equipment Used**	**Shoot traits**
Mass (g)	Portable scale spring balance	Mass Bulk density (g.cm^{-3}) (mass / volume) Shoot volume (cm^{3}) as an elliptical cylinder (π × shoot length × shoot width × 0.5 × shoot height × 0.5)
Size (width x length x height) (cm)	Ruler	
Number of branches	Visual count	Branching intensity (BI)
Number of leaves	Visual count	Leafing intensity (LI) – no. of leaves in comparison to no. of branches
Variables Measured on 'Trait' Shoot		
Fresh shoot mass (g)	Sartorius A 120 S Analytical Balance	Fuel moisture content (%) ([air-dried mass − oven-dried mass]/air-dried mass)
Dry shoot mass (g)	Drying oven (80°C for 48 hours) and Sartorius A 120 S Analytical Balance	

2.2.4 Statistical analysis

First, to detect any coordination among the flammability attributes (TTF, FD, nF and FT), I tested all pairwise combinations of flammability attributes using mean species values. For TTF and nF, ln and sqrt transformations were used respectively. Next, I explored patterns among species in their flammability attributes, fitting separate linear models to each attribute with species as a categorical term (fixed factor with 12 levels). Where the model was significant for a given flammability attribute, I used post-hoc comparisons (with Tukey correction), to determine where there were significant differences between species in that flammability attribute. Using mean values from these models, I ranked species from high-flammability to low-flammability for each flammability attribute (i.e. fastest TTF to slowest TTF, longest FD to shortest, most numerous nF to least numerous, and hottest FT to coldest). These rankings were then used in pairwise comparisons to determine if species ranks were coordinated across pairs of the flammability attributes. These comparisons were tested using paired-sample Wilcoxon tests.

To test for shoot trait associations with each of the flammability attributes, I first built a correlation matrix of species mean values of shoot mass (ln transform), bulk density (ln transform), volume (sqrt transform), leafing intensity (ln transform) and branching intensity (ln transform), and FMC (Table 2.3). Where traits were correlated with r > 0.6, one of the traits was excluded from further analysis and represented by the trait that was retained for modelling purposes. Shoot mass was correlated with bulk density (r = 0.63, P = 0.03), and branching intensity with leafing intensity (r = 0.83, P < 0.001) so I excluded shoot mass and branching intensity respectively. These choices were made to reflect the likely importance of fuel aeration (reflected by bulk density), and fuel complexity (reflected by leaf number).

Table 2.3 Table showing correlation coefficients (r) and P values (in parentheses) for bivariate tests between pairs of shoot traits. The shoot traits abbreviated within this table are bulk density (BD), branching intensity (BI), leafing intensity (LI) and fuel moisture content (FMC). Blank cells represent the redundant values of pairwise correlation repeats and the results corrected for multiple comparisons using the Bonferroni correction.

	Mass	**BD**	**Volume**	**BI**	**LI**	**FMC**
Mass	1	0.63(0.028)	0.43(0.16)	0.22(0.49)	0.07(0.83)	-0.11(0.73)
BD		1	-0.33(0.29)	0.44(0.15)	0.53(0.08)	0.38(0.22)
Volume			1	-0.16(0.62)	-0.44(0.15)	-0.49(0.11)
BI				1	0.83(< 0.001)	0.52(0.08)
LI					1	0.35(0.26)
FMC						1

To determine the best predictors of shoot flammability from the four retained shoot traits, I used an information theoretic approach. For the flammability attributes, I built all combinations of one, two and three-term models, in addition to a model with all four trait terms, and selected the most informative model from the suite of models (on the basis of lowest Bayesian information criterion [BIC]). For these models all observations were used, and a further fixed 12-level categorical term for species was included in all models. The selected models (one per flammability attribute) were then tested using ANOVA. For all models, the same transformations used to build the correlation matrix were applied. The flammability attributes were then modelled (linear mixed effect models) using plant status, i.e. exotic and native status (two-level fixed categorical term) and species (random term with 12 levels to control for species), to allow me to test for differences between native and exotic species. The same transformations used to test correlation among flammability attributes was reused here. Finally, to determine if any differences associated with plant status existed in the shoot traits which emerged as important predictors of shoot flammability, I modelled these traits as a function of status, again with a random term for species (linear mixed models using all observations).

All analyses were performed in R (R Core Team, 2023), using the packages car (Fox & Weisberg, 2019) (ANOVA for both linear and random effects models), emmeans (Lenth, 2021) (estimates of marginal effects and pairwise testing), and lme4 (Bates et al., 2015) (random model fitting). Full modelling outputs are included in Appendix B.

2.3 Results

2.3.1 Relationships between flammability attributes

There was only one significant relationship between pairs of flammability attributes, between nF and FT, with more numerous nF related to cooler FT (Fig. 2.2; r = 0.70, P = 0.011). No significant pairwise relationships emerged among TTF, FD and nF, or between FT and either FD or TTF.

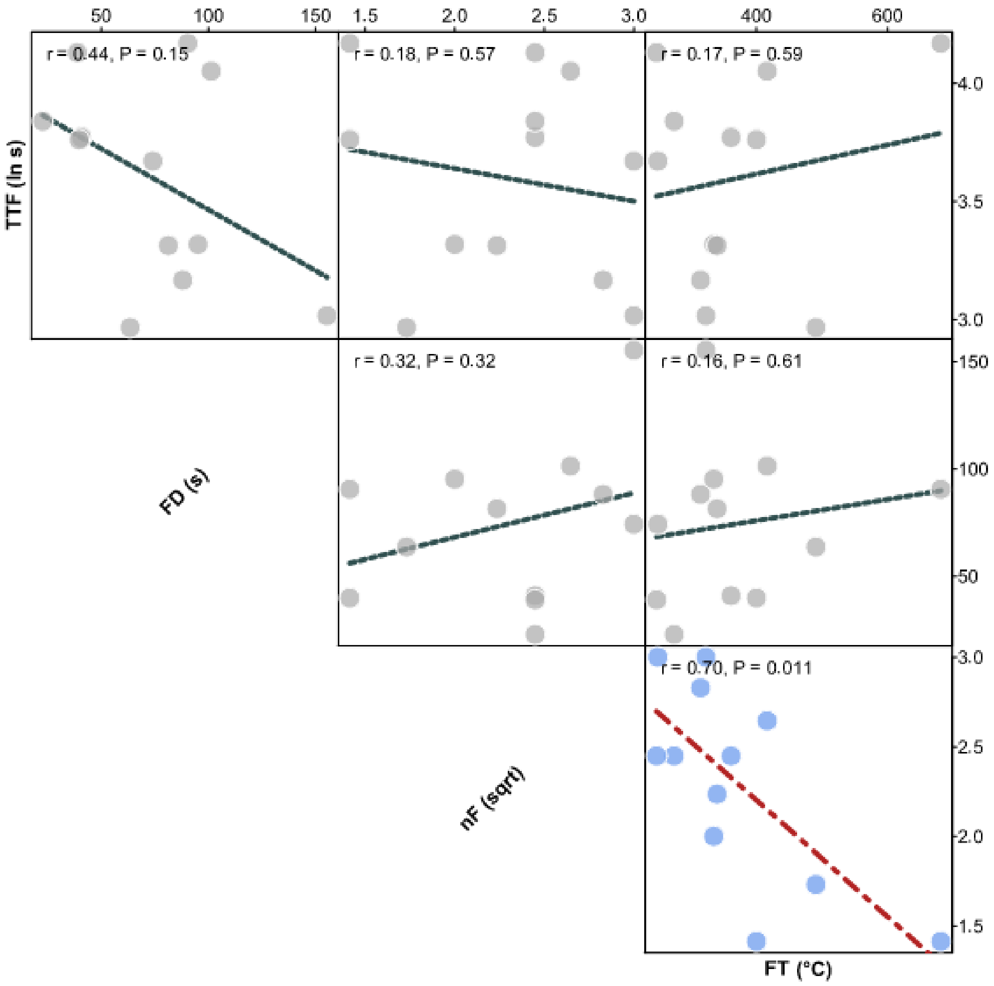


Fig. 2.2 Pairwise correlations between flammability attributes time-to-flame (TTF), flame duration (FD), number of flaming events (nF), and flame temperature (FT). Broken lines represent the linear relationship, r and P values for each relationship are shown at top left of each plot. Significant relationships are colourised.

2.3.2 Inter-species differences in shoot flammability attributes

Among species, significant differences were found for TTF (Fig. 2.3a; $F_{11,96} = 9.281$, $P < 0.001$), FD (Fig. 2.3b; $F_{11,96} = 14.591$, $P < 0.001$), nF (Fig. 2.3c; $F_{11,96} = 11.629$, $P < 0.001$) and FT (Fig. 2.3d; $F_{11,96} = 7.905$, $P < 0.001$). For TTF, the three fastest igniting species (*W. fruticosa, W. floribunda,* and *C. viminalis*) were native species, followed by *F. griffithii* (exotic) and *Grevillea* 'Moonlight' (native). These species did not differ significantly in TTF, but as a group were significantly faster to ignite than the other species. The longest TTF species were exotics (*C. leylandii*, *V. odoratissimum* and *M. grandiflora;* Fig. 2.3a), while not differing significantly from the species with intermediate TTF lengths (*E. robusta, G. augusta*, *L. indica* and *A. smithii)*. *Westringia fruticosa* had significantly longer FD compared to all other species (Fig. 2.3b), while *L. indica, V. odoratissimum, G. augusta, E. robusta* and *W. floribunda* had the shortest FD (not differing significantly among themselves). The balance of species, *C. leylandii*, *M. grandiflora*, *F. griffithii, C. viminalis, Grevillea* 'Moonlight' and *A. smithii* did not significantly differ in their FD. *Magnolia grandiflora*, *E. robusta*, *W. floribunda* and *F. griffithii* (not differing significantly among themselves) flamed significantly fewer times compared to *A. smithii*, *W. fruticosa*, *C. viminalis*, *C. leylandii, L. indica*, *G. augusta*, *Grevillea* 'Moonlight' and *V. odoratissimum* (in order from most times flaming to least, with no significant differences among the group; Fig. 2.3c). *Magnolia grandiflora* displayed significantly hotter FT compared to all other species (Fig. 2.3d), with no significant differences among other species, with the exception of *A. smithii* (with the lowest FT) compared to *W. floribunda* and *C. leylandii* (second and third hottest burning respectively).

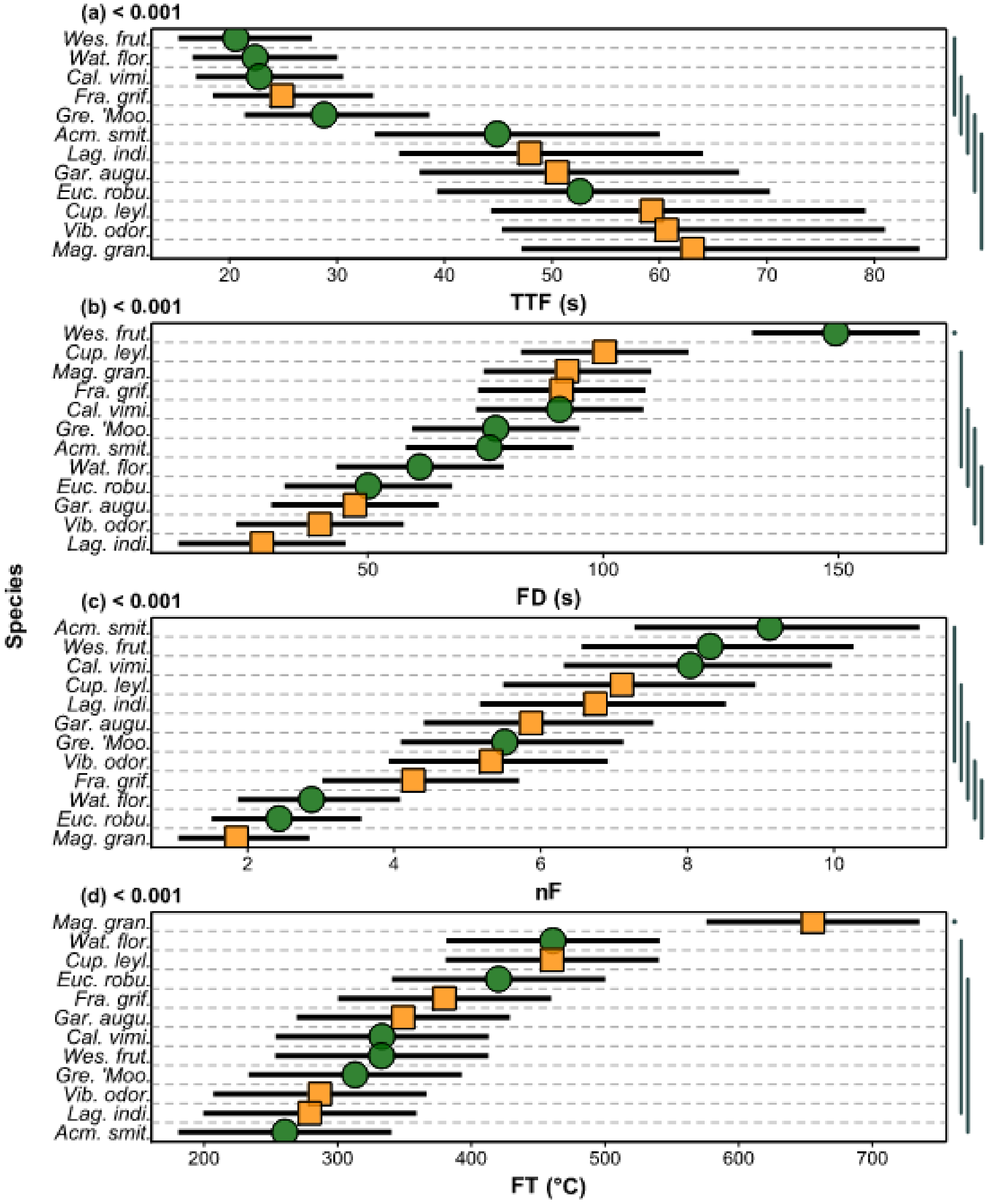


Fig. 2.3 Inter-species variation in flammability attributes (points represent means, black bars 95% CI), for TTF (a), FD (b), nF (c) and FT (d). The vertical lines at the right margin of plots indicate the overlaps among means, with no overlap indicating significant difference. Species are ordered from most to least flammable from top to bottom. Exotic species are represented in orange, native species in green. Squares and circles show mean values as estimated by models with a 95% confidence interval (black horizontal lines). Presented are P values from linear models.

2.3.3 Comparisons of species' ranking between shoot flammability attributes

While certain species emerged as having high-flammability combinations of attributes, e.g. *W. fruticosa* with fast TTF, long FD, and more numerous flaming (Fig. 2.3), no consistent coordination across species in flammability ranks was evident (Fig. 2.4), with all rank comparisons significant. On the other hand, *V. odoratissimum* maintained below average results in each flammability category except nF making it a good low-flammability selection. *A. smithii* presented in the middle ground for each of the flammability attributes except for FT in which it burnt the coolest in temperature out of all species also making it a good selection.

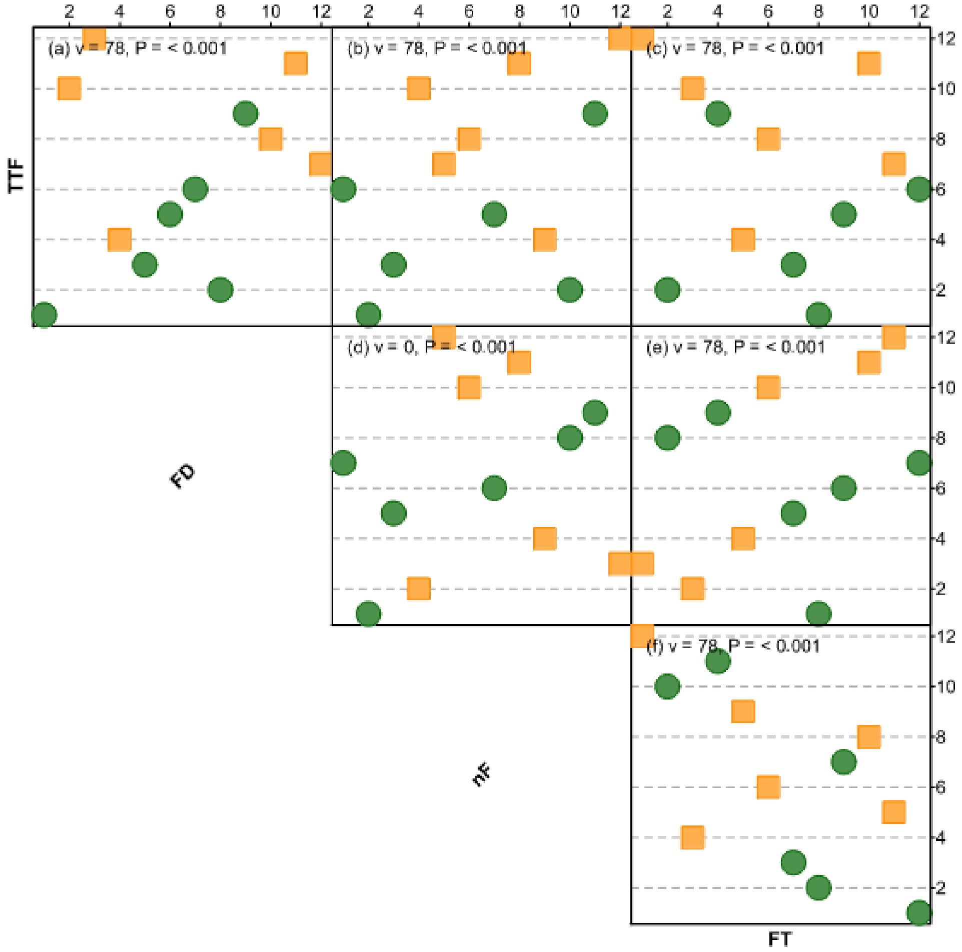


Fig. 2.4 Fig. Rank correlations of bivariate relationships between the flammability attributes of time to flame (TTF), flame duration (FD), number of flaming events (nF) and flame temperature (FT). Exotic species are represented with orange squares, native species with green circles. Each relationship is presented with v and P values from Wilcoxon signed rank tests. Values of FD, nF and FT were made negative and TTF left as is, so that a rank closer to one (out of twelve) indicates faster TTF, longer FD, more flaming events (nF) and higher FT.

2.3.4 Relationships between shoot traits and shoot flammability attributes

While no significant predictor for TTF emerged, the most explanatory trait was leafing intensity (Fig. 2.5a; $F_{1,95}$ = 1.557, P = 0.22), with a trend between higher leafing intensity and longer TTF. Higher leafing intensity was significantly associated with longer FD (Fig. 2.5b; $F_{1,95}$ = 15.005, P < 0.001), and the most explanatory trait for nF was FMC (Fig. 2.5c; $F_{1,95}$ = 1.056, P = 0.31). Higher bulk density (Fig. 2.5d; $F_{1,94}$ = 12.968, P = < 0.001) and larger volume (Fig. 2.5e, $F_{1,94}$ = 12.514, P < 0.001) were found to be significant predictors of hotter FT.

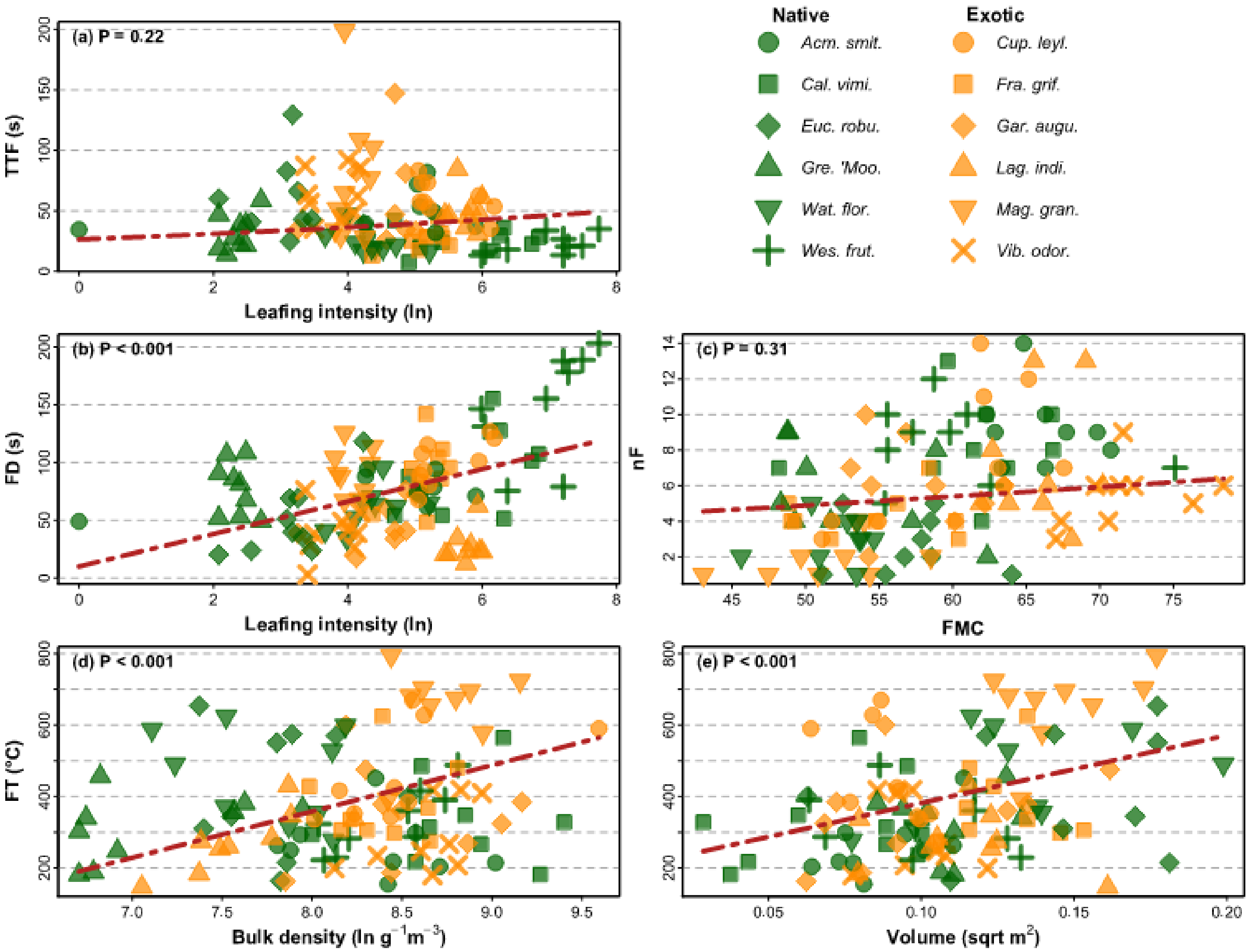


Fig. 2.5 Plots of the flammability attributes TTF (a), FD (b), nF (c), and FT (d and e) and the shoot traits which best explained the observed patterns in flammability (on the basis of BIC). Symbols and colours of points denote species and status (native or exotic), with a key.

2.3.5 Shoot trait differences between species

Species differed significantly in bulk density (Fig. 2.6a; $F_{1,96} = 18.011$, $P < 0.001$), leafing intensity (Fig. 2.6b, $F_{1,96} = 30.500$, $P < 0.001$) and volume (Fig. 2.6c; $F_{1,96} = 7.989$, $P < 0.001$), with complex patterns of overlaps among species (i.e. not differing significantly). *Cupressocyparis leylandii*, *G. augusta*, *M. grandiflora, C. viminalis, W. fruticosa, F. griffithii* and *A. smithii* did not differ significantly in their bulk density, while *F. griffithii* and *A. smithii* also showed no significant difference to *E. robusta* with lower mean bulk density. *Grevillea* 'Moonlight' had the lowest overall bulk density, but did not differ significantly from *L. indica,* which displayed similar bulk density to *W. floribunda* and *E. robusta.*

Westringia fruticosa had significantly greater leafing intensity relative to all other species (Fig. 2.6b), followed by *C. viminalis* and *L. indica* (not differing significantly between species), which also did not differ significantly from the leafing intensities observed for *C. leylandii* and *F. griffithii. Grevillea* 'Moonlight' had the lowest leafing intensity, although did not significantly differ from that of *E. robusta*, which showed values similar to *M. grandiflora* and *V. odoratissimum. Waterhousea floribunda*, *A. smithii* and *G. augusta* showed intermediate leafing intensities, not differing significantly to *M. grandiflora* or *V. odoratissimum*, while *A. smithii* and *G. augusta* also did not differ significantly from species with more numerous leaves (*C. leylandii* and *F. griffithii*).

Magnolia grandiflora and *E. robusta* (no significant difference between species) showed larger volume relative to most species, although not differing significantly to *F. griffithii, L. indica, W. floribunda,* or *G* 'Moonlight'. *Callistemon viminalis* had lowest mean volume, not differing significantly to *A. smithii*, *C. leylandii*, *G. augusta*, *V. odoratissimum*, *W. fruticosa*, or *G.* 'Moonlight'.

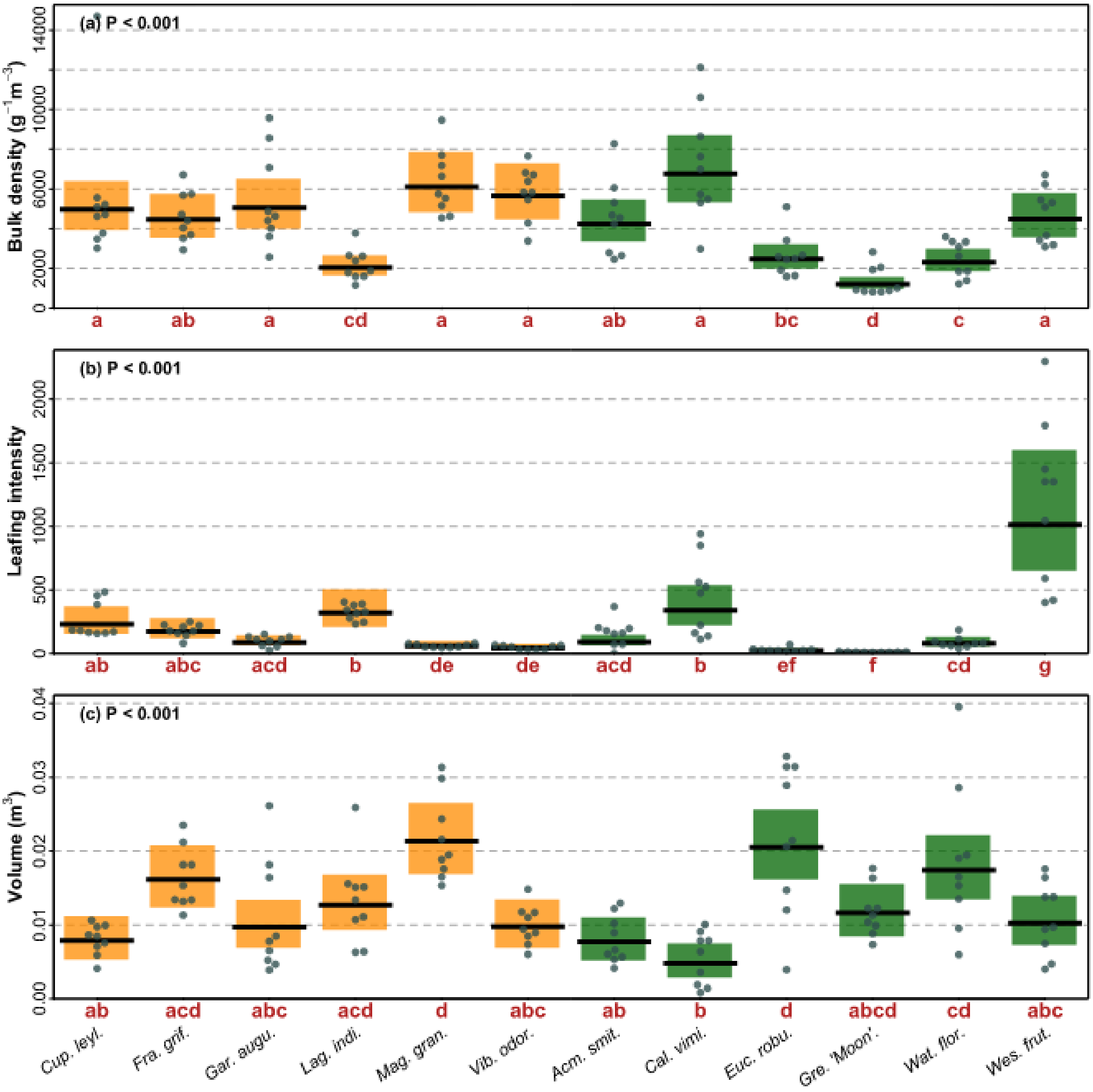


Fig. 2.6 Plots of shoot traits by species, showing bulk density (a), leafing intensity (b) and volume (c), which were found to be informative predictors of shoot flammability. Black lines represent means, shaded areas the 95% CI of the mean, the points are the observations. Red letters on the x-axis of each plot indicate the which species did not significantly differ in any given trait. Species names are shown at the bottom of (c), with P values for the overall test at top left.

2.3.6 Shoot flammability differences between native and exotic species

As a group, exotic species showed significantly slower TTF than native species (Fig. 2.7a; χ^2 = 5.224, DF = 1, P = 0.022), with no significant differences in FD (Fig. 2.7b; χ^2 = 0.838, DF = 1, P = 0.36), nF (Fig. 2.7c; χ^2 = 0.224, DF = 1, P = 0.64), or FT (Fig. 2.7d; χ^2 = 0.553, DF = 1, P = 0.46), compared to native species. For shoot traits, no significant differences were found between native and exotic species for leafing intensity (Fig. 2.8a; χ^2 = 0.121, DF = 1, P = 0.73), bulk density (Fig. 2.8b; χ^2 = 1.495, DF = 1, P = 0.22), or volume (Fig. 2.8c; χ^2 = 0.133, DF = 1, P = 0.72).

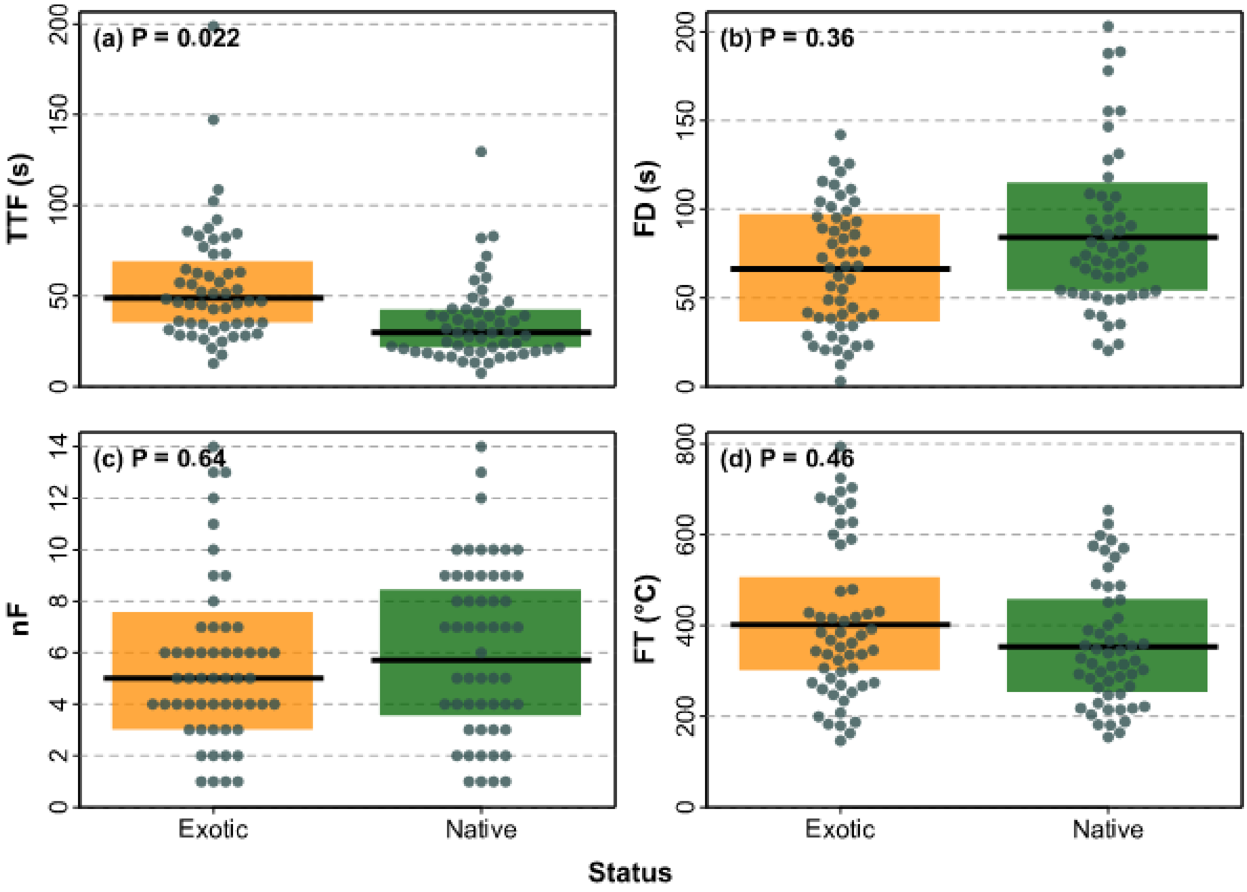


Fig. 2.7 Plots of flammability attributes by plant native/exotic status, showing TTF (a), FD (b), nF (c) and FT (d). Black lines represent means, shaded areas the 95% CI. The points show observations for species. At top left of each plot the P value for test is shown.

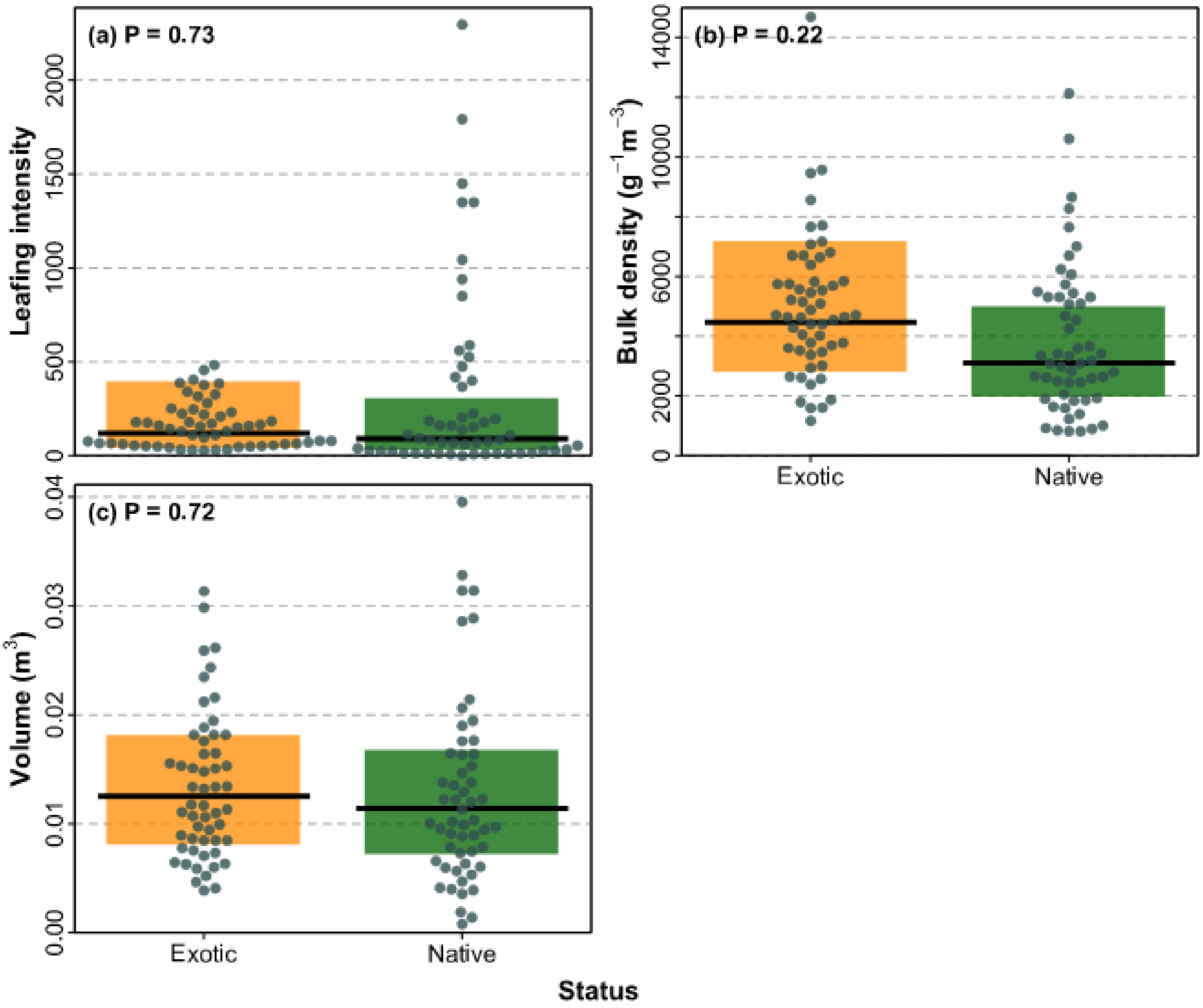


Fig. 2.8 Plots of shoot traits by plant native/exotic status, showing leafing intensity (a), bulk density (b) and volume (c). Black lines represent means, shaded areas the 95% CI. The points show observations for species. At top left of each plot the P value for test is shown.

2.4 Discussion

Measurements of the shoot flammability attributes TTF, FD, nF, and FT provide an informative overview of the intrinsic nature of how plant species burn in terms of the dimensions of ignitibility, sustainability, and combustibility (Anderson, 1970; Martin et al., 1994). In this study, the ignitibility of a shoot was described by TTF, which provides a direct measure of the lag time between when a shoot experiences moderately high radiant heat from a wildfire and when the shoot begins flaming combustion. The sustainability of a shoot flame was measured here by using the attributes FD and nF, both of which provide an indication of the longevity of flames and flaming events during a wildfire. The overall combustibility of a shoot was represented by the temperature of the flame itself. All three of these flammability dimensions are worth considering in the context of the most appropriate low-flammability species that can be used in residential gardens at the WUI. When selecting a low-flammability plant species, an ideal species (sensu Murray et al. 2018) would have a long time to ignite (TTF), only burn for a short time (FD), have few flaming events (nF), and not burn at very hot temperatures (FT).

2.4.1 Shoot flammability variation among garden species

The results of my study show that such ideal low-flammability plant species were not present among the 12 garden species. This was demonstrated most particularly by the fact that the species were not consistent in the rankings of their flammability attributes. Indeed, there were some remarkably idiosyncratic patterns within each of the species. For example, *Magnolia grandiflora* displayed the longest TTF making it the least flammable in the flammability dimension of ignitibility, yet it also burnt significantly hotter than every other species, making it the most flammable in terms of the combustibility dimension of flammability. Overall, due to the lack of concordance between the flammability rankings, it is apparent that each flammability attribute must be considered individually on a case-by-case basis when considering the planting of these garden species in fire-resilient gardens, as some flammability attributes may be more relevant to particular locations. How representative were these species of residential garden plants in the Greater Sydney region, with respect to generalising the findings from these 12 species to the broader pool of garden species? First, I selected some of the most common species for this study, from nine different taxonomic families. Second, I included a mix of native and exotic species and included cultivars. Together, these selection criteria for the species support the notion that my findings are likely to be representative of other woody garden species growing in residential gardens.

In terms of the most important of the flammability attributes to consider in residential gardens, one suggestion is that it might be helpful to plant species with low ignitibility (i.e. long TTF) first and foremost around homes. This would mean that in situations where residents require time to reach and extinguish spot fires, the fewer plants igniting in a given period time provides more time for preventing spot fires expanding to fuller fires. The three species in this study with the lowest ignitibility included the exotics *Cupressocyparis leylandii*, *Viburnum odoratissimum*, and *Magnolia grandiflora*. At first glance, these three species might seem to be appropriate species for fire-resilient landscapes. However, my research shows why it is essential to examine multiple dimensions of shoot flammability. Two of these species, *Cupressocyparis leylandii* and *Magnolia grandiflora* were both highly flammable with respect to long flame durations and high flame temperatures. In contrast, the other species, *Viburnum odoratissimum*, demonstrated lower flammability for both FD and FT, ranking second slowest to start flaming, second shortest in flame duration, whilst maintaining the third lowest FT, making it one of the least flammable species in this study. This means that *Viburnum* *odoratissimum* has the potential to be planted near other plants and structures in the garden in a low to moderate intensity fire. However, considering that exotic ornamental species have the risk of 'jumping the garden fence' (Groves et al., 2005), I recommend that native species with low-ignitibility are preferentially planted in residential gardens (see in section 2.4.4).

2.4.2 Shoot traits affects on shoot flammability patterns

A common explanation for the differences in flammability among species, as observed in the present study, is the natural variation of plant traits that each species displays (Jaureguiberry et al., 2011; Murray et al., 2013; Pérez-Harguindeguy et al., 2013; Krix & Murray, 2018; Alam et al., 2020; Kraaij et al., 2022; Morley, 2022; Potts et al., 2022; Murray et al., 2023). To explore this, a BIC interpretation showed the traits with the most explanatory power for the flammability attributes results (Fig. 2.5). Leafing intensity (number of leaves in comparison to number of branches) is an attribute that has not been widely considered within practical flammability work. However, Calitz et al. (2015) found that a high leafing intensity on sample shoots influenced a high category burn. This directly supports the finding in this study whereby a higher leafing intensity best explained a longer FD (Fig. 2.5). For example, *M. grandiflora* leaves were very large and plentiful, and with this higher fuel load within the 50cm shoot, it allowed them to burn for a long time. The number of flame events (nF) as a flammability attribute has not been considered in previous studies, and although the positive relationship between nF and FMC in this study is not significant, a high FMC was the trait that best explained a greater number of nF (Fig. 2.5c). This could mean that a higher FMC may reduce the sustainability and consistency of a burn. Due to the traits only explaining significant results to the attributes of TTF FD and FT and not nF; it can be determined that nF is not as strong of an indicator for the overall flammability of a shoot sample.

Alternatively, the trait of bulk density has been a consistently measured trait within shoot flammability studies. My experiments found that an increase in bulk density meant a significantly increase in FT (Fig. 2.5d). This finding is supported in other shoot level studies across Australia (Morley, 2022; Murray et al., 2023) and New Zealand (Alam et al., 2020), and reflects the leafing intensity findings. Lastly, an increasing FT was also significantly found to also be best explained by an increase in volume (Fig. 2.5e). In Murray et al. (2023)'s study, shoots with a low burning temperature were found to have a low volume as well. From these outcomes it can be concluded that the physical shoot traits of leafing intensity, bulk density and volume are likely great indicators for the flammability attributes of TTF, FD and FT. These general patterns uncovered through the BIC model show us that as a shoot becomes larger and with a greater number of leaves, there will likely be higher flammability outcomes. This is an important consideration in terms of garden design at the WUI, as current advice for residents, is to not plant trees near each other or structures (Country Fire Authority 2011; Strahan et al. 2018; Power 2020; Corbett 2021; Papathoma-Köhle et al. 2022) (Country Fire Authority, 2011; Strahan et al., 2019; Power, 2020; Corbett, 2021; Papathoma-Köhle et al., 2022). From the results of this study, it is advised to not to plant species with a high leafing intensity, bulk density and volume next to structures as it would allow a greater transfer of high intensity fire.

Although the species differed significantly for each trait in Fig. 2.6, the complex overlap between species for within each trait (bulk density, leafing intensity and volume) meant only a few distinct conclusions could be drawn. It can be concluded that *Grevillea* 'Moonlight' and *Lagerstroma indica* had the lowest BD values respectively and thus should also display low FT values (Fig. 2.6a). This pattern is supported by the Fig. 2.3d by which *Grevillea* 'Moonlight' ranked fourth coolest and *Lagerstroma indica* ranked second coolest in FT values (Fig. 2.3d).

Magnolia grandiflora displayed both a high bulk density and volume in Fig. 2.6 affecting its flammability attributes. Even though *Magnolia grandiflora* took the longest to ignite (Fig. 2.3a) making it resistant to radiant heat, once ignited it was found to burn for the third longest duration (Fig. 2.3c) and significantly hotter than the other study species (Fig. 2.3d). This means that a careful site assessment must be conducted if *Magnolia grandiflora* is to be planted in a garden. It could be planted near potential radiant heat sources such as undergrowth but should not be planted near other trees or structures due to its flammable nature once it ignites. Similarly, in Fig. 2.6b *W. fruticosa* displayed a significantly higher leafing intensity than all other species. The results show us that a high leafing intensity significantly explains a longer FD and shorter TTF, making a species more flammable (Fig. 2.5). This pattern can be seen in the rank plots whereby *W. fruticosa* has the shortest TTF and significantly longest FD (Fig. 2.3). Although this means that *W. fruticosa* may have a higher likelihood of spreading fire to other vegetation as it maintains flame for a long time, it may not mean that it is overall the most flammable species, as it ranks fifth lowest in the FT rankings (Fig. 2.3d). Due to *W. fruticosa*'s ability to maintain flames, albeit at a low intensity, it is recommended to not plant this species below or in close proximity other plants with a fast ignition time.

Fuel moisture content was maintained consistently for all samples in this study through regular irrigation at the plant nurseries, allowing the FMC to retain close to each species potential. This explains why FMC did not emerge as a plant trait causing differing flammability outcomes. To determine if a lower FMC would create different outcomes in real world scenarios, it is advised that further studies should lower plants FMC in a controlled manner through drought periods. This will allow a good representation of both well-watered and disregarded plant species within peri-urban environments. This is especially important for native species, as they are often selected for their hardiness and drought resistance.

2.4.3 Differences and similarities between the shoot flammability of garden species

To address if there was a difference in the flammability attributes between the native and exotic species sampled, a comparison was completed (Fig. 2.7). Only the TTF was found to be faster in the native study species than the exotic species (Fig. 2.7a). Few studies have compared Australian native species' shoot flammability with exotic species', however Murray et al. (2023) also found that TTF was significantly faster in wildland native plant species compared to urban exotics. This allows me to conclude within the species in this study, that the natives were more ignitable than the exotic species and that leafing intensity was best able to explain TTF. *Westringia fruticosa, Callistemon viminalis* had the highest leafing intensities for native species (Fig. 2.6b), and presented as some of the fastest species to ignite (Fig. 2.3a). These species may want to be avoided in areas of high risk such as in gardens edging the WUI, and it should be ensured that they do not overlap with other vegetation as they may trigger further ignition (Power, 2020). However, overall, there were no consistent differences in shoot flammability between native and exotic species. Given this finding, I suggest that future efforts target the identification of native garden species with low flammability, given the increased likelihood of biodiversity benefits from native urban plants for native fauna (Threlfall et al., 2016; Mata et al., 2021; Mata et al., 2023).

2.4.4 Selection of low-flammability species in garden design

Whilst reducing the flammability of gardens is essential for the protection of homes at the WUI, other factors must be considered when creating a wholistically beneficial garden. The design of a garden is a key factor in its flammability, with assessments in slope, potential wind channels, ground fuel load, and islands of fuel being essential (Power, 2020). By determining plants flammability, it can be determined how they can best be used or avoided in a fire-resistant garden design. Additionally for the creation of a wholistically resilient garden design, Murray et al. (2018) suggests a workflow considering plants biodiversity promoting qualities before how low flammability they are, followed by how climate change resistant they are. Due to these factors of importance, I suggest preferencing low-flammability native species over exotic species, despite native's being found to have a faster TTF (Fig. 2.7a). This is because the other flammability attributes of FD and FT were found to equally contribute to a plant's flammability. The limited number of species in the study resulted in natives presenting as a faster TTF, but these results can't claim that the same patterns would occur in all native species. Planting native species over exotics is also advised due to the biodiversity benefits native vegetation provide to native wildlife, such as providing food and habitat (Murray et al., 2018) for groups like birds (Driscoll, 1977; Murray et al., 2007; Threlfall et al., 2016) and insects (Robson et al., 2009; Sands, 2018; Mata et al., 2021; Mata et al., 2023). From my experiments I have identified *Acmena smithii* (Common Lilly Pilly) and *Grevillea* 'Moonlight' as native species found to have an average TTF and FD, and low FT (Fig. 2.3), making them potential selections in a low flammability garden. My experiments show that there isn't a single way of determining flammability, and that each attribute must be considered within each species in relation to a particular site. Further research should look for more low-flammability native plant species, that can also provide other desired properties for the ecosystem and community (Murray et al., 2018). This research shows that although there isn't a singular way to define flammability it has been able to inform wildfire conscious plant selection for gardens at the WUI.

Chapter 3 | Shoot flammability patterns in native and exotic street tree species: Implications for wildfire spread at the wildland-urban interface

Abstract

Street trees provide ecosystem services such as heat mitigation, improved human well-being, and biodiversity conservation. At the wildland-urban interface, however, street tree fuel loads may provide a conflicting ecosystem disservice, heightening wildfire spread risk into urban areas. To mitigate this service-disservice conflict, low-flammability species must be identified for street tree plantings. We assessed shoot flammability patterns in 10 common street tree species and found significant inter-species differences in time-to-flame, flame duration, number of flaming events, and flame temperature. Rankings of species from least to most flammable, however, were not consistent between pairs of these flammability attributes. These results indicate for street trees that a one-size fits all approach to species selection, with respect to the contributions of these different dimensions of flammability to mitigating wildfire risk, is not optimal. Nevertheless, the native tree species Tuckeroo (*Cupaniopsis anacardioides*), emerged as a likely candidate for further exploration as a low-flammability street tree species. The findings of our study can be used to inform broader strategies involving the planting of low-flammability street trees at the wildland-urban interface.

3.1 Introduction

At the wildland-urban interface (WUI), urbanized landscapes sit within areas of undeveloped wildland vegetation (Radeloff et al., 2005). Wildfires that spread from wildland to urban areas pose a serious risk for residents living at the WUI (McWethy et al., 2019). While houses and infrastructure can propagate wildfires into urban areas (Haight et al., 2004), vegetation in recreational parks and home gardens, and trees planted along streets, can also provide fuel for wildfire spread (Caton et al., 2017). In many regions of the world, urban greening strategies are increasing tree canopy cover to combat urban heat island (UHI) effects (Pincetl et al., 2013; Wang & Akbari, 2016; Nguyen et al., 2017). As a result, efforts to increase street tree coverage, which also increase vegetative fuel load, may lead to urban areas at the WUI becoming more vulnerable to the impacts of wildfires. Indeed, previous research has found that areas of the WUI with low residential housing density and broader tree coverage are at greater risk from wildfires (Gibbons et al., 2012; Villaseñor et al., 2016; Price et al., 2021).

Urban tree plantings are vital for communities as they provide residents with a range of ecosystem services (Willis & Petrokofsky, 2017). In addition to mitigating UHI effects, tree ecosystem services include positive impacts on the health of residents (Turner-Skoff & Cavender, 2019), opportunities for urban permaculture that contribute to sustainability and strengthening of community ties (Holmgren, 2006; Fadaee, 2019), and biodiversity conservation (Bodnaruk et al., 2017; Turner-Skoff & Cavender, 2019). However, tree ecosystem services can be offset by a range of disservices (Roman et al., 2021), including safety risks to residents from falling branches, and damage to infrastructure from tree roots (Kirkpatrick et al., 2012; Mullaney et al., 2015). The increase in vegetative fuel load from street tree plantings can also provide an ecosystem disservice, because high-flammability tree species contribute to risks of wildfire spread (Murray et al., 2023). In contrast, despite increasing vegetative cover, plantings of low-flammability tree species could reduce wildfire risks, providing an ecosystem service in the form of opportunistic green firebreaks that help to slow or stop the spread of wildfires in urban regions (Mell et al., 2010; Curran et al., 2018; Gibbons et al., 2018; Murray et al., 2018; Cui et al., 2019; Murray et al., 2020; Corbett, 2021; Drew-Smythe et al., 2023). As a first step to address this service-disservice tree conflict, flammability assessments of street tree species are needed to distinguish low-flammability from high-flammability species. In this way, evidence-based selection of tree species is prioritized to maximise the potential for the beneficial service of green firebreaks.

In this study, we assessed shoot flammability patterns in five native and five exotic species widely used as street trees in the Central Coast region of New South Wales (NSW), Australia. The aims of this study were (1) to compare and rank the ten species based on their relative flammability to distinguish low-flammability from high-flammability species; (2) to identify the relative roles of a range of shoot traits in driving variation in shoot flammability among species; and (3) to determine whether shoot flammability differs between native and exotic tree species. There is a growing body of research exploring shoot flammability patterns among species in non-WUI areas (e.g. Argentina, (Santacruz-García et al., 2019); Australia, (Potts et al., 2022; Murray et al., 2023); New Zealand, (Wyse et al., 2016; Padullés Cubino et al., 2018; Cui et al., 2020a); South Africa, (Burger & Bond, 2015; Calitz et al., 2015; Kraaij et al., 2022)). However, there have been no studies that specifically examine patterns of shoot flammability among species that are commonly planted as street trees in areas of the WUI, despite such information being of critical importance for understanding wildfire risks posed by street trees. Our identification of plant traits defining low-flammability species can be used to suggest other species worthy of further exploration as low-flammability species based on the traits that they possess (Krix & Murray, 2022; Murray et al., 2023).

3.2 Methods

3.2.1 Study region and species

Our study region was the Central Coast Local Government Area (LGA), on the east coast of NSW (33◦ 31′55″S, 151◦ 10′51″E). The Central Coast LGA is one of eastern Australia's largest urban population centres (Fig. 3.1). The LGA covers 1,681 km^2 and has a population of 346,596 people, which is predicted to increase to 400,000 by 2036 (Central Coast Council, 2020; Australian Bureau of Statistics, 2021b). The region is characterised by an urban to peri-urban landscape primarily composed of separate low-density houses (78.4% of dwellings in the LGA) (Australian Bureau of Statistics, 2021b) and National Parks covering over half of the LGA (Central Coast Council, 2019). Risks of wildfire incursion into urban areas are posed from surrounding fire-prone dry sclerophyll forest, which is the dominant wildland vegetation at the region's WUI (Central Coast Bush Fire Management Committee, 2020). The region was heavily impacted by the 2019–2020 'Black Summer' bushfires along eastern Australia, when 459 km^2 (27%) of the LGA was burnt (NSW Government, 2020). The region has a fire season of six months over spring and summer (September to February), when the average daily maximum temperatures are 21°C in spring and 33°C in summer, with humidity averaging between 70–90% throughout the year (Australian Bureau of Meteorology, 2020).

Approximately 70% of the land surface of the LGA is covered by plants, with nearly 20% of the vegetation found in home gardens, recreational parks, and as street tree plantings in residential and city-centre areas (Central Coast Council, 2019). Mature trees are often commissioned by Central Coast Council for street plantings from specialised tree nurseries as part of urban greening projects (Drew-Smythe et al., 2023). In consultation with the Council, we selected five native and five exotic street tree species commonly occurring in the LGA as street trees (Table 1). All 10 study species grow taller than 5 m, with branches concentrated high on the trunk, allowing ease of passage for pedestrians and cars, while providing shade and offering shelter for wildlife. The species are all broad-leaved, which aids in the creation of shade to mitigate urban heat island effects (Wang & Akbari, 2016) and the provision of shelter to support native bird biodiversity (Pena et al., 2017). We collected shoot samples of the study species for our flammability experiments from Trees Impact (Lake Munmorah, Central Coast NSW) (Fig. 3.1), a large wholesale tree nursery that is the only dedicated containerised large-tree grower in eastern Australia. The widespread use of the study species as street trees in the region was confirmed by Trees Impact, with the 10 species among those most commonly commissioned for large-scale planting projects.

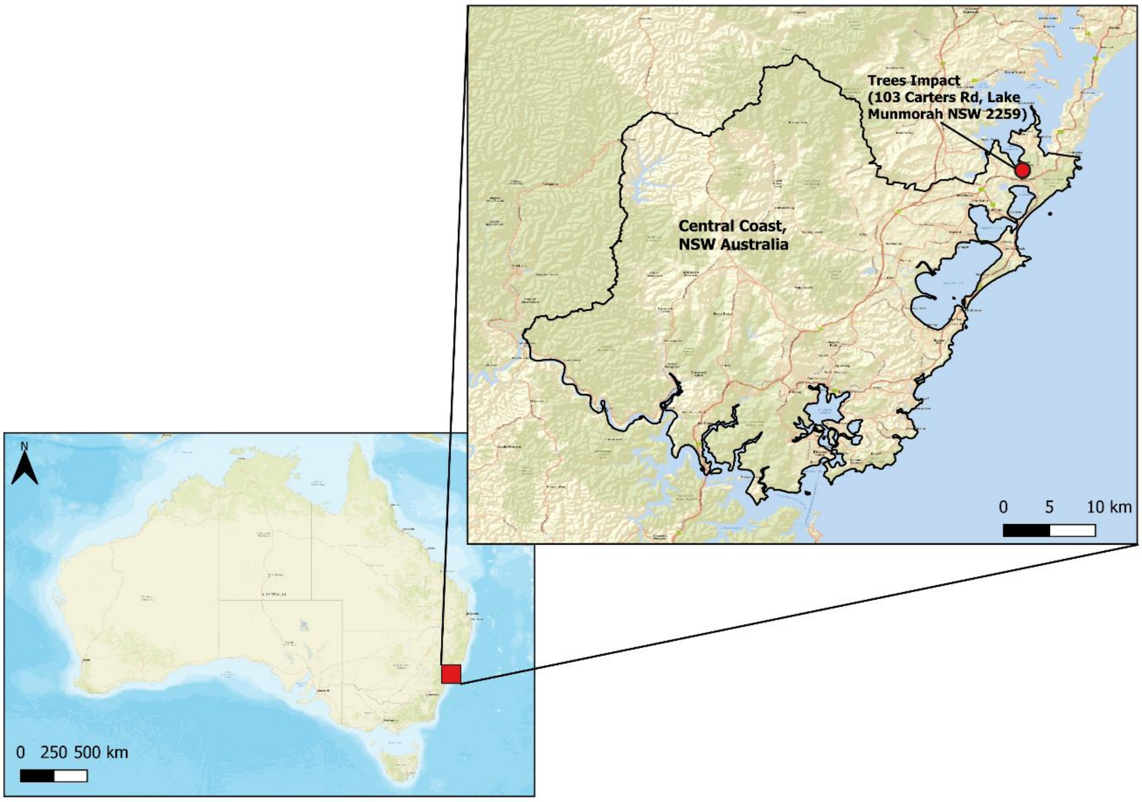


Fig. 3.1 Map of the Central Coast study region in New South Wales in eastern Australia.

Table 3.1 The ten street tree species assessed for shoot flammability with their common name, taxonomic family and status as either native or exotic in Australia.

Species	Common Name	Family	Status
Banksia integrifolia	Coastal banksia	Proteaceae	Native
Corymbia maculata	Spotted gum	Myrtaceae	Native
Cupaniopsis anacardioides	Tuckeroo	Sapindaceae	Native
Fraxinus pennsylvanica	Cimmaron ash	Oleaceae	Exotic
Jacaranda mimosifolia	Jacaranda	Bignoniaceae	Exotic
Lophostemon confertus	Brush box	Myrtaceae	Native
Quercus palustris	Pin oak	Fagaceae	Exotic
Tristaniopsis laurina	Water gum	Myrtaceae	Native
Ulmus parvifolia	Chinese elm	Ulmaceae	Exotic
Zelkova serrata	Japanese zelkova	Ulmaceae	Exotic

3.2.2 Shoot collection

Trees Impact provided access to their nursery for collecting shoots of the 10 species in the summer (January–February) of 2023. We collected shoot samples from the exposed terminal branches of healthy, mature, and well-watered individuals following a standardised sampling protocol (Jaureguiberry et al., 2011; Wyse et al., 2016; Potts et al., 2022). Shoots were sampled from nine replicate individual plants of each species (Pérez-Harguindeguy et al., 2013; Murray et al., 2023). Two representative and adjacent 50 cm shoot samples were collected from each plant. One shoot was the ‘burn’ shoot and used in flammability assessments, while the other shoot was the ‘trait’ shoot and used to measure a range of shoot traits. All shoots possessed multiple leaves, twigs and small branches to include key factors influencing the flammability of vegetation such as fuel arrangement, continuity and quantity (Martin et al., 1994; Alam et al., 2020; Murray et al., 2023). Immediately after sampling, the cut ends of shoots were wrapped in dampened cloth, and shoots were placed in sealed plastic bags. Shoot samples were stored at room temperature overnight before experimental assessment of shoot flammability the following day. Previous studies have allowed shoot samples to air-dry overnight to increase the likelihood that shoots of all species ignite under experimental conditions (Wyse et al., 2016; Wyse et al., 2018; Cui et al., 2022; Potts et al., 2022). This drying procedure was unnecessary in the present study as initial pilot studies showed that all 10 study species ignited within minutes of exposure to fire without any prior drying treatment.

3.2.3 Measurement of shoot flammability and shoot traits

Shoot flammability experiments were performed using a portable device following the standardised design of Jaureguiberry et al. (2011) (Jaureguiberry et al., 2011) and modified by Wyse et al. (2016). We measured four flammability attributes including the time taken for a shoot to begin flaming combustion (time to flame, TTF); the length of time a shoot spent in flaming combustion (flame duration, FD); the number of times a shoot entered flaming combustion (number of flaming events, nF), which included the initial flaming event and any other times the shoot entered flaming combustion after having ceased flaming; and the maximum heat of combustion of a shoot (flame temperature, FT). Observations ceased when a shoot did not enter flaming combustion again after two minutes. Our assessments focused on shoot flammability as it was not feasible to burn replicates of whole large trees of the study species (Jaureguiberry et al., 2011). While flammability testing of entire plants can provide a direct assessment of whole-plant flammability (Etlinger & Beall, 2004), recent research has demonstrated that flammability assessments of shoots from plant canopies provide an efficient and robust assessment of whole plant flammability (Wyse et al., 2016). In this context, Alam et al. (2020) compared a ranking of shoot flammability among 42 indigenous New Zealand plant species to a ranking of the same species derived from elicitation of expert opinion of fire managers (based on field observations by 59 fire managers of the burning characteristics of species during wildfires or prescribed burns across New Zealand; (Fogarty, 2001)), and found a good correlation between the two rankings.

The liquefied petroleum gas (LPG) powered flammability device provided heat when lit to radiate from below and through each burn shoot, with shoots burned one at a time. Each of a species' nine replicate burn shoots was placed horizontally on a mesh grill in the device set 20 cm above the flames, ensuring that overall shoot architecture was kept intact. The grill temperature was maintained at approximately 185°C. As soon as a shoot was placed on the BBQ grill above the flames, a timer was started to measure TTF and FD. We recorded nF for each shoot, with FD calculated as a summed value of time across all separate flaming events. A handheld infrared laser thermometer (Digitech QM 7226) was used at a distance of 50 cm from the shoot sample to measure the maximum temperature (FT) reached by the external flame plume (Jir-Ming & Jun-Hsien, 1996; Pérez-Harguindeguy et al., 2013; Calitz et al., 2015; Wyse et al., 2016; Murray et al., 2023). The field of view of the infrared laser thermometer at this distance was approximately 1.67 cm in diameter. When large or multiple flame events occurred, the sample was quickly scanned back and forth by the thermometer to determine maximum flame temperature.

We weighed each burn shoot prior to flammability assessment using a portable scale spring balance to determine shoot mass (g), and measured shoot length, width and height (cm) to estimate shoot volume (cm^3) as an elliptical cylinder (π × shoot length × shoot width × 0.5 × shoot height × 0.5). We also measured minimum and maximum stem thickness (cm) and counted the number of leaves (to determine leafing intensity, i.e. number of leaves in comparison to number of branches) and branches (branching intensity) on each burn shoot. Further detail in the definitions of leafing and branching of the study species can be found in Appendix A. The nine replicate trait shoots collected for each species were weighed (using a

Sartorius A 120 S Analytical Balance) to determine fresh mass (g), placed in a drying oven at 80°C for 48 hours, then weighed again to determine shoot dry mass (g). Shoot fuel moisture content was expressed as a percentage and calculated as the ratio of the difference between air-dried and oven-dried mass to air-dried dry mass ([air-dried mass − oven-dried mass]/air-dried mass). Shoot bulk density (g.cm^{-3}) was calculated as shoot air-dried mass divided by shoot volume. Leaf area (mm^{2}) was measured on five representative leaves from each trait shoot using a portable leaf area meter (LI-3000A).

3.2.4 Statistical analysis

We examined relationships between all pairwise combinations of the four flammability attributes using species' mean data (all sqrt transformed) (Fig. 3.2). Five of the six bivariate correlations in the matrix were non-significant ($P > 0.05$), while the sixth between TTF and FT was only marginally significant ($P = 0.048$). Consequently, we elected to explore shoot flammability patterns separately for each flammability attribute rather than use a principal components analysis to reduce the attributes into a smaller subset. We fitted a linear model on each flammability attribute, using species as a categorical factor (ten-level fixed factor), to determine whether there was significant variation among species in shoot flammability. For these models, TTF was ln transformed, nF was sqrt transformed, FD and FT were used without transformation, and all replicate observations were used (nine per species). Where the species term was significant, pairwise tests (with Tukey correction) were used to determine patterns of differences between species. Paired-sample Wilcoxon tests were performed on modelled values for species' means to determine if flammability rankings were consistent between all pairs of flammability attributes. For this test, FD, nF, and FT were made negative and TTF left as is, so that a rank closer to one (out of ten) indicated faster TTF, longer FD, more flaming events (nF) and higher temperature.

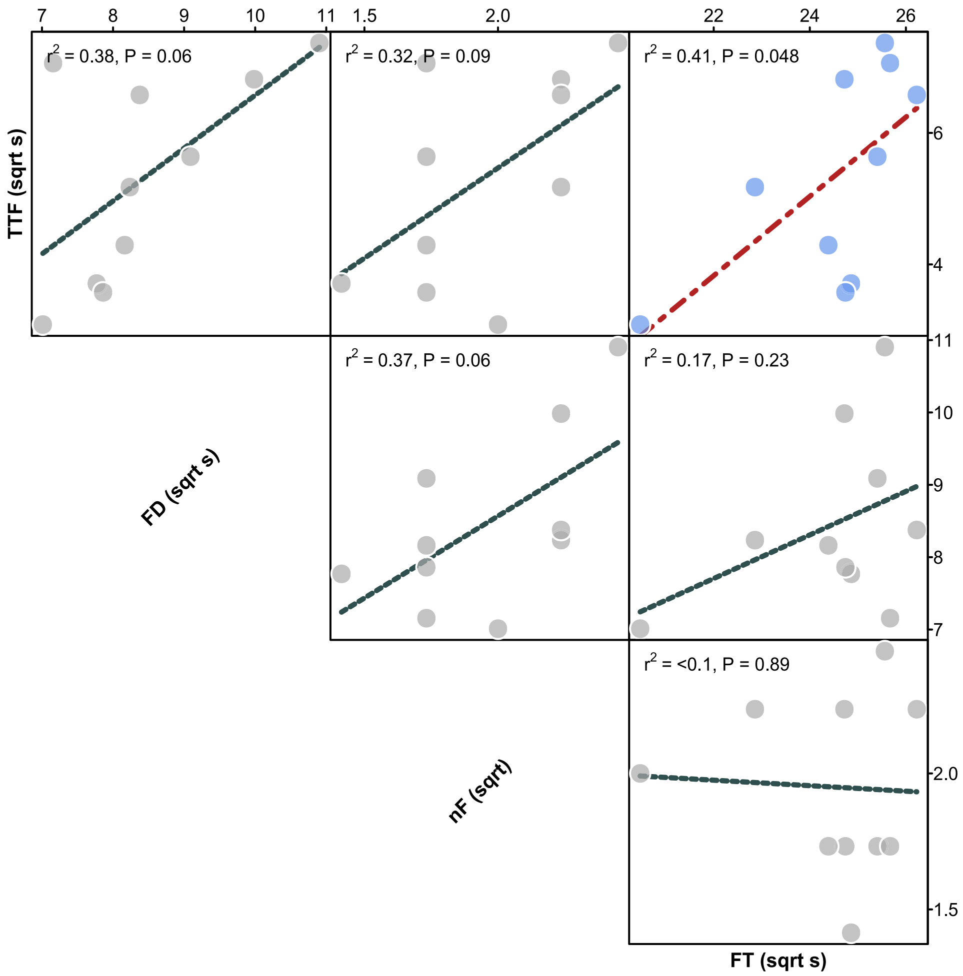


Fig. 3.2 Correlation coefficients (r) with P values of bivariate relationships between time to flame (TTF), flame duration (FD), number of flaming events (nF) and flame temperature (FT). Significant relationships are colourised.

To identify trait drivers of species-level patterns in shoot flammability, we first built a correlation matrix (Table 2) of the shoot traits that we measured using species' mean data for shoot mass, bulk density, branching and leafing intensity, fuel moisture content (ln transformed); volume, and minimum and maximum stem thickness (all sqrt transformed); and untransformed values for leaf area. Variables uncorrelated with other variables (i.e. r < 0.70) were then selected for further analysis (bulk density, leafing intensity, volume, fuel moisture content, minimum stem thickness and LA). Shoot mass, branching intensity and maximum stem thickness were omitted from further analyses as they were highly correlated with other traits (Table 2). As the number of candidate traits (six) used in our analyses was relatively high given the number of species (10), we used an information theoretic approach to identify the most explanatory candidate model containing four or fewer shoot traits and a term for species (all observations were used). A suite of models were then fitted to each flammability attribute using all unique four, three, and two term combinations of the selected shoot traits, as well as models using individual shoot traits, with all models including a controlling term for species. The most explanatory model was then selected on the basis of having the lowest Bayesian information criterion (BIC, chosen for its strong penalisation for number of model terms relative to other metrics, e.g. Akaike's information criterion). This approach allowed identification of the subset of traits driving shoot flammability while also favouring more parsimonious models. The trait models identified using the information theoretic approach were then tested for statistical significance using multiple regressions. We then fitted a linear model on each of these shoot traits, using species as a categorical factor (ten-level fixed factor), to determine whether there was significant variation among species in the traits. The same transformations of shoot traits were used as described above.

Table 3.2 Correlation matrix of all pairwise relationships between shoot traits. Correlation coefficients (r) are presented above the line of equivalence and P values below. BD = bulk density, Vol. = volume, BI = branching intensity, LI = leafing intensity, FMC = fuel moisture content, MinS = minimum stem thickness, MaxS = maximum stem thickness, LA = leaf area.

	Mass	BD	Vol.	BI	LI	FMC	MinS	MaxS	LA
Mass	1	0.66	0.82	0.58	0.49	0.29	0.71	0.84	0.32
BD	0.008	1	0.15	0.15	0.34	0.63	0.58	0.43	0.02
Vol.	0.001	0.60	1	0.74	0.46	-0.17	0.44	0.83	0.38
BI	0.03	0.59	0.002	1	0.77	-0.35	0.03	0.66	-0.10
LI	0.06	0.21	0.09	0.001	1	-0.03	0.18	0.53	-0.43
FMC	0.29	0.01	0.54	0.20	0.91	1	0.40	-0.03	0.18
MinS	0.003	0.03	0.10	0.91	0.53	0.14	1	0.48	0.29
MaxS	0.001	0.11	0.001	0.007	0.04	0.93	0.07	1	0.13
LA	0.25	0.93	0.16	0.73	0.11	0.51	0.29	0.65	1

To examine the relationship of plant native or exotic status to each of the four shoot flammability attributes, we fitted a linear mixed model on each flammability attribute separately with a fixed term for status (two-level factor; exotic or native species) and a random term for species (nine observations per species). We then fitted a linear mixed model on each shoot trait separately, with a fixed term for status and a random term for species, to determine native-exotic differences in shoot traits underpinning native-exotic differences in shoot flammability. For these two sets of analyses exploring native-exotic patterns, we used the same transformations as in the previous analyses.

All analyses were performed in R (R Core Team, 2023), using the packages car ((Fox & Weisberg, 2019); ANOVA for both linear and random effects models), emmeans ((Lenth, 2021); estimates of marginal effects and pairwise testing), and lme4 ((Bates et al., 2015); random model fitting).

3.3 Results

3.3.1 Comparison of shoot flammability attributes among species

There was a significant difference in TTF among species ($F_{9,80}$ = 16.63, P < 0.001; Fig. 3.3a). The fastest species to ignite were the exotics *J. mimosifolia* (median = 9.52 s) and *Q. palustris* (median = 12.78s), which demonstrated significantly (P < 0.05) faster TTF than all native species (*T. laurina* median = 54.27 s; *C. anacardioides* median = 49.86 s; *B. integrifolia* median = 46.45 s; *L. confertus* median = 43.26 s; *C. maculata* median = 31.79 s). A larger variance in TTF occurred among species than within species (65% vs 35%).

A significant difference in FD was found among species ($F_{9,80}$ = 5.01, P < 0.001; Fig. 3.3b). Here, a larger variance in FD occurred within species than across species (64% vs 36%). Nevertheless, two native species *T. laurina* (median = 118.88 s) and *B. integrifolia* (median =

99.69 s) sustained significantly ($P < 0.05$) longer flaming combustion than the three species that flamed for the shortest time, which were the exotics *J. mimosifolia* (median = 49.17 s) and *Q. palustris* (median = 61.78 s), and the native *C. anacardioides* (median = 51.22 s).

There was a significant difference in nF among species ($F_{9,80} = 5.08$, $P < 0.001$; Fig. 3.3c). As with FD, a larger variance in FD occurred within species than across species (64% vs 36%). However, two native species *T. laurina* (median = 6 flame events) and *L. confertus* (median = 5 flame events) had significantly ($P < 0.05$) higher nF than the exotics *Q. palustris* (median = 3 flame events) and *F. pennsylvanica* (median = 3 flame events), as well as the native *C. anacardioides* (median = 3 flame events).

We found a significant difference in FT among species ($F_{9,80} = 5.57$, $P < 0.001$; Fig. 3.3d). A larger variance in FT occurred within species than across species (61% vs 39%). Indeed, all but one species had highly overlapping median flame temperatures between 500°C and 700°C. The exception was *J. mimosifolia* which had the lowest FT (median = 419°C), overlapping with the exotics *Z. serrata* (median = 522°C) and *U. parvifolia* (median = 594°C), but differing significantly ($P < 0.05$) from the other seven species *Q. palustris* (median = 607°C), *B. integrifolia* (median = 611°C), *F. pennsylvanica* (median = 618°C), *C. maculata* (median = 646°C), *T. laurina* (median = 653°C), *C. anacardioides* (median = 659°C), and *L. confertus* (median = 688°C).

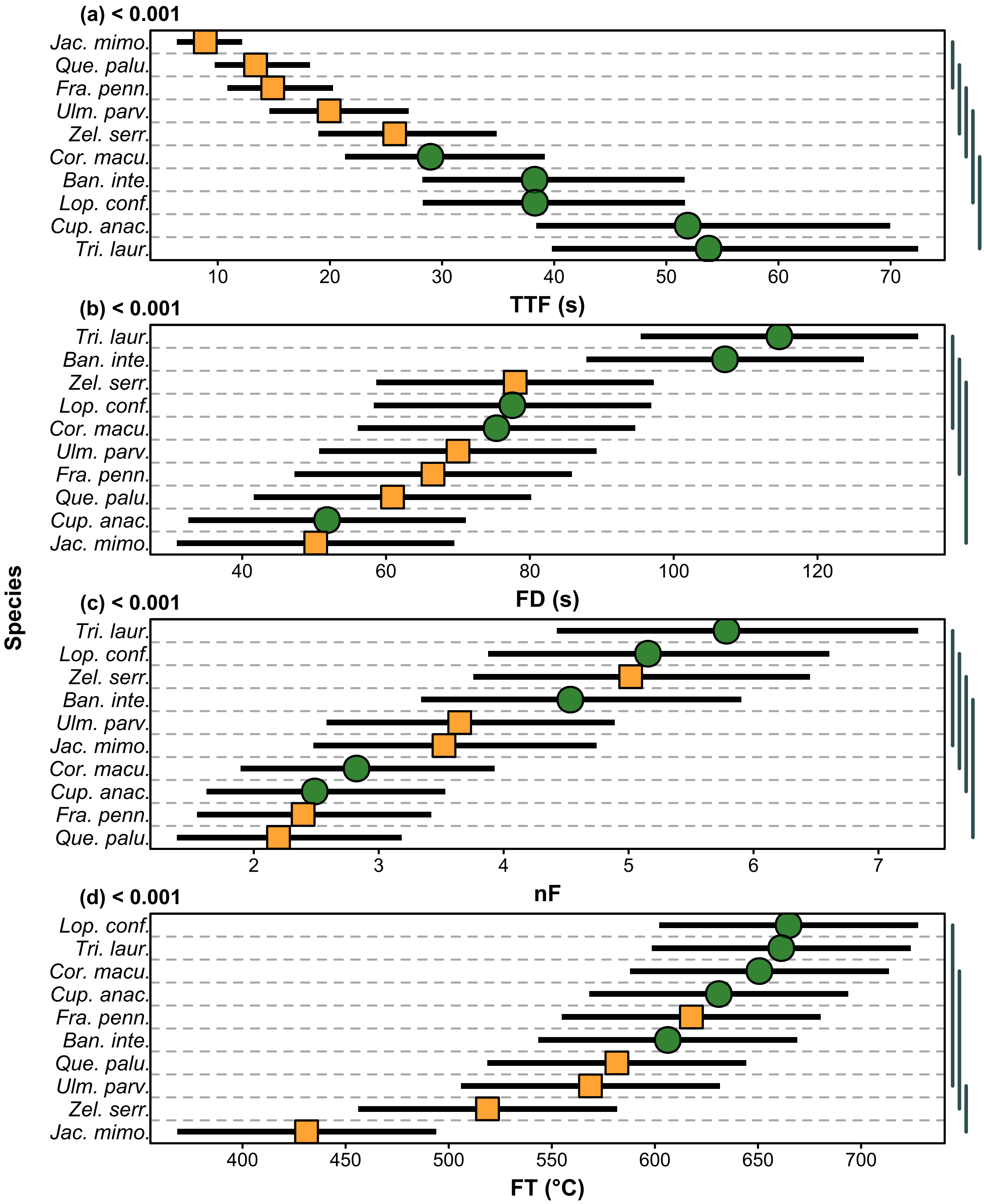


Fig. 3.3 Comparisons among species of (a) time to flame (TTF), (b) flame duration (FD), (c) number of flaming events (nF) and (d) flame temperature (FT). Exotic species are represented in orange, native species in green. Squares and circles show mean values as estimated by models with 95% confidence intervals (black lines). Presented are P values from linear models. Lines on the right-hand side group together species that are not significantly different (P > 0.05) based on pairwise tests (with Tukey correction).

Overall, the ranking of species from most to least flammable differed significantly between all pairs of flammability attributes, with little evidence of concordance in the ranking of species between all possible pairs of TTF, FD, nF, and FT (Fig. 3.4). For example, *Q. palustris* ranked second most flammable for TTF but eighth for FD; *T. laurina* ranked the least flammable (tenth) of all species for TTF yet most flammable (first) for nF; *J. mimosifolia* ranked most flammable for TTF yet least flammable for FT; *C. maculata* ranked fifth most flammable for FD but seventh for nF; *C. anacardioides* ranked fourth most flammable for FT but ninth for FD; and *U. parvifolia* ranked fifth most flammable for nF and eighth for FT.

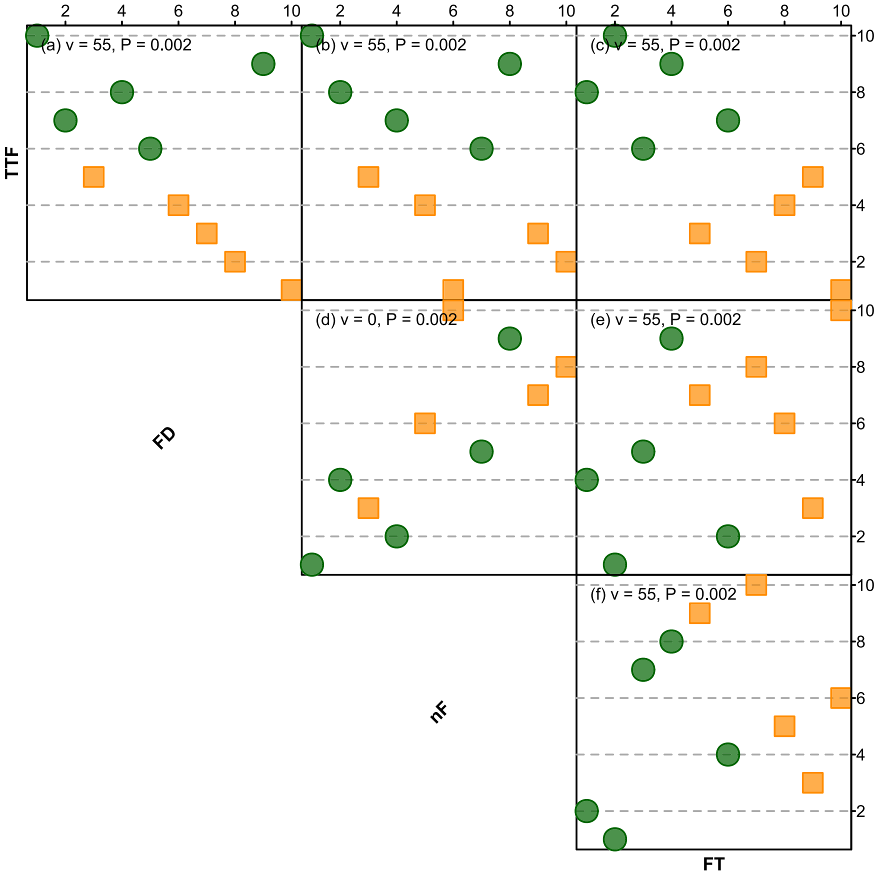


Fig. 3.4 Rank correlations of bivariate relationships between time to flame (TTF), flame duration (FD), number of flaming events (nF) and flame temperature (FT). Exotic species are represented with orange squares, native species with green circles. Each relationship is presented with v and P values from Wilcoxon signed rank tests. Values of FD, nF and FT were made negative and TTF left as is, so that a rank closer to one (out of ten) indicates faster TTF, longer FD, more flaming events (nF) and higher temperature.

3.3.2 Relationships between shoot traits and shoot flammability

The best explanatory model for TTF had a BIC value lower than the saturated trait model and contained three shoot traits in addition to the species term (Table 3.3). Faster TTF was significantly related to lower shoot bulk density, greater leafing intensity, and smaller shoot volume (Fig. 3.5a–c). Only one shoot trait, bulk density, was retained in the best explanatory model for FD (Table 3.3). While this model indicated a trend for a relationship between longer FD and higher shoot bulk density (Fig. 3.5d), this relationship was not statistically significant (Table 3.3). The best explanatory model for nF had a BIC value lower than the saturated trait model and contained one shoot trait (Table 3.3). A larger number of flame events was significantly related to lower leafing intensity (fewer leaves per branch) (Fig. 3.5e). For FT, the best explanatory model had a BIC value lower than the saturated trait model and contained three shoot traits (Table 3.3). Higher FT was significantly related to greater leafing intensity, higher fuel moisture content, and larger stem thickness (Fig. 3.5f–h). All shoot traits that were significantly related to shoot flammability were found to differ significantly among species, including bulk density ($F_{9,80} = 3.12$, $P = 0.003$; Fig. 3.6a), leafing intensity ($F_{9,80} = 18.63$, $P < 0.001$; Fig. 3.6b), volume ($F_{9,80} = 6.16$, $P < 0.001$; Fig 3.6c), FMC ($F_{9,80} = 12.74$, $P < 0.001$; Fig. 3.6d), and stem thickness ($F_{9,80} = 14.66$, $P < 0.001$; Fig. 3.6e).

Table 3.3 Multiple regression results of the significance of shoot traits for shoot flammability. The combination of traits included for each attribute are those generating the lowest BIC values from information theoretic models. TTF = time to flame, FD = flame duration, nF = number of flaming events, FT = flame temperature.

Flammability attribute	Term	SS	DF	F	P
TTF	Bulk density	1.84	1	11.78	< 0.001
	Volume	0.70	1	4.484	0.04
	Leafing intensity	2.34	1	15.02	< 0.001
	Species	19.56	9	13.921	< 0.001
	Residuals	12.02	77		
FD	Bulk density	608.92	1	0.748	0.39
	Species	31792.70	9	4.337	< 0.001
	Residuals	64351.72	79		
nF	Leafing intensity	1.26	1	6.765	0.01
	Species	10.26	9	6.139	< 0.001
	Residuals	14.67	79		
FT	Leafing intensity	36205.76	1	4.802	0.03
	Fuel moisture content	36036.10	1	4.780	0.03
	Min. stem thickness	33367.43	1	4.426	0.04
	Species	222285.40	9	3.276	0.002
	Residuals	580503.90	77		

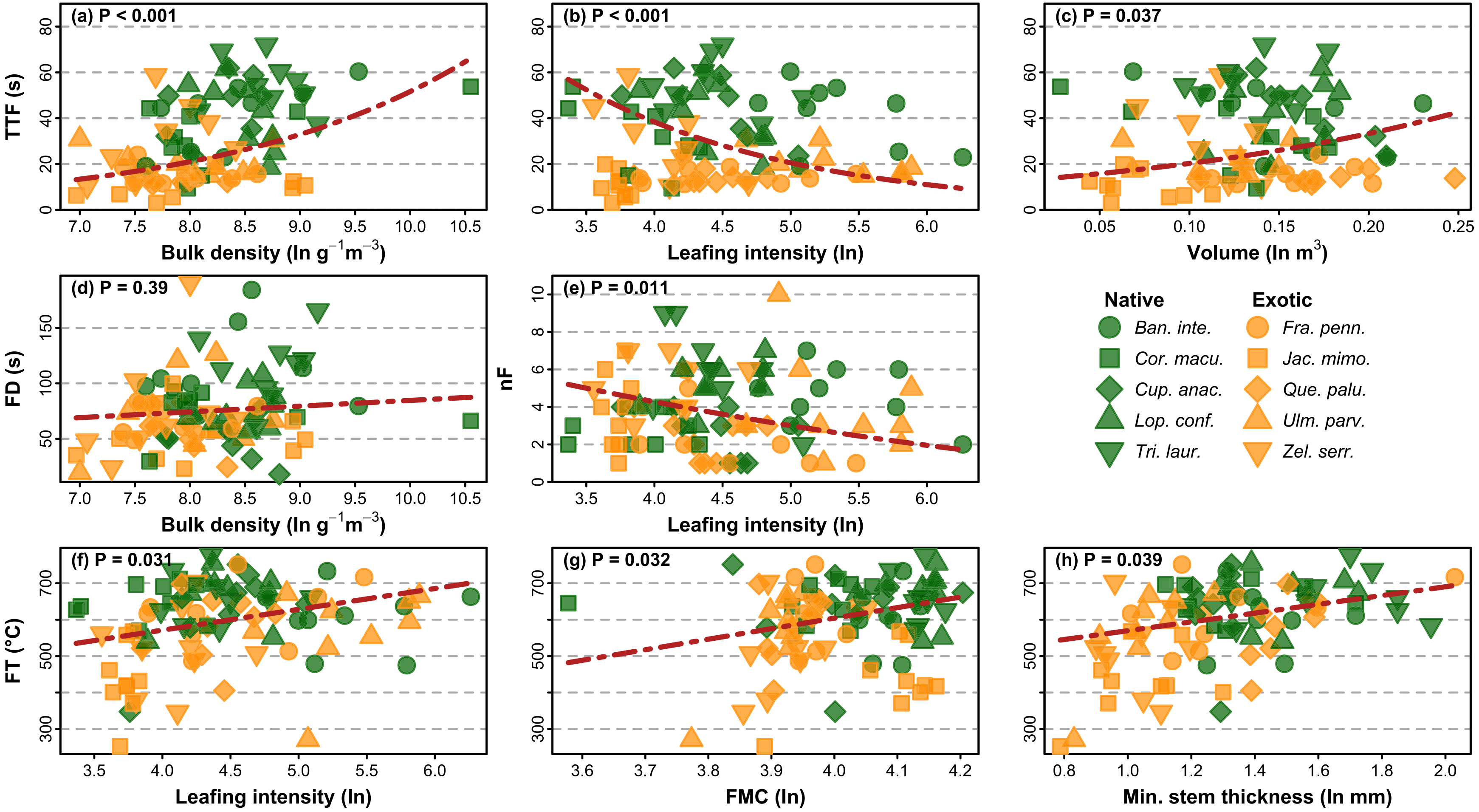


Fig. 3.5 Relationships between flammability attributes and shoot traits (**a**–**h**) with P values from multiple regressions. Exotic species are represented in orange, native species in green. Species are represented by symbols of different shape and colour combinations. The traits included for each attribute are those generating the lowest BIC values in information theoretic models. TTF = time to flame, FD = flame duration, nF = number of flaming events, FT = flame temperature, FMC = fuel moisture content.

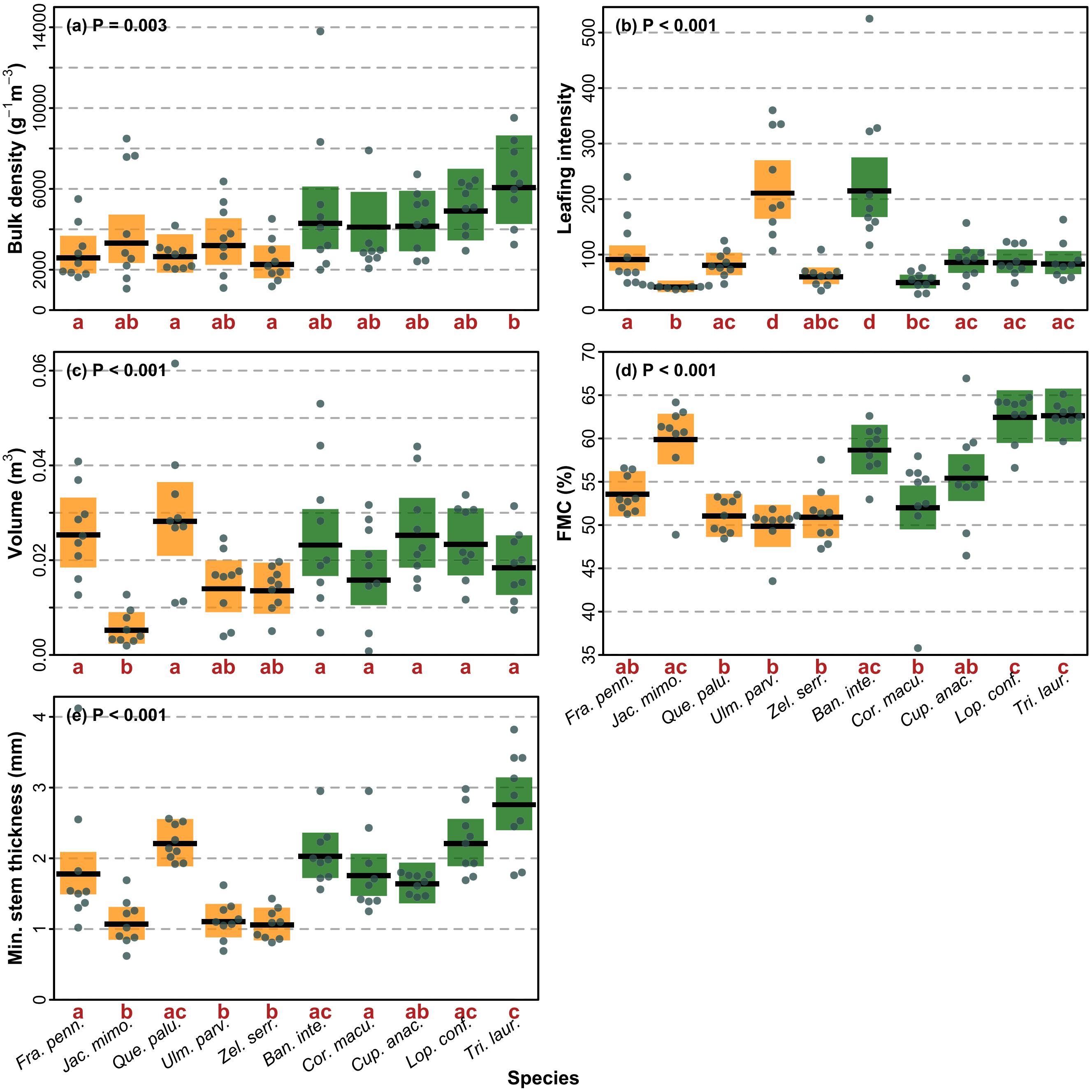


Fig. 3.6 Shoot trait differences among species for the traits that were significantly related to one or more of the flammability attributes. Exotic species are represented in orange, native species in green. Different letters under species in each graph indicate that the species differ significantly from each other based on pairwise tests (with Tukey correction). The mean (black line) with 95% CI (shading) is shown with observations for species as points, and P values from linear models. Fuel moisture content is abbreviated to FMC.

3.3.3 Shoot flammability differences between native and exotic species

We found that TTF was significantly faster in exotics compared to natives (χ^2 = 20.75, DF = 1, P < 0.001; Fig. 3.7a), and that FT was significantly higher in natives compared to exotics (χ^2 = 8.49, DF = 1, P = 0.004; Fig. 3.7d). There were no significant differences in either FD (χ^2 = 2.67, DF = 1, P = 0.10; Fig. 3.7b) or nF (χ^2 = 0.89, DF = 1, P = 0.35; Fig 3.7c) between native and exotic species. Two shoot traits were found to differ significantly between natives and exotics, including bulk density (χ^2 = 21.70, DF = 1, P < 0.001; Fig. 3.8a) and stem thickness (χ^2 = 4.62, DF = 1, P = 0.03; Fig 3.8b). None of the other shoot traits differed significantly between natives and exotics (volume χ^2 = 1.01, DF = 1, P = 0.31; leafing intensity χ^2 = 0.09, DF = 1, P = 0.77; fuel moisture content χ^2 = 3.64, DF = 1, P = 0.06; leaf area χ^2 = 0.25, DF = 1, P = 0.62).

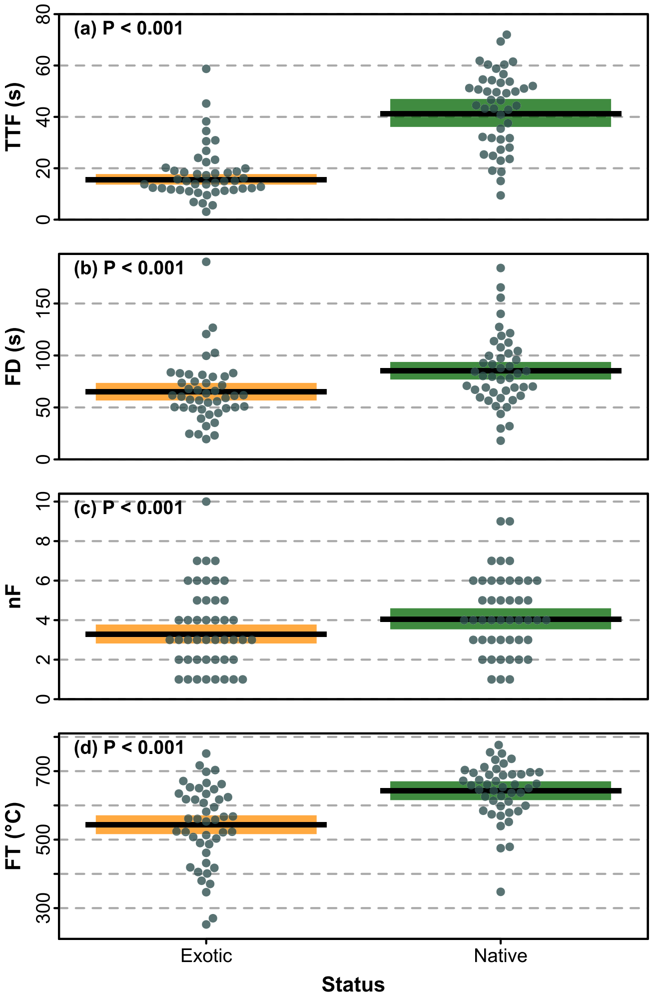


Fig 3.7 Comparisons of flammability attributes (a) time to flame (TTF), (b) flame duration (FD), (c) number of flame events and (d) flame temperature (FT), between exotic (orange) and native (green) species. The mean (black line) with 95% CI (shading) is shown with observations for species as points, and P values from linear mixed models.

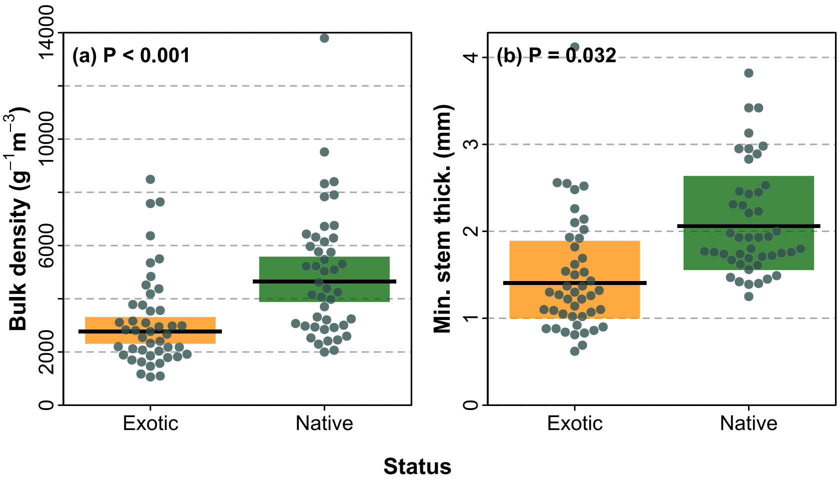


Fig. 3.8 Comparisons of shoot traits (a) bulk density and (b) minimum stem thickness between exotic (orange) and native (green) species. The mean (black line) with 95% CI (shading) is shown with observations for species as points, and P values from linear mixed models.

3.4 Discussion

3.4.1 Shoot flammability variation among tree species

Our results demonstrate that shoot flammability differs among common street tree species of eastern Australia. This finding contributes to a relatively small but growing body of evidence showing that species vary considerably in the intrinsic flammability of their shoots (Jaureguiberry et al., 2011; Burger & Bond, 2015; Calitz et al., 2015; Wyse et al., 2016; Padullés Cubino et al., 2018; Santacruz-García et al., 2019; Cui et al., 2020a; Kraaij et al., 2022; Potts et al., 2022; Murray et al., 2023). The differences that we observed in all four flammability attributes among species provide an important first step for evidence-based selection of low-flammability street tree species at the WUI to minimize the risk of wildfire incursion into urban areas. At the same time, our experiments have distinguished high-flammability street tree species that may increase fire incursion risks. Importantly, we found that rankings of species from low-flammability to high-flammability were not consistent across the four flammability attributes. For example, native water gum (*T. laurina*) took the longest time to ignite (i.e. a low-flammability characteristic), yet burned for the longest period of time (i.e. a high-flammability characteristic). Our finding for a lack of coordination among the four flammability attributes effectively means that selection of low-flammability street tree species needs to consider carefully how each flammability attribute may differentially contribute to fire risk at the WUI (Murray et al., 2020).

Time to flame is a critical flammability attribute that provides a relative measure of ignition delay times of among species (Anderson, 1970; Wyse et al., 2016). There are two advantages of street trees that have relatively long ignition delay times in the context of preventing the spread of wildfires into urban areas. First, fire conditions might change during a longer delay period, which means that some slow-igniting trees might not ignite, thus reducing the risk of localised fires. Second, if trees do ignite, slow-igniting trees provide more time for organised efforts to cover large areas to eliminate spot fires (i.e. fires started by flying sparks or embers at a distance from the main fire). Street trees identified in the present study as having the longest ignition delay times (median TTF > 50 s) were the native species water gum (*T. laurina*) and tuckeroo (*C. anacardioides*). Coastal banksia (*B. integrifolia*) and brush box (*L. confertus*) also had relatively long ignition delay times (median TTF just under 40 s). In contrast, the shortest ignition delay times (median TTI < 15 s) were observed in the exotics jacaranda (*J. mimosifolia*) and pin oak (*Q. palustris*), which suggests that these species may pose immediate fire risks at the WUI. Jacaranda in particular is often planted or retained in urban settings in the east coast of Australia based in part on its favoured ornamental features and cultural values (Boon M., 2020). One potential way to mitigate its fire risk could be to ensure that jacaranda canopies do not overlap with other trees to minimise the risk of rapid fire spread. In addition, previous work has demonstrated that the proximity of vegetation to houses influences fire impact, with homes situated less than 40 m to vegetation more prone to fire damage (Price et al., 2021). We suggest that further research on plant flammability in the context of opportunistic green fire-breaks should focus on how and where to plant low-flammability species in this context.

The length of time over which flaming combustion occurs, which is a measure of sustainability (Anderson, 1970), describes the ability of a fuel to keep burning and sustain the spread of fire (Martin et al., 1994). The primary advantage of street trees that have relatively short flaming times is to reduce the likelihood that wildfires will spread to other vegetation, homes and infrastructure within urban areas. Despite being identified as low-flammability species in terms of ignitibility in our study, water gum (*T. laurina*) and coastal banksia (*B.*

integrifolia) emerged as relatively high-flammability species in terms of both sustainability (median FD > 100 s) as well as the number of flaming events (median nF > 4). In a similar vein, brush box (*L. confertus*) was also a relatively high-flammability species for sustainability (median FD just under 80 s) and number of flaming events (median nF > 5). Interestingly, however, the native species tuckeroo (*C. anacardioides*) emerged as a relatively low-flammability species for sustainability (median FD just over 50 s) and number of flaming events (median nF < 3). When considered together with its low ignitibility, the observed low-flammability characteristics of these three flammability attributes suggest that tuckeroo could be targeted for further study as an appropriate candidate for planting as a low-flammability tree along streets. Interestingly, tuckeroo was also highlighted as a fire-retardant plant in the list of Sands and Hosking (2005).

Measurements of flame temperatures provide an assessment of combustibility (Jaureguiberry et al., 2011). Although we found that maximum flame temperatures reached by shoots differed significantly among species, these differences were primarily generated by one major difference between eight species with relatively high maximum flame temperatures and two species with significantly lower maximum flame temperatures (Fig. 3.3d).

3.4.2 The role of shoot traits in shaping shoot flammability patterns

Our study has identified important relationships among street tree species between shoot flammability and some of the shoot traits. We found that bulk density and leafing intensity in particular had the most explanatory power of all shoot traits that were measured, with these two traits explaining variation across the largest number of flammability attributes (Fig. 3.5). Higher shoot bulk density was associated with longer TTF and longer FD, a result supported by the findings of previous studies (Wyse et al., 2018; Murray et al., 2023). These two flammability attributes work together antagonistically, with high bulk density (especially in high-volume shoots, Fig. 3.5c) producing low-flammability shoots in terms of ignitibility, yet high-flammability shoots in terms of sustainability. A similar antagonistic role of the leaf trait, leaf mass per area (LMA), has been observed in previous work on leaf-level flammability (Krix et al., 2019). In that study, high LMA was associated with slow ignitibility but long sustainability. In our study, we suggest that a larger shoot mass within a given area provides for less aeration for flames, which provides for longer ignition delay times. However, once the shoot starts to burn, flames can spread more easily to other close parts of the shoot, with the greater mass available to burn leading to longer and hotter fires (Murray et al., 2023).

We found that high leafing intensity in shoots was related to faster TTF, lower nF, and higher FT, which broadly supports the findings of (Calitz et al., 2015). However, the role of leafing intensity in driving variation in shoot flammability has generally not been explored to any great extent, even though leaf density has been correlated with patterns of other measures of flammability (e.g. (Plucinski & Anderson, 2008; Schwilk & Caprio, 2011; de Magalhaes & Schwilk, 2012)). We suggest that all else being equal, shoots with more leaves have more opportunity for a leaf to begin flaming, which would explain faster TTF in shoots with high leafing intensity. The lower NF observed in shoots with high leafing intensity likely emerged as a result of faster fire spread in these shoots among more leaves, leading to one large flame event instead of several small and unrelated flame commencements. Higher leafing intensity also likely leads to higher FT, with the burning of more leaves leading to hotter flame temperatures.

Some physiological traits of plant species should be further researched within the field of fire ecology. Traits such as thick waxy cuticles, can allow plants to be resilient to moisture loss from heat and drought (Jordan et al., 2005; Ormeño et al., 2020). This trait is common in the Myrtaceae (Battersby et al., 2017) and Proteaceae families (He et al., 2011). Within this chapter, four of the five slowest to flame species (long TTF) (Fig. 3.3a) were of the families Myrtaceae and Proteaceae, and all five of these native species (*T. laurina, C. anacardioides, L. confertus, B. integrifolia* and *C. maculata*) presented with thick waxy leaves upon observation. There are several possible reasons for this relation between this physiological syndrome and a longer FD. Firstly, it could be adaptation which allowed these species within fire prone areas to not ignite when a low intensity fire passes through. Secondly, the families Myrtaceae and Proteaceae often rely on the process of smoke and heat exposure to stimulate the release of their seeds through the process of serotiny (Battersby et al., 2017 and He et al., 2011); and by not allowing the whole plant to easy ignite in a passing low intensity wildfire it can allow for seed release without extensive damage to the plant. This relationship between waxy cuticles and flame duration should be further researched, with a wider variety of plant families to explore the implications of this relationship further.

3.4.3 Native-exotic differences and similarities in shoot flammability of street tree species

Shoot flammability was found to differ between native and exotic tree species for the flammability attributes of TTF and FD (Fig. 3.7). Exotic species ignited significantly faster than native species, while in contrast, natives were found be more flammable than exotics for the FT attribute. This means that when deciding whether to plant exotic or native species based on their flammability, each flammability attribute should be looked at individually in response to the location being planted. At the WUI, species that ignite quickly should be avoided as this reduces their capability of acting as a green firebreak in being able to withstand radiant heat and embers (Curran et al., 2018). Out of the species studied, bulk density was found to be higher in natives than exotics (Fig. 3.8); and a high bulk density was found to help explain a longer TTF and FD in Fig. 3.5, showing that the natives are more likely to have a later ignition and longer burn. Whilst exotics species were found to have a shorter FD, were determined to have significantly faster ignition than natives. Indigenous cultural fire management aims for frequent, small scale, slow burning, and low-intensity fires (McKemey et al., 2021). The native species reflect these ideal burning characteristics in terms of the TTF and FD. However, native species were found to have a higher FT and a significantly thicker minimum stem thickness than exotics (Fig. 3. 8). A wider minimum stem thickness was also found to help explain hotter FT (Fig. 3.5), which supports the results of natives having a higher FT than exotics.

3.5 Conclusion

Selection of plant species for use as street trees at the WUI should be based on a wholistic assessment of a range criteria, including the ability of the plants to be biodiversity-promoting, climate-change resistant, health-safe, and to encompass aesthetic and functional community values (Murray et al., 2018; Murray et al., 2023). In terms of the functionality of street trees in shaping opportunistic green fire-breaks of low-flammability species, we have shown that a one-size fits all approach to selecting individual trees in relation to their relative contribution to increased bushfire risk is not optimal. Street tree plantings within new estate developments, for example, should consider both the interactive effects of flammability among species, with the use of 'early igniters' (i.e. high-flammability species in terms of ignitibility) and 'late igniters' (i.e. low-flammability species in terms of ignitibility) in combination increasing the possibility of introduction of wildland fire into the urban matrix. Further research on the interactive effect of species on carrying fire is, however, required. In addition, for species commonly used at the WUI, like our ten study species, the basic assumption that exotic species are overall less flammable is not correct. Our advice is to focus on the selection of low-flammability native species, with further studies exploring which of these species are good value in terms of promoting the persistence of native biodiversity in urban landscapes.

Chapter 4 | Testing the effects of ambient temperature on shoot flammability attributes: Do hotter temperatures increase shoot flammability?

4.1 Introduction

Australia has a range of natural wildfire regimes across its bioregions that have evolved over evolutionary time. These wildfire regimes are predominantly explained by the availability of vegetative fuel load based on rainfall exposure in the region, and the likelihood of wildfire weather risk conditions in the wildfire season (Murphy et al., 2013; Campbell et al., 2022a). For example, Verhoeven et al. (2020) found using Landsat that extreme annual rainfall events in arid Australian grasslands effectively predicted large wildfires two years later over a study period between 1972 and 2014. Such relationships that shape fire regimes lead to low-intensity annual fires in the tropical savannahs of Northern Australia where monsoon seasons facilitate fast vegetation regrowth, which are followed by a dry season (Bradstock, 2010; Murphy et al., 2013). Alternatively, in temperate climates with more intermittent rainfall, dry sclerophyll forests of the south-east of Australia have a longer fire interval of every 5–10 years, producing higher-intensity wildfires (Bradstock & Kenny, 2003; Bradstock, 2010; Morley, 2022). Intense wildfires in the south-east occur in the wildfire season of spring to summer with most occurring late spring and early summer (October–January) (Australian Bureau of Meteorology, 2017). This trade-off between frequency and intensity is a part of the natural rhythm of wildfire behaviour (Murphy et al., 2013). Furthermore, for the last 65 thousand years, Indigenous Australians have managed the landscape through mosaic hazard reduction burns for culture, hunting and ceremony (Bowman, 1998; Cahir et al., 2018). With the prevalence of this practice having been reduced since European settlement (Bowman et al., 2012; McKemey et al., 2021), and the combined effects of recent climate change, the potential for worsening wildfire events is of a high likelihood.

It has been found that in correlation with climate change, the intensity and frequency of wildfires in Australia have increased. For example, Canadell et al. (2021) found that the mean number of years between large wildfires has decreased over the last four decades with a growing occurrence of megafires (>1 Mha burned) since 2000. This means that wildfires are happening more than their background rate of occurrence and are having serious impacts. As climate change take its effect, there are shifts in the timing of seasonal weather patterns globally. For example, California in the United States has recorded shifts in the duration of summer wildfire weather into autumn (Goss et al., 2020). Similarly in temperate eastern Australia, climate change is inducing longer and hotter summers, which is triggering shifts in wildfire behaviour, and thus creating a longer and more dangerous fire season (Swann & Ogge, 2020). Due to this, it is becoming more difficult for biodiversity (Gill et al., 1999; Silveira et al., 1999; Dickman, 2021; Shepherd et al., 2021), health systems (Rossiello & Szema, 2019; Ebi et al., 2021) and the economy (Michael et al., 2018; Filkov et al., 2020) to cope with increasing wildfires.

The reason that climate change raises the frequency and intensity of wildfires is due to it increasing the rate of wildfire risk conditions. Some examples of these weather conditions that assist in the ignition and spread of wildfires include prolonged heatwaves (Varga et al., 2022), drought (Mukherjee et al., 2018; Nolan et al., 2020), high wind (Goss et al., 2020), low humidity (Australian Bureau of Meteorology, 2017), fire generated thunderstorms (Komesaroff & Kerridge, 2020; Canadell et al., 2021), and dry lightning (Canadell et al., 2021; Varga et al., 2022). The increased rate of fire weather (90th percentile Forest Fire Danger Index values) has been directly linked to the lengthening fire season in recent decades in south-eastern Australia (CSIRO, 2021). The extension and increasing severity of the fire season in NSW means that there will be a reduction in the environment's recovery capacity (CSIRO &

Bureau of Meteorology, 2018; CSIRO, 2021). As these risk conditions occur throughout different times of the year due to climate change, wildfires are likely to occur outside of their natural seasonal regimes.

There is a paucity of studies that have asked and tested whether shifts in seasonal weather conditions affect the intrinsic flammability of plant species. Temperature is one of the largest changes between seasons. Raising the question whether increased temperature, which is a key feature of increasing fire weather conditions, influences the intrinsic flammability of plants. This is a potential outcome as hotter weather may mean plants live at a higher intrinsic temperature, meaning different FMC levels and less heat needed to begin flaming. Previous work at the leaf scale has shown that for the most part, leaf flammability increases with increasing temperature (Kreye et al., 2020; Krix & Murray, 2022). Theoretically, it has been demonstrated that even if plant leaves vary in their thermal conductivities, specific heat capacities and densities, the absolute changes in these leaf traits are considerably smaller than more marked reductions in flammability with increasing radiant temperature (Quintiere, 2006; Torero & Simeoni, 2010; Reszka et al., 2012). At the plant shoot scale, only one study from South Africa (Msweli et al., 2020) has broadly tested this idea, showing a relationship between the increasing severity of fire weather conditions when shoots were sampled and found an increase in shoot flammability. However, no study has yet explored the effects of the immediate ambient weather conditions on the intrinsic shoot flammability of plants. For the first time in Australia, the research presented in this chapter compares the flammability of native plants in relation to shifting ambient temperatures. Comparisons of shoot flammability are made among five native street tree species between winter (June–August 2022) and summer (January–February 2023), and among six native garden plant species between spring (September–November 2022) and autumn (March–April 2023).

The aim of this study is to determine the effect of increasing maximum ambient temperature on four intrinsic flammability attributes, with the prediction that as ambient temperatures increase, there will be a concomitant change in four shoot flammability attributes including reducing the time-to-flame (TTF), and increasing the flame duration (FD), number of flaming events (nF), and flame temperature (FT). In addition, in cases where temperature is shown to increase flammability, I seek to determine which shoot traits are critical for driving inter-species variation in shoot flammability over and above any effects of ambient temperature.

4.2 Methods

4.2.1 Study Regions and Species

This study is conducted in the Greater Sydney Region of NSW, Australia (see chapters 2 and 3). This region is along the temperate lower east coast of Australia, where wildfires have been occurring with worsening intensity in recent decades (Central Coast Bush Fire Management Committee, 2020; Komesaroff & Kerridge, 2020; NSW Government, 2020; Canadell et al., 2021; CSIRO, 2021; Gallagher et al., 2021). This has affected much of the wildland-urban interface (WUI) in the region (Villaseñor et al., 2016; Krix et al., 2019; Murray et al., 2023). The study species were selected due to their abundance as native planted urban species at the WUI in this area. The winter (June–August 2022) and summer (January–February 2023) comparison was conducted on five native street trees common to the Central Coast local government area (LGA), located north in the Greater Sydney Region (Table 4.1). These trees were selected in consultation with the Central Coast council and a tree nursery called Trees Impact in Lake Munmorah, NSW where the sampling was also conducted. The spring (September–November 2022) and autumn (March–April 2023) comparison was conducted on six common native garden plants to the greater Sydney Region (Table 4.1). These ornamental garden plants were selected due to their high frequency of purchase from the large nursery, Andreasens Green Wholesale nursery in western Sydney, where the sampling was also conducted. Both nurseries that provided samples for this study grow plants for large scale plantation projects across the Sydney region.

Table 4.1 Native species examined in this study for temporal effects on shoot flammability.

Garden plants (spring and autumn)			**Street trees (winter and summer)**		
Scientific Name	**Common Name**	**Family**	**Scientific Name**	**Common Name**	**Family**
Acmena smithii 'Minor'	Dwarf Lilly Pilly	Myrtaceae	*Banksia integrifolia*	Coastal banksia	Proteaceae
Callistemon viminalis 'Dawson River Weeper'	Bottlebrush	Myrtaceae	*Corymbia maculata*	Spotted gum	Myrtaceae
Eucalyptus robusta	Swamp Mahogany	Myrtaceae	*Cupaniopsis anacardioides*	Tuckeroo	Sapindaceae
Grevillea 'Moonlight'	Grevillea 'Moonlight'	Proteaceae	*Lophostemon confertus*	Brush box	Myrtaceae
Waterhousea floribunda 'Amaroo'	Amaroo	Myrtaceae	*Tristaniopsis laurina*	Water gum	Myrtaceae
Westringia fruticosa	Coastal Rosemary	Lamiaceae			

4.2.2 Sampling methods

By selecting to sample from nursery plants, it allowed consistent growing conditions (e.g. same soil, sun exposure, nutrients and watering) between the seasons. For example, all species' replicates were watered consistently at the nursery following a consistent regime. Shoot testing as an alternative for whole plant flammability is considered effective, as shoots retain the architectural integrity of each species whilst being on a more manageable scale (Jaureguiberry et al., 2011; Pérez-Harguindeguy et al., 2013).

The shoot sampling methods were based off internationally recognised and standardised procedures (Jaureguiberry et al., 2011; Wyse et al., 2016; Potts et al., 2022; Murray et al., 2023). Two 50 cm shoots were sampled for each of the nine replicates from the nurseries. The shoots were representative with multiple leaves and were sampled from healthy individuals that were representative of the species. Only sun exposed outer branches were sampled. One of the shoots measured was tested for its flammability and named the "burn shoot". The other was used to measure other traits unable to be taken off the shoot being burnt (e.g. FMC) and named the "trait shoot". To reduce moisture loss and retain shoot integrity before testing the following day, the cut ends of the sample were wrapped in a dampened cloth and the samples sealed into heavy duty plastic bags. Due to these precautions and the great growing conditions of the plants at the nurseries, it means the shoots likely retain their highest moisture content potential for the species prior to burning.

4.2.3 Shoot traits measurements

Shoot traits were measured in both datasets throughout their respective seasons and were conducted 1–3 hours prior to burning for the burn shoots and about three hours after that for the trait shoots. The shoot traits measured on the burn shoots, were the weight (g) and size of the shoot (50 cm length x width x height), the number of leaves and branches (Table 4.2). This allowed the calculation of bulk density ($g.cm^{-3}$), and branching and leafing intensity (Table 4.2). The measurements conducted on the garden species' trait shoot was one leaf length and width to get an average for the species, and the fresh and dry shoot mass (g) to calculate the fuel moisture content (%) (Table 4.2). Further detail of the leafing and branching of the study species can be found in Appendix A. During winter and summer, the same trait measurements were taken on the street trees with a few more. For the street tree "burn shoots", the min. and max. stem thicknesses (mm) were also measured (Table 4.2). For the street tree "trait shoot" samples, instead of one leaf being sampled for size and averaged over the nine replicates like in the garden dataset, instead, five leaves were sampled for their length, width, thickness (mm) and area (mm^2) to get an average from each replicate first.

Table 4.2 Traits measured on each shoot for both the garden plant species in spring and autumn, and the street tree species in winter and summer. (Blue highlights are the trait used).

Garden plants (spring and autumn)			**Street Trees (winter and summer)**		
Burn Shoot Traits	**Equipment Used**	**Calculation**	**Burn Shoot Traits**	**Equipment Used**	**Calculation**
Weight (g)	Portable scale spring balance	**Bulk density** (g.cm^{-3}) (mass / volume) Shoot volume (cm^3) as an elliptical cylinder (π × shoot length × shoot width × 0.5 × shoot height × 0.5)	**Weight** (g)	Portable scale spring balance	**Bulk density** (g.cm^{-3}) (mass / volume) Shoot volume (cm^3) as an elliptical cylinder (π × shoot length × shoot width × 0.5 × shoot height × 0.5)
Size (**width** x **length** x **height**) (cm)	Ruler		Size (**width** x **length** x **height**) (cm)	Ruler	
Number of branches	Visual count	**Branching intensity** (BI)	No. of Branches and leaves	Visual count	**Branching intensity** (BI) & **Leafing intensity** (LI)
Number of leaves	Visual count	**Leafing intensity** (LI)	**Min** and **max stem thickness** (mm)	–	–
Trait Shoot Traits			**Trait Shoot Traits**		
Fresh shoot mass (g)	Sartorius A 120 S Analytical Balance and Drying oven (80°C for 48 hours) and Sartorius A 120 S Analytical Balance	**Fuel moisture content** (%) ([air-dried mass – oven-dried mass]/air-dried mass)	**Fresh shoot mass** (g)	Sartorius A 120 S Analytical Balance and Drying oven (80°C for 48 hours) and Sartorius A 120 S Analytical Balance	**Fuel moisture content** (%) ([air-dried mass – oven-dried mass]/air-dried mass)
Dry shoot mass (g)			**Dry shoot mass** (g)		
Leaf length (mm)	Vernier Kincrome 150mm Digital Caliper	Averages based on one representative leaf per sample (i.e. 9 per species)	**Leaf length** (mm)	Vernier Kincrome 150mm Digital Caliper	Average based on five representative leaves per sample (i.e. 45 per species)
Leaf width (mm)	(above)		**Leaf width** (mm)	(above)	
–	–	–	**Leaf thickness** (mm)	(above)	
–	–	–	**Leaf area** (mm^2)	Portable leaf area meter (LI-3000A)	Average leaf area based on five representative leaves per sample

4.2.4 Flammability experiments

The shoot samples were retained at room temperature for 22–24 hours after collection before burning, with the cut stems bound in dampened cloth and in seal plastic bags. Up to three hours prior to flammability tests, the "burning" samples were removed from the bags and the trait measurements were taken. They remained uncovered in the shade when outside, to allow any surface moisture from their storage to evaporate off prior to the samples being burnt for 1–3 hours. The trait shoots were measured in parallel conditions, but remained in their bags a few more hours, as they were measured after the burns finished.

The shoot flammability experiments were conducted using an open flamed device following an internationally standardised design, which was slightly modified to meet Australian standards (Jaureguiberry et al., 2011; Pérez-Harguindeguy et al., 2013; Wyse et al., 2016). LPG fuelled the flammability device, and the temperature was maintained at approximately 185°C. Four flammability attributes were used to determine the flammability of shoot samples throughout all seasons (Wyse et al., 2016; Krix et al., 2019). The time the shoot took to begin flaming (time to flame, TTF) was measured using a timer from the moment the sample was placed down and exposed to flames. The number of times the sample had a flaming event (including the initial flaming event) was recorded throughout the exposure period (number of flaming events, nF). The flame duration was the cumulative amount of time the shoot burnt for throughout the flaming events (flame duration, FD). Lastly the maximum flaming temperature (flame temperature, FT) was measured using a handheld infrared laser thermometer (Digitech QM 7226) at a distance of 50 cm pointing at the external flame plume as per standard practice (Jir-Ming & Jun-Hsien, 1996; Pérez-Harguindeguy et al., 2013; Calitz et al., 2015; Wyse et al., 2016; Murray et al., 2023). The field of view of the infrared laser thermometer at this distance was approximately 1.67 cm in diameter. When large or multiple flame events occurred, the sample was quickly scanned back and forth by the thermometer to determine maximum flame temperature. The flammability experiments were only conducted on days with temperatures 35°C or lower due to health and safety prevention measures.

4.2.5 Weather data collection

Weather data was collected from the PRIVA climate control system that was used in adjacent greenhouses to where the flammability experiments were conducted at the University of Technology Sydney. The greenhouse's external weather values were measured, and the maximum ambient temperature (°C) in the hours of burning (09:00-14:00) were recorded. This aspect of weather was selected due to the linked nature of temperature with both rainfall and the onset of wildfire (Australian Bureau of Meteorology, 2017; Mukherjee et al., 2018; Goss et al., 2020; Nolan et al., 2020; CSIRO, 2021; Varga et al., 2022).

4.2.6 Statistical analysis

A linear model was fitted to mean ambient temperature data (response variable) covering all days on which shoots were burned to determine the magnitude of differences in temperature among the four seasons (four-level explanatory variable). Pairwise comparisons (with Tukey correction for multiple tests) were used to identify where there were significant temperature differences between pairs of seasons.

A series of linear models was fitted to each of the flammability attributes TTF (ln transformed), FD, nF (sqrt transformed), and FT as response variables, separately for street tree and garden plant species, using a term for species (five-level explanatory variable for street trees, six-level explanatory variable for garden plants), a term for ambient temperature (continuous explanatory variable), and a species x ambient temperature interaction term. This allowed me to determine if species' flammability attributes responded similarly to the ambient temperature gradient, while controlling for the use of all replicates (nine replicates per species) with the main effect of species. Where the species x ambient temperature term was significant, the ambient temperature coefficients for individual species were tested for differences using pairwise comparison (with Tukey correction for multiple tests).

I then focused on models where there was either a significant main effect of ambient temperature, a significant species x ambient temperature interaction, or both, on one or more of the flammability attributes. In new models, each of the shoot traits were added individually to the original models relating the flammability attributes to ambient temperature described above. Where there was solely a significant main effect, models were simplified to remove the species x ambient temperature term. In these models with the shoot traits added, if significant effects of the main effect of ambient temperature, or the effect of the species x ambient temperature term, became non-significant with a trait added, this was interpreted as seasonal differences in the shoot trait driving seasonal differences in flammability. Where the main effect of ambient temperature, or the effect of the species x ambient temperature term, remained significant with a trait added, this provided evidence that temperature differences underpinned differences in shoot flammability between seasons.

All analyses were conducted in R (R Core Team, 2023), using the packages car (Fox & Weisberg, 2019), and emmeans (Lenth, 2021). Where modelled effects are presented in figures, estimates have been back-transformed to the response scale.

4.3 Results

4.3.1 Ambient temperatures throughout the seasons

Overall, there were significant differences in mean ambient temperature on days when shoots were burned among seasons ($F_{1,16}$ = 10.537, $P < 0.001$). These differences were driven by significantly higher mean temperatures in summer and autumn compared to winter (Fig. 4.1). Mean temperatures did not differ significantly between summer and autumn, and the mean temperature in spring did not differ significantly from the other three seasons (Fig. 4.1).

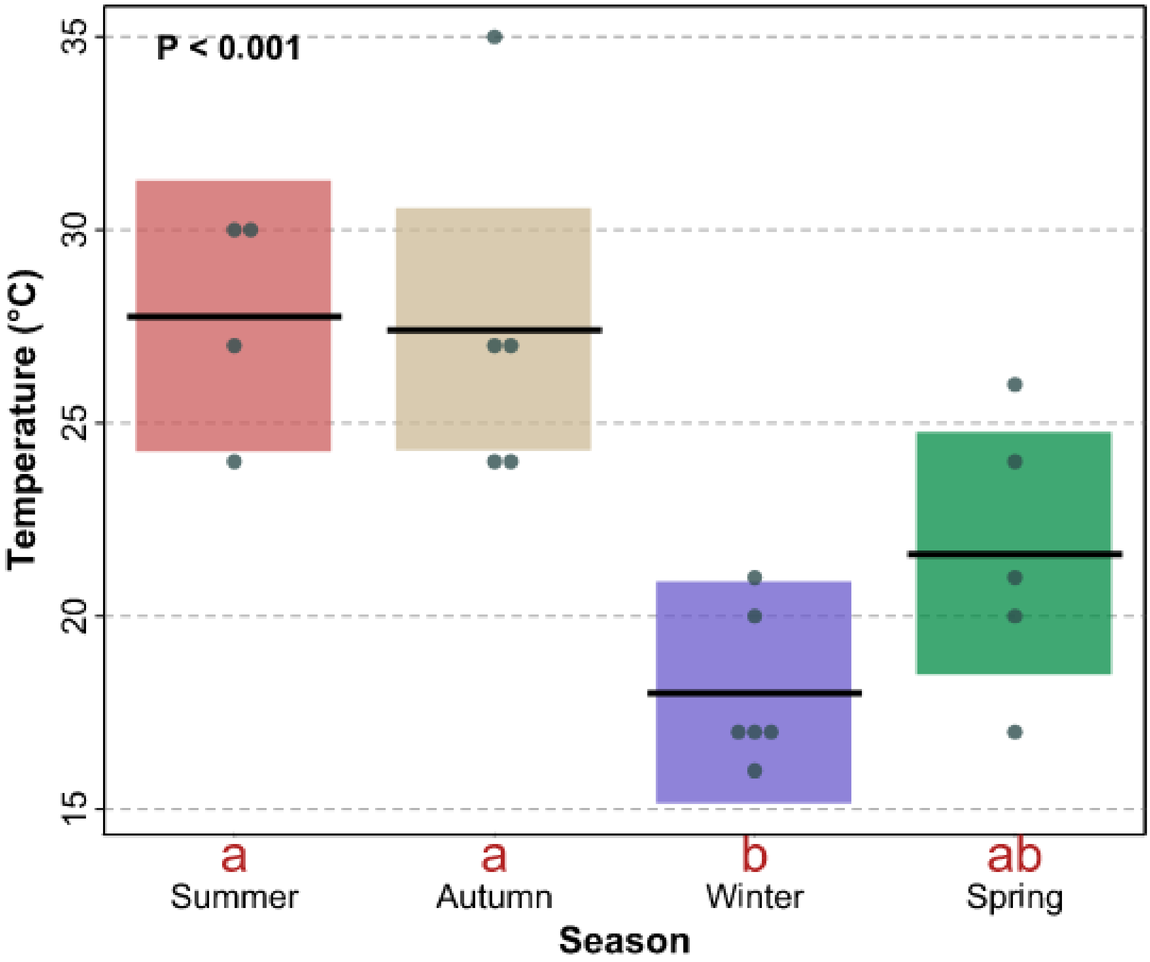


Figure 4.1 Plot of mean ambient temperatures on days shoots were burned as a function of season. Shaded areas show 95% CIs and the black lines show the means. Grey points are observations. The P value for the effect of season is shown at top left, and significant pairwise differences are indicated by the red letters below the x-axis.

4.3.2 The effect of ambient temperature on time-to-flame (TTF)

Significantly faster TTF was related to increasing ambient temperature in street tree species ($F_{1,80}$ = 18.972, P < 0.001; Fig. 4.2a), with all species behaving similarly (i.e. there was a non-significant species x ambient temperature interaction: $F_{4,80}$ = 0.858, P = 0.49). There was a significant relationship between increasing ambient temperature and faster TTF in garden plants ($F_{1,96}$ = 7.11, P = 0.009; Fig. 4.2b), however, there was also significant species x ambient temperature interaction ($F_{5,96}$ = 4.907, P < 0.001; Fig. 4.2b), driven by a relatively stronger relationship between faster TTF and increasing ambient temperature in *E. robusta* compared to other garden plant species.

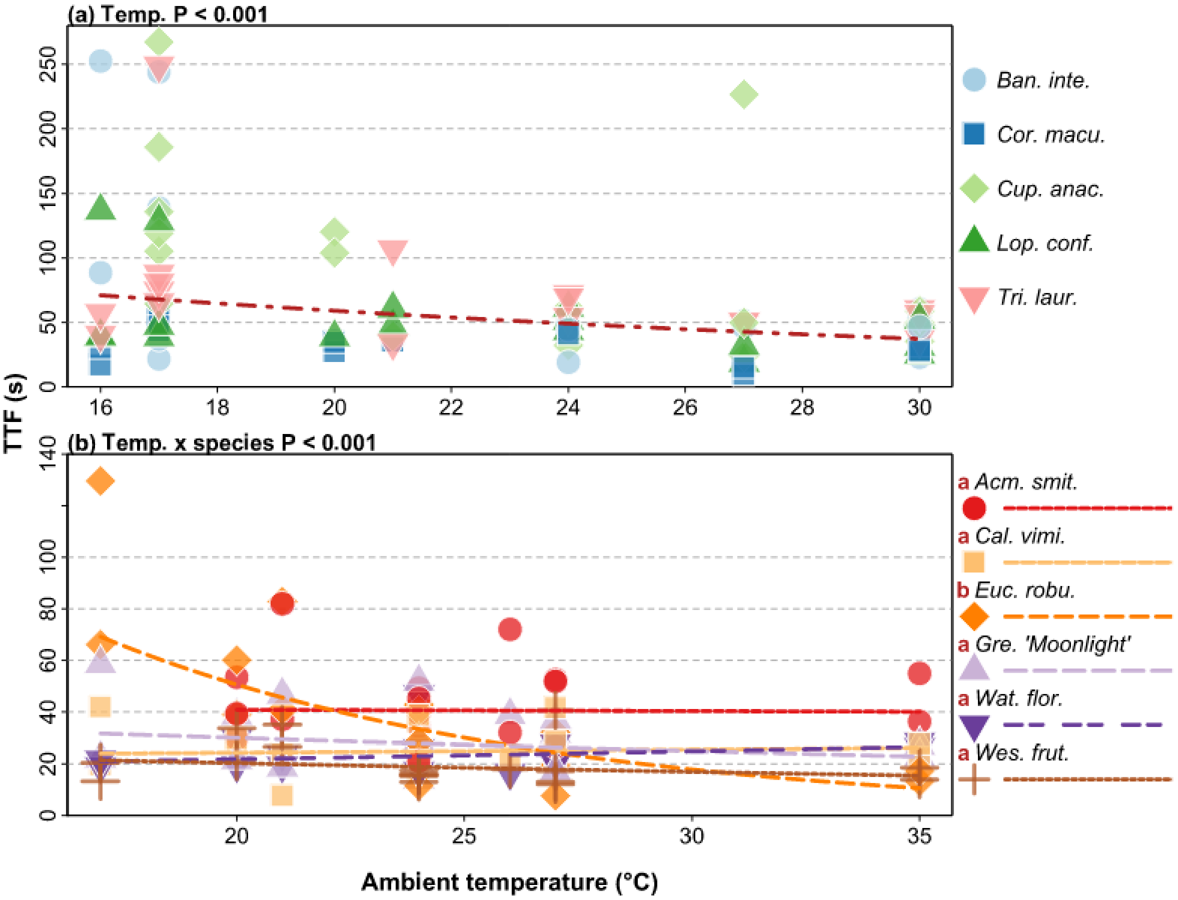


Figure 4.2 Effects of increasing ambient temperature on TTF for (a) street trees (non-significant species x ambient temperature interaction term) and (b) garden plant species (significant species x ambient temperature interaction term). Keys for points and lines are shown to the right of each plot and the relevant model effect P value shown at top left. For (b), the pairwise differences among species x ambient temperature coefficients are shown next to the species' names in the key.

4.3.3 The effect of ambient temperature on flame duration (FD)

There was a significant relationship between increasing ambient temperature and longer FD in street trees ($F_{1,80}$ = 46.332, P < 0.001; Fig. 4.3a), however, there was also a significant species x ambient temperature interaction ($F_{4,80}$ = 2.728, P = 0.035). Here, *T. laurina* demonstrated a sharper increase in FD with increasing ambient temperature relative to *C. maculata* and *C. anacardioides* (Fig. 4.3a). In garden species, no significant relationship between FD and ambient temperature was detected ($F_{1,96}$ = 0.628, P = 0.43) and there was no significant species x ambient temperature interaction ($F_{5,96}$ = 1.172, P = 0.33) (Fig. 4.3b).

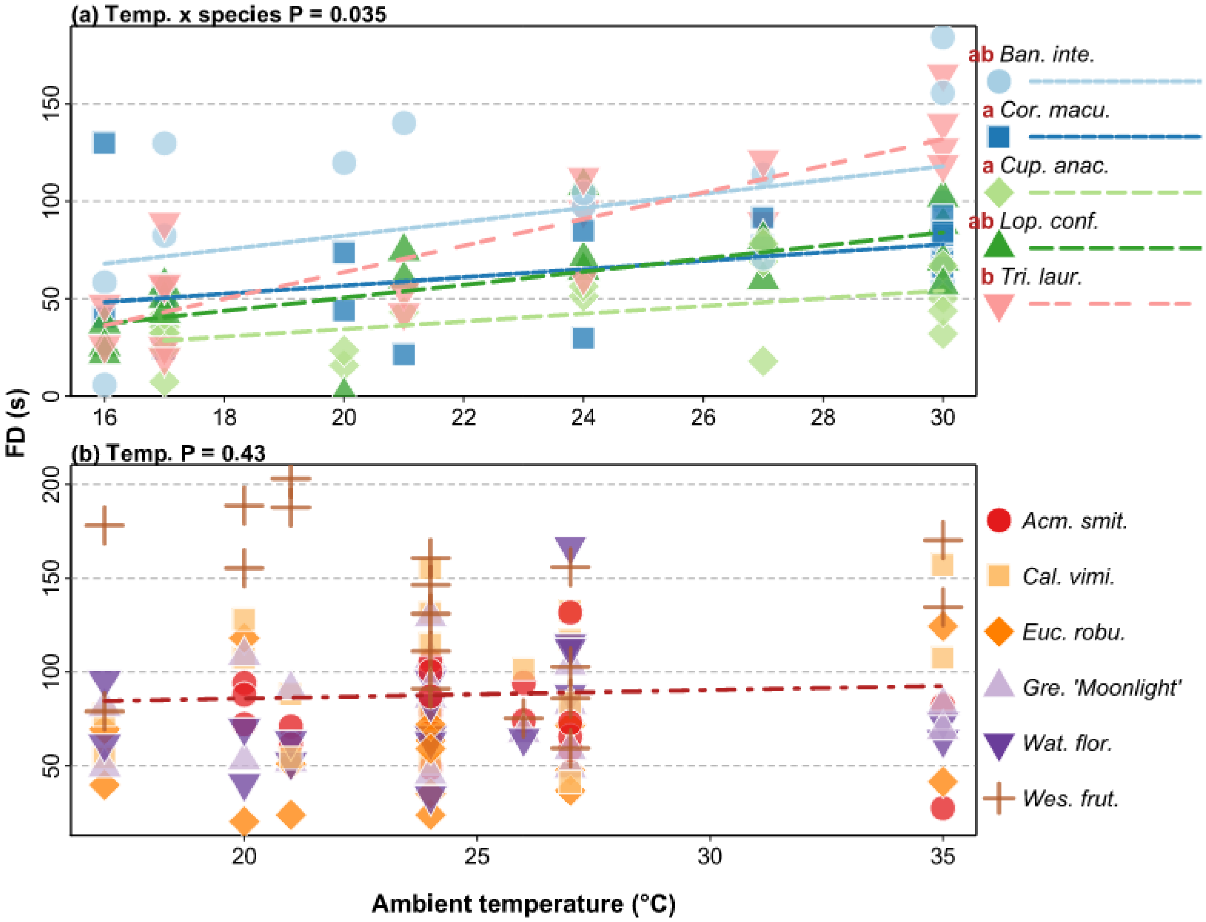


Figure 4.3 Effects of increasing ambient temperature on FD for (a) street trees (significant species x ambient temperature interaction term) and (b) garden plant species (non-significant species x ambient temperature interaction term). Keys for points and lines are shown to the right of each plot and the relevant model effect P value shown at top left. For (a), the pairwise differences among species x ambient temperature coefficients are shown next to the species' names in the key.

4.3.4 The effect of ambient temperature on the number of flame events (nF)

Street tree species had significantly higher nF with increasing ambient temperature ($F_{1,80}$ = 46.064, P < 0.001; Fig. 4.4a). This pattern was not repeated in garden plants ($F_{1,96}$ = 0.585, P = 0.45; Fig. 4.4b). There was no significant species x ambient temperature interaction on nF for either street trees ($F_{4,80}$ = 2.456, P = 0.05; Fig. 4.4a) or garden plants ($F_{5,96}$ = 1.718, P = 0.14; Fig. 4.4b).

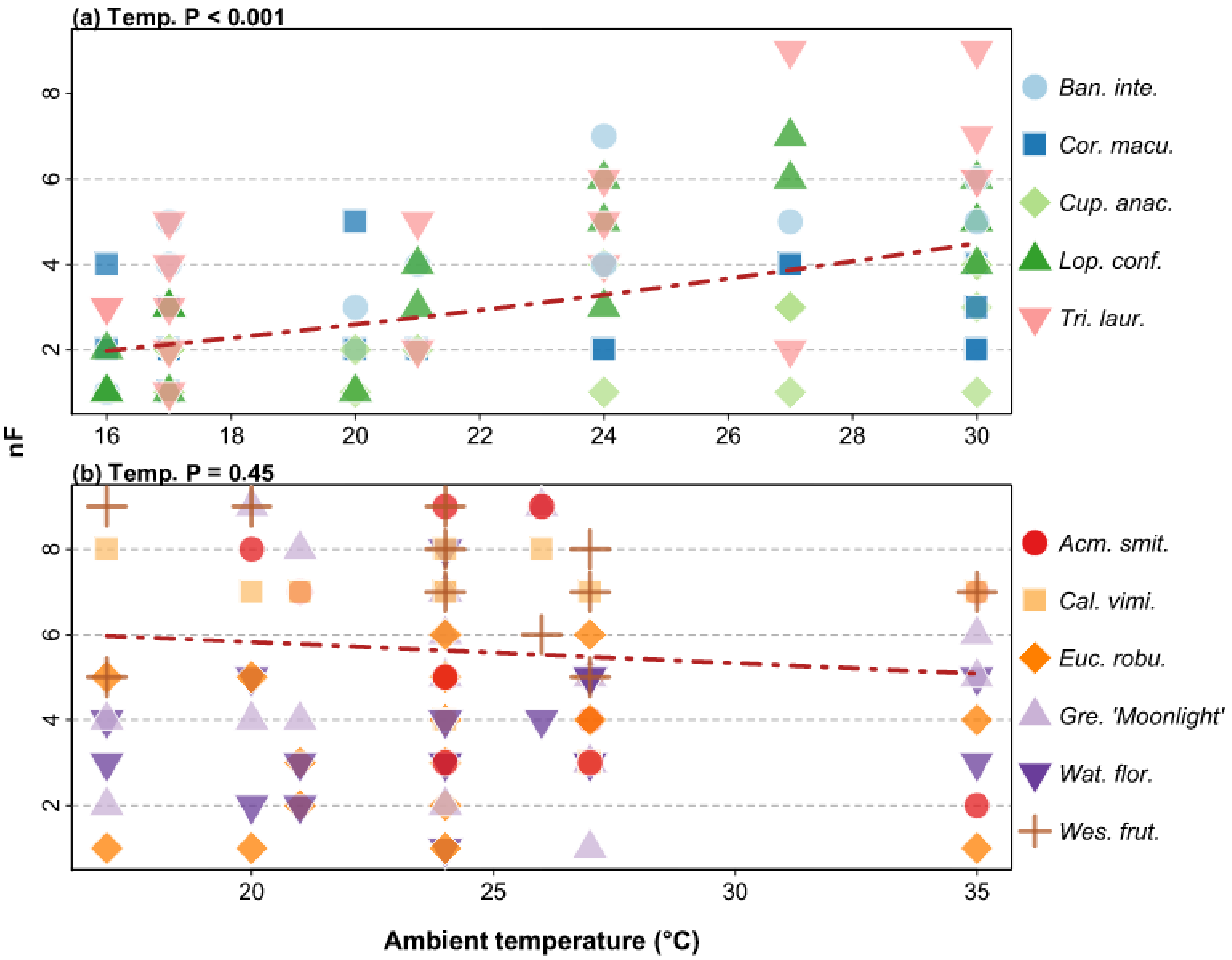


Figure 4.4 Effects of increasing ambient temperatures on nF for (a) street trees and (b) garden plant species, both models having non-significant terms for the species x ambient temperature interaction. Keys for points and lines are shown to the right of each plot and the relevant model effect P value shown at top left.

4.3.5 The effect of ambient temperature on the maximum flame temperature (FT)

There was a significant relationship between increasing ambient temperature and higher FT in street trees ($F_{1,80}$ = 4.024, P = 0.048; Fig. 4.5a), and an even stronger relationship for garden plants ($F_{1,96}$ = 13.085, P < 0.001; Fig. 4.5b). No significant species x ambient temperature interaction was found for either street trees ($F_{4,80}$ = 0.242, P = 0.91; Fig. 4.5a) or garden plants ($F_{5,96}$ = 1.104, P = 0.36; Fig. 4.5b).

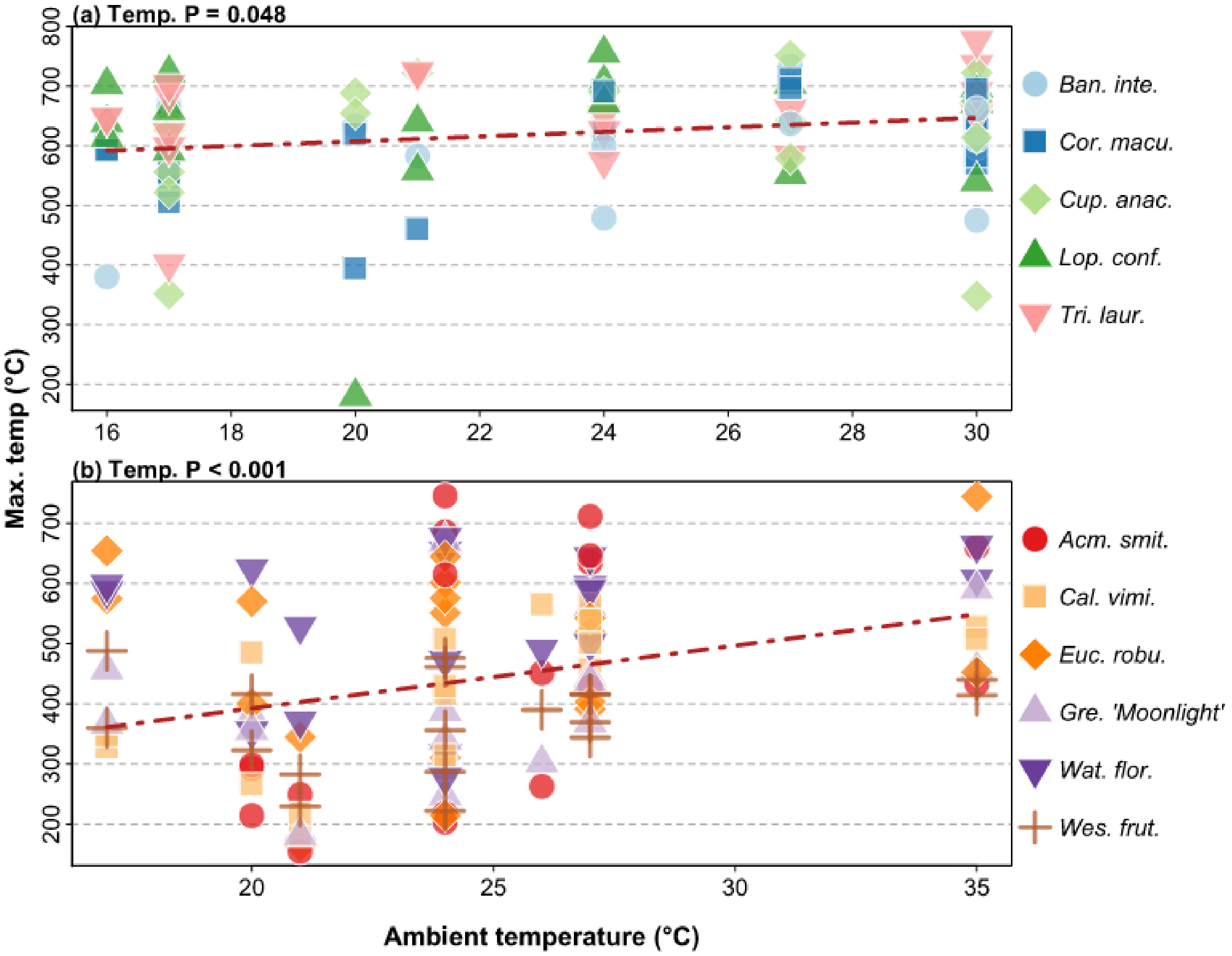


Figure 4.5 Effects of increasing ambient temperatures on FT for (a) street trees and (b) garden plant species, both models having non-significant terms for the species x ambient temperature interaction. Keys for points and lines are shown to the right of each plot and the relevant model effect P value shown at top left.

4.4 Discussion

The results of this study demonstrate that the hypothesis of ambient temperatures affecting the time to flame (TTF), flame duration (FD), number of flaming events (nF) and maximum flame temperature (FT) of shoot samples was supported. Shoot traits were also found to drive inter-species variation in shoot flammability attributes in addition to ambient temperature. This study took a unique approach to intrinsic flammability assessments, in that temporal comparisons of shoot flammability has not been done before in Australia.

4.4.1 Temperature and Season

Temperature measurements were taken on the days of flammability assessments throughout the seasons of winter (2022), spring (2022), summer (2023), and autumn (2023). In this experimental period, it was found that winter was significantly cooler than summer and autumn (Fig. 4.1). Spring was found to be similar to summer, autumn and winter but the mean temperature lay between the other seasons values. Although not statistically different from spring, due to the limited number of experimental days, both summer and autumn presented similar hot weather conditions. Eastern Australia's wildfire season naturally lays within the spring–summer period (Australian Bureau of Meteorology, 2017). Although one years' worth of data cannot describe long term seasonal patterns, these results support ongoing reports worldwide of a lengthening summer season into the autumn months (Goss et al., 2020; Swann & Ogge, 2020; CSIRO, 2021). Similarly, Fig. 4.1 demonstrates how it is not the binary of wildfire season (spring and summer) which allow wildfires to occur, but rather the occurrence of wildfire risk conditions such as the high temperatures that occurred in autumn.

4.4.2 Temperature effects on shoot flammability attributes

Time to Flame (TTF)

All street tree species showed that the higher the temperature, the faster the TTF (Fig. 4.2a). This supports the findings of Msweli et al. (2020) in South Africa, whereby the increasing severity fire weather in turn reduced the time to ignition of live shoot samples. This has important implications as plant species may have a higher likelihood of igniting in future wildfire seasons, due to it becoming increasingly hotter in eastern Australia due to climate change (Moore, 2010; CSIRO & Bureau of Meteorology, 2018). The garden species interacted differently, with most species' TTF not being affected by the temperature except for *Eucalyptus robusta* which drove the results (Fig 4.2b). *Eucalyptus robusta* interestingly followed similar patterns to the street trees for TFF where it ignited faster on warmer days. The garden dataset also contained multiple specimens of the family Myrtaceae, ruling out the potential for that family being especially ignitable in this study. Studies in New Zealand have found that growth form can be a potential driver for flammability, but there has been no finding that large trees exhibit greater flammability over other growth forms (Mason et al., 2016; Cui et al., 2020b). Whilst *E. robusta* was the largest growing tree out of the garden species and was more aligned with the physical characteristics of the street tree species, it may instead be other physiochemical properties that drive its TTF.

Flame Duration (FD)

Conversely for the species interaction for FD, I found that *Tristaniopsis laurina* drove the results of FD lengthening with the temperature (Fig. 4.3a). Long burning durations provide a greater chance for adjacent plants to ignite. Due to *T. laurina*'s dense canopy, it has been considered a good candidate in previous studies in reducing the urban island heat effect, especially when used in a continuous planting design (MacLeod et al., 2019). I suggest that when this species is planted in urban settings, it is not planted close to easily ignitable plant species at the wildland-urban interface. I also suggest that individuals of *T. laurina* are well spaced apart so as not to provide large areas of continuous canopy, to avoid long-lasting and difficult to put out canopy fires. Unlike *T. laurina,* the ambient temperature was not found to influence any flame duration in the garden species.

Number of Flame Events (nF)

The number of flame events was found to increase with ambient temperature in the street tree species (Fig. 4.4a). This nF pattern reflects both the initial ignition but also the re-ignitability of the street tree species. It is therefore logical that the street tree dataset which had a strong relationship of faster ignition on hotter days (Fig 4.2a), also displayed a strong nF reignition pattern (Fig. 4.4a). Alternatively, the ambient temperature had no effect on the nF for the garden species. The garden species' TTF predominantly was not influenced by the ambient temperature in Fig 4.2a, so it is unsurprising that the number of flaming events was also unaffected. The nF is a flammability attribute has not been widely considered in previous studies, despite it being relevant to both the flame duration and ignitability. Having a high potential number of flame events makes a plant similarly have a higher likelihood of reigniting and potentially spreading wildfire just as a fast TTF and long FD would.

Maximum Flame Temperature (FT)

Both the street trees and garden species displayed significant positive results between the FT and the ambient temperature (Fig. 4.5). This means that as the ambient temperature increased so did the maximum temperature of the flames produced by shoot ignition. Similarly, Msweli et al. (2020) found that with worsening fire weather (including ambient temperature) it caused an increase in burning intensity. This measure of FT is relevant to a plants ability to spread wildfire, as the hotter a plant burns the higher likelihood it will have in the direct or indirect ignition of those around it.

4.4.3 Plant traits and temperature effects on shoot flammability attributes

The models in Appendix C (Appendix C.1 to Appendix C.4) were made to add shoot traits as a factor to the original models (Fig 4.2 to 4.5), which related flammability attributes to ambient temperature. This analysis showed evidence for a continued effect of temperature on shoot flammability even with the inclusion of the traits. The new models also provided evidence for the continued importance of shoot traits on shoot flammability in addition to the role of temperature (Appendix C.1 to Appendix C.4).

Temperature was the only significant correlation for nF (Appendix C.1) and FD (Appendix C.2) for the street trees. The flame duration is directly related to the nF, as it is the accumulation of time of each flaming event. For this reason, it is logical for them to present similar results. The FT was found to increase with a heavier shoot mass, higher branching intensity and higher leafing intensity, which surprisingly made the ambient temperature affects not significant (Appendix C.1). This implies that the FT may be more influenced by the physical traits of the species rather than the external temperature. Supporting this finding without measuring the effect of ambient temperature in several other studies, a higher mass and bulk density of the shoot sample was found to increase the flame temperature (Alam et al., 2020; Morley, 2022; Murray et al., 2023). Alternatively, ambient temperature was found to significantly quicken the TTF of street trees along with having a high leafing intensity (Appendix C.1). This means in street trees a high number of leaves per branch will likely result in a fast ignition. This result is important, as street trees are often selected for their ability to provide shade to people and their ability to support wildlife, which consequentially often means a dense canopy (Threlfall et al., 2016; Pena et al., 2017; MacLeod et al., 2019). Greater consideration of plant growth patterns should be considered at the WUI, and plants with a high leafing intensity should potentially be avoided in areas at risk of fast igniting specimens. This trade-off between supporting wildlife and mitigating the spread of wildfires should be considered on a case-by-case basis at each location, whilst taking into consideration that a tree with a lower leafing intensity would still provide greater opportunities for wildlife than a space with no trees.

As temperature was not found to influence the FD and nF for garden plants (Fig 4.3b and 4.4b) and therefore shoot traits were added as in comparison for FT and TTF. Contrary to the street tree results, after the addition of shoot traits to the FT model, ambient temperature remained a significant correlate for FT (Appendix C.3). The shoot traits that caused a higher FT in the garden species was a heavier shoot mass, larger volume, higher branching intensity and higher leafing intensity (Appendix C.3). The mass, branching intensity and leafing intensity traits were found to affect the street tree FT in the same way, which supports the claim that these traits affect the temperature at which a shoot burns. As ambient temperature was found to be an influencing factor on the garden species FT unlike the street trees, further research should be conducted to solidify if physiochemical plant traits, ambient temperatures or both, drive FT results. Just like the street trees, the TTF of the garden species was also found to be significantly correlated with the ambient temperature, further supporting the results that high ambient temperatures increase plant flammability (Appendix C.4). The traits that were found to affect a fast TTF in garden species were samples with a large volume and high branching intensity, which did not match the street trees. Despite this, these trait findings support that the size of the shoot as well as the density of branches and leaves may be a driving factor in the ignitability of native Australian shoots.

4.4.4 Further implications of the results

Although there was some variability between the two datasets, each flammability attribute was found to increase with increases in ambient temperature. This relationship has not previously been explored in Australia in practical flammability experiments. Therefore, this study is able to stand in support of claims of worsening wildfire events with hotter temperature conditions (Australian Bureau of Meteorology, 2017). As climate change is causing higher rates of hot weather conditions than ever before (Moore, 2010; Ying et al., 2014; CSIRO & Bureau of Meteorology, 2018; Goss et al., 2020; Canadell et al., 2021; Varga et al., 2022), this study has found that it creates even greater risk conditions for wildfires by increasing a plant's ignitability, burning duration, number of flaming events and flame temperature. Climate change must be stopped to reduce this effect on the flammability of Australian native plants and prevent further wildfire catastrophes such as the recent 2019–2020 'Black Summer' bushfires (Australian Institute for Disaster Resilience, 2020; Filkov et al., 2020; Dickman, 2021). With evidence to support this mechanism, it means that future shoot flammability studies must control for the ambient temperatures of the experimental environment. This can also be done by conducting the experiments within a certain temperature range within a specified season. Due to the results showing similar weather conditions within and outside the natural wildfire season and the flammability results increasing with higher temperatures, it means that wildfire season will likely follow higher temperatures outside of the natural wildfire season ranges. This will make biodiversity impacts hard to recover from as there will be a reduced time between wildfires (Gill et al., 1999; Silveira et al., 1999; Dickman, 2021; Shepherd et al., 2021). By reducing increasing temperatures from climate change in Australia, it will help reduce the immediate flammability of native species and thus help protect biodiversity into the future.

Chapter 5 | General Discussion

5.1 Were the aims of this thesis met?

This thesis sought to explore differences in shoot flammability and shoot traits among urban plants common to the wildland-urban interface of the Greater Sydney region. Examination of flammability patterns in ornamental garden plants and in street trees has not occurred in Australia, despite garden plants and street trees often being the last vegetation barrier between houses and wildland areas. My thesis met it's aims by (1) ranking the study species based on their flammability attributes, (2) identifying the shoot traits underpin inter-species variation in shoot flammability, (3) determining whether there were any flammability differences between native and exotic plants, (4) determining that there were differences in ambient temperature between seasons, and (5) determining that the intrinsic flammability of the plant species increased with warmer ambient temperature conditions.

5.1.1 Ranking ornamental garden plants and street trees based off their flammability attributes

Overall, in both the garden and street tree datasets, I found that the ranking of species was overwhelmingly uncorrelated across the flammability attributes. In other words, I was not able to identify an 'ideal' low-flammability species, one that exhibited low flammability in all measured dimensions of shoot flammability. As a consequence, some species were found to have high-flammability properties for one attribute and low-flammability properties in another. For real-world application, this subsequently means that different locations consisting of a different suite of species would have to be evaluated in terms of which flammability attribute would likely cause the most risk of wildfire spread into urban regions. Then, species selected for planting could be based on the most relevant attribute. In low-intensity wildfire scenarios, the most relevant flammability attribute in the perpetuation of wildfire would be a plant species TTF. The ignitability of a plant species reflects their ability to withstand radiant heat and embers, and thus reducing the immediate ability of wildfire to spread (Curran et al., 2018).

Within the garden plant dataset, the four slowest to ignite species were *Magnolia grandiflora, Viburnum odoratissimum, Cupressocyparis leylandii,* and *Eucalyptus robusta.* Although these species were slow to ignite, three of them presented in the four highest FT values. *Viburnum odoratissimum* was a standout within this dataset as it was found to take a long time to ignite, have a short flame duration and burn with a low temperature. This makes it a good candidate as a low-flammability garden species. In the street tree dataset, the four slowest species to ignite were *Tristaniopsis laurina, Cupaniopsis anacardioides, Lophostemon confertus and Banksia integrifolia*. *Cupaniopsis anacardioides* also had the shortest flame duration and *B. integrifolia* an average flame temperature, making them potential candidates in a low-flammability garden. These results show that each plant species burnt in a unique way and that flammability patterns were generally not consistent between plant species.

5.1.2 Linking shoot traits and flammability

Despite shoot traits predominantly varying in which flammability attributes they affected in the garden and street tree BIC models, there were overlaps in traits of importance. The traits that best explained variation in the flammability attributes within both studies were leafing intensity, bulk density, shoot volume and fuel moisture content. Bulk density, shoot volume and fuel moisture content have been found to be good indicators of flammability in previous research (Murray et al., 2013; Kauf et al., 2015; Dehane et al., 2017; Krix & Murray, 2018; Wyse et al., 2018; Krix et al., 2019; Alam et al., 2020; Cui et al., 2020a; Morley, 2022; Murray et al., 2023). This makes them good candidates for basic shoot trait measurements (Pérez-Harguindeguy et al., 2013). Interestingly, leafing intensity (number of leaves per branch) of shoots is not a commonly measured shoot trait in shoot flammability studies. However, due to the recurring significance of leafing intensity throughout all three studies, leafing intensity should be considered alongside the other shoot traits. The nature of leafing intensity measurements helps describe the physical architecture of the shoot unlike other trait measurements taken. Maintaining this plant architecture has been at the forefront of the transition to shoot flammability studies over leaf level studies, as it better reflects whole plant flammability (Pérez-Harguindeguy et al., 2013). This is because the plant traits (especially those reflecting size and number of leaves) described on shoot samples of the species should directly reflect the whole plant.

The first principles of flammability refers to the combination of fuel, energy and the environment in which their interaction can lead to combustion. The main shoot traits found to impact the flammability attributes in this study reflected the size and density of the shoots, creating a general pattern of that when a shoot sample is larger it will create higher flammability outcomes. This reflects some expected relationships between the flammability and shoot traits, as when plants have a greater fuel load there is more potential for energy transfer and expenditure through combustion. In these experiments the flammability device kept the energy input quite constant which allowed changes in the fuel characteristics (i.e. trait measurements) of the shoots to create the greatest differentiations in their flammability. Chapter 4 of this thesis took into account the environmental factor of the first principles and how ambient temperature may affect the flammability of the shoots through general warming and energy. When the environment was taken into greater account it led to the conclusion for the first time in research that hotter ambient temperatures may lead to greater flammability outcomes within plants.

The street tree dataset had collectively more similar results in their physical traits than the garden species dataset. One possible explanation for this pattern is that there was less variation between the physical traits in the street tree dataset compared with the variety of different species in the garden plant dataset. Street tree species are selected to be of similar size and shape to allow the functionality of their intended purpose in allowing people and cars to pass easily underneath. On a smaller scale they also generally have good leafing intensity and large leaves to provide shelter for animals and shade to the street. In comparison, the garden species varied much more in leaf size and vegetation type which ranged from low lying undergrowth, bushed and trees, allowing for more variation.

5.1.3 Flammability differences between native and exotic species

The comparison between native and exotic species was essential in this study in achieving the goal of being able to advise residents, councils and organisations on what plants may be more suited to at risk areas. Native species are often anecdotally considered to be more flammable than exotic species in the Greater Sydney region by the public, but without any scientific evidence underpinning this notion. This thesis shows that this is not a notion that should continue to be spread for plants in this region. Despite TTF in the garden dataset being faster for native plants, compared with exotics, the street tree dataset showed the opposite, that exotics ignited faster and were more flammable in that regard. These findings provide support for the suggestion of Murray et al. (2023) that native-exotic patterns in flammability will be highly context-dependent. The street tree dataset also showed that native plants burnt hotter than exotic plants, a pattern that did not emerge for the garden plants. These results indicate that native and exotic species flammability is unlikely based on their endemic status but rather each species and their individual physical traits, with the physical trait variation between native and exotic plants dependent on a range of factors other than flammability. This demonstrates that the hypothesis that native species are more flammable is not a conclusion easily drawn from my study.

5.1.4 The effect of ambient temperature on shoot flammability

No other study has been conducted in Australia, or indeed in the world, that assesses if intrinsic shoot flammability is affected by increases in ambient temperature at the time of flammability assessments. The hypothesis of this study was supported, with warmer temperatures associated with higher flammability outcomes for each of the flammability attributes in both of the datasets. This conclusion has serious implications, as climate change is increasing the temperature it will not only increase the likelihood of wildfire risk conditions (Australian Bureau of Meteorology, 2017; CSIRO & Bureau of Meteorology, 2018; Mukherjee et al., 2018; Goss et al., 2020; Nolan et al., 2020; Canadell et al., 2021; Varga et al., 2022), but also may lead to increases in the intrinsic flammability of plants. As the wildfire season lengthens it also means that plants will be exposed to hotter temperatures for longer and consequently have a higher intrinsic flammability for a longer duration, again increasing the likelihood of wildfire. This study supports the expanding evidence that it is not the binary of wildfire season that allows wildfire to occur, but rather the occurrence of wildfire risk conditions. This means that with climate change increasing the occurrence of high temperature conditions, wildfires will likely occur outside of their natural season if risk conditions are present. To mitigate this effect of increasing the flammability of plants with high temperatures, it is recommended that action must be taken to reduce and stop climate change.

5.2 Study limitations

Due to the limited research in the field of practical plant flammability, the research presented in this thesis is predominantly of an exploratory nature to determine if patterns exist and create pathways for future research to determine why they exist. Because of this, there are a few limitations within the chapters that can be expanded upon in future research to help apply these concepts to real world scenarios.

The evergreen nature of Australian native plants meant that there may be intrinsic physiological differences throughout the seasons that affect deciduous plants differently. For example, all of the exotic street trees in Chapter 3 and one exotic species in Chapter 2 were deciduous which may result in their leaves drying out more in summer and autumn months, potentially creating large fluctuations and increasing their flammability. From this it is likely a good idea to keep all plants well-watered in fire seasons. Alternatively, native plants are often selected for their drought resistant properties and may be less watered in gardens and as street trees which may also affect their FMC.

The scope of this research was not able to determine if we would expect different flammability outcomes in wild or un-monitored plants in the field. FMC may vary more in unwatered individuals compared to the well-watered replicates within my study. FMC remained quite stable between the replicates and species within chapter 2 and 3, this was likely because they retained close to their maximum FMC. To make this plant trait more applicable to the real world it would first have to be determined if native plants are likely to be less irrigated than exotic plants in gardens and public green spaces. The plants selected for these studies were also preferred by people for a variety of reasons and often the selection of native species involves their drought resilience. It currently has not been researched whether drought resilient plants retain a high FMC or if they can continue to live with a low

FMC. From this it is advisable for future research to determine the FMC of plants in varying drought conditions. This will help advise the public on whether irrigating your gardens may help protect their properties.

A trait that was potentially overlooked in these studies, was the inclusion of leaf area. Leaf size (length, width and thickness) was measured in each study, but it may not have provided the whole picture for all the leaves included. Some of the leaves in this study such as *Jacaranda*, *Leylandii* and *Grevillea* had compound leaf type structures (Appendix A). Which were not able to be captured easily as leaf size. Their leaves had gaps and different surface areas in comparison to a simple leaf of the “same size” , which in turn may have lent itself to quicker ignitions. This aspect was a limitation of the research and in future research, leaf area should be considered.

There was some need for potentially increasing the replicate sizes within the studies as there was within species variability for some flammability attributes. But with this notion, the results still stand strong with their statistical power, as other studies (e.g. Wyse et al. 2016) had lower minimum replicate sizes than this research.

5.3 Additional future research directions

The field of practical shoot plant flammability assessments is in its infancy within Australia despite the high rates of wildfire occur (Australian Bureau of Meteorology, 2017). More practical shoot flammability studies to broaden the suite of results will allow further confirmation of the results in this thesis and will allow for more specific advice to give residents and decision-making bodies. In addition, more research on a greater number of plant species will allow broader conclusions to be made about exotic and native species flammability. It is important that when assessing plants species for their flammability that the interplay of the four flammability attributes should be considered. If an area with regular low intensity fires is needing to be assessed, then favouring plants with a longer TTF is likely a great choice as it will allow the plant to be more heat resistant. Alternatively in a location with mid to high intensity fires it may be beneficial to favour plant species with low FT and FD to reduce the likelihood of spread. The interplay of flammability attributes on the overall flammability of the plant is highly dependent on type of wildfire it is exposed to. This should always be considered when selecting low flammability plants at the WUI.

The physiochemical composition of plants has recently been linked to flammability patterns. This field of interest is in the relationship between volatile organic compounds in the form of terpenes and intrinsic plant flammability. There have been studies that link high concentrations of terpenes with high levels of flammability (Ormeño et al., 2009; Pausas et al., 2016; Della Rocca et al., 2017; Romero et al., 2019; Ganteaume et al., 2021; Romero & Ganteaume, 2021). This however, has not been conducted in conjunction with shoot flammability results within Australia. I suggest future research should compare the terpene content of shoots samples with their shoot flammability, to determine what forms of volatile organic compounds impact flammability of plants. This will also address the growing public concerns of a high presence of oil in some plants such as the Myrtaceae family (Padovan et al., 2014).

A greater exploration in urban design and how and where you can implement plants based on their flammability attributes, whilst maintaining diversity and variability in planting design is needed (MacLeod et al., 2019). For instance, this future research would have to address where can you still plant easily ignitable plants and where you may consider placing plants that don't burn as hot. Murray et al. (2018) presents a framework that shows what should be considered in planting design at the WUI. The main considerations of this paper asks to select plant species that are biodiversity-promoting, low-flammability, and climate change resistant. These concepts directly align with the outcomes of this thesis, and provide a baseline in what to look for in regards to plantations at the WUI. This balance between supporting wildlife and mitigating the spread of wildfires should be considered on a case-by-case basis at each location, as some locations may be at too greater risk from wildfire to consider plantations. However, areas at potential risk of low to moderate wildfires can benefit from the plantation of low-flammability species through green firebreaks and still provide opportunities for wildlife.

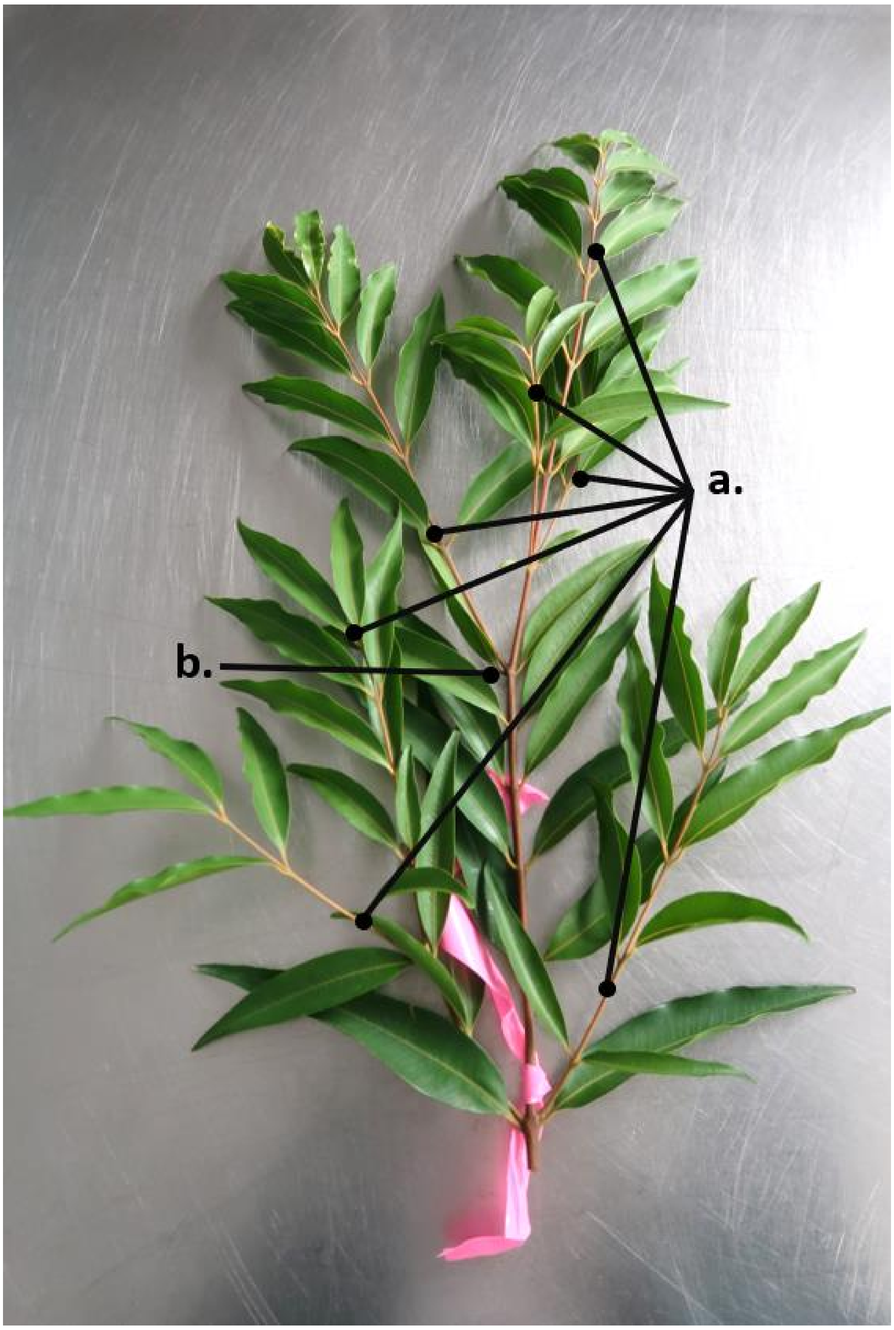
Each site has different challenges in terms of wildfire spread. Current fire risk analysis often considers wind direction and slope in wildfire spread. In regards to this research, a sloped garden may favour species that burn at a low temperature, with smaller flames (even if they display a high likelihood of multiple flame events), as these characteristics may reduce the chance of the fire spreading uphill. Alternatively on a flat piece of land, plants which can withstand some more fire exposure before igniting may be preferable as they can be used as a windbreak in low intensity fires and being able to within radiant heat and embers. Existing vegetation, it’s plantation structure and its proximity to structures also will determine if you can risk planting fast igniting species nearby and how easily the fire can spread between individual plants. For instance, clustered planting and creating plant “islands” reduces the likelihood of touching canopies spreading fire. These considerations are imperative if there is a close proximity of homes to wildland areas. In cities where there is a lower chance of wildfires encroaching onto properties higher weight should be placed onto how to support biodiversity in the region, and closer plantation and connection between canopies would be advisable where possible.

5.3 Conclusion

There are several main take-aways from this thesis. Little difference was able to be found between native and exotic species. This means that I suggest continuing to favour native plants over exotics to help support native wildlife. However, whilst planning a garden I suggest considering each plant's flammability attributes and whether they are appropriate for the site design. Some shoot traits were found multiple times throughout the three studies to increase the likelihood of a higher intensity burn, that is, a high leafing intensity, high shoot mass, high bulk density and high volume. These traits were often the ones that relate to the overall size of the shoot. This makes sense as more material to burn would allow a higher potential for the burn. Whilst there is still a low level of research available, it is suggested that at-risk locations avoid plant species with these traits. The finding that high ambient temperatures potentially increases the flammability of each flammability attribute must be considered in future wildfire mitigation strategies on all levels of decision-making parties. The effects of climate change must be mitigated to reduce this phenomenon, as with a greater number of high temperature days it will create longer periods where plants also have an increased intrinsic flammability. Finally, my hope for this thesis is that it can assist in a deeper understanding of the flammability of plants, be used to help in the appropriate selection of plants at the wildland-urban interface, and to ultimately help protect homes from wildfire whilst still providing for wildlife.

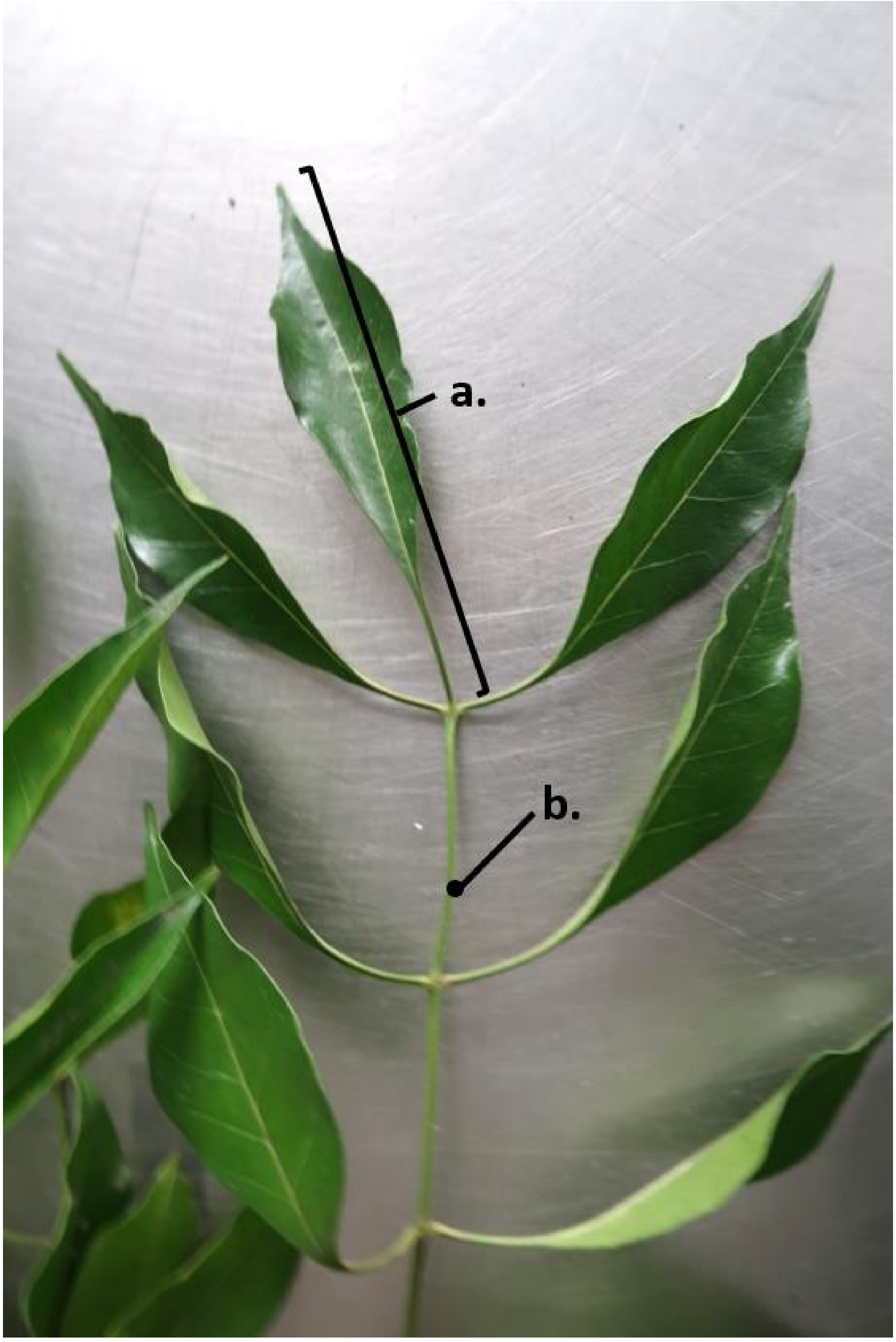
Appendix

Appendix A – Leaf and branch definitions with examples



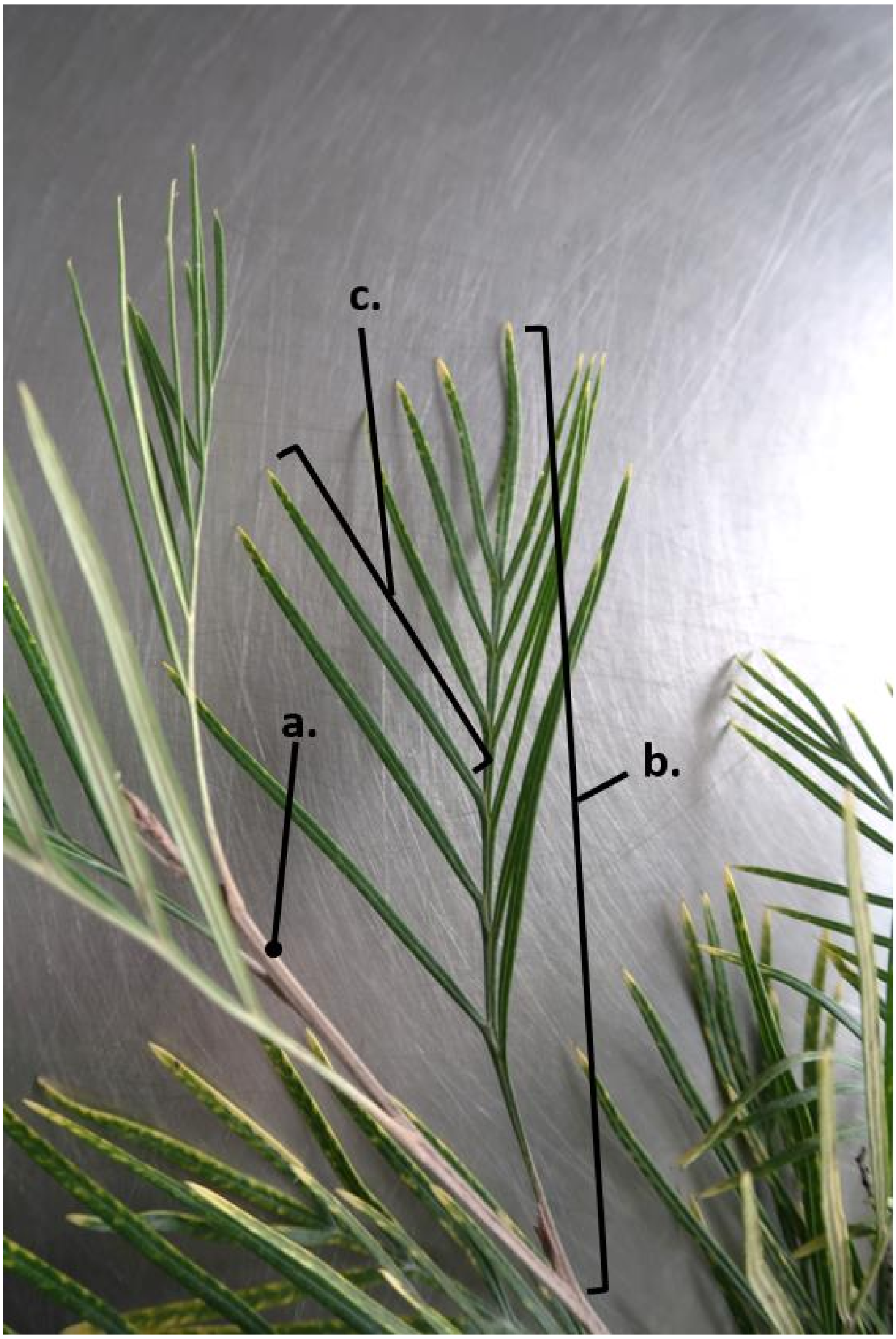
Appendix A.1 Photo diagram of garden species *Eucalyptus robusta.*

Points labelled a. indicate the sections of stem that have diverged off from each other and represents a branch in this study. Point b. indicates an example of branching of a stem within a specimen.



Appendix A.2 Photo diagram of a *Fraxinus griffithii* sample from the garden species used in this study.

The section of the sample indicated by a. is what was considered a ‘simple leaf’ within this study. A simple leaf’s length is measured from the longest most point of the leaf to where it meets the stem. Point b. in this diagram indicates the stem or branch on which a simple leaf attaches. All species in this thesis with this leaf type include: *Acmena smithii, Callistemon viminalis, Eucalyptus robusta, Waterhousea floribunda, Westringia fruticosa, Fraxinus griffithii, Gardenia augusta, Lagerstroemia indica x L. fauriei, Magnolia grandiflora, Viburnum odoratissimum, Banksia integrifolia, Corymbia maculata, Cupaniopsis anacardioides, Fraxinus pennsylvanica, Lophostemon confertus, Tristaniopsis laurina, Ulmus parvifolia* and *Zelkova serrata.*



Appendix A.3 Photo diagram of a *Grevillea* 'Moonlight' sample from the garden species used in this study.

This species is an example of a pinnatifid compound leaf. Point a. indicates the stem or branch of the sample. Point b. indicates the leaf which is used for measurements within this study. The leaf extends from the furthest point from the branch, to where it meets the branch. Section c. is considered apart of the pinnatifid compound leaf, and not considered its own leafing body. All species in this thesis with this leaf type include: *Grevillea* 'Moonlight' and *Quercus palustris.*

Appendix A.4 Photo diagram of a *Cupressocyparis leylandii* shoot sample from the garden dataset.

This type of leaf is considered a bi-pinnatifid compound leaf, whereby two degrees of division have occurred on each leaf. The section indicated by a. is the first degree of division from the stem and is considered the leaf by which measurements were taken in this thesis. Section b. is considered a leaflet. Point c. indicates the stem or branch counted in this study. All species in this thesis with this leaf type include: *Cupressocyparis leylandii* and *Jacaranda mimosifolia.*

Appendix B – Chapter 2, Garden species full modelling outputs

Appendix B.1 Tables of ANOVA results from models of flammability attributes modelled using a term for species.

Response	Terms	SS	DF	F	P
TTF	species	19.016	11	9.281	< 0.001
	residuals	17.882	96		
FD	species	108720.468	11	14.591	< 0.001
	residuals	65028.546	96		
nF	species	29.135	11	11.629	< 0.001
	residuals	21.864	96		
FT	species	1201518.012	11	7.905	< 0.001
	residuals	1326466.462	96		

Appendix B.2 Table of BIC values for the suite of models built for each flammability attribute, including terms for shoot traits as explanatory factors. Abbreviations for traits are Bulk density (BD), volume (Vol.), leafing intensity (LI). Not included in the model terms count is the controlling term of species (included in all models).

Response	Terms	n of terms	BIC
TTF	BD	1	176.07
	Vol.	1	177.76
	LI	1	176.07
	FMC	1	177.23
	BD, Vol.	2	180.41
	BD, LI	2	179.1
	BD, FMC	2	180.36
	Vol., LI	2	180.09
	Vol., FMC	2	181.88
	LI, FMC	2	180.34
	BD, Vol., LI	3	183.78

	BD, Vol., FMC	3	184.66
	BD, LI, FMC	3	183.54
	Vol., LI, FMC	3	184.51
	BD, Vol., LI, FMC	4	188.22
FD	BD	1	1063.28
	Vol.	1	1056.88
	LI	1	1047.45
	FMC	1	1063.17
	BD, Vol.	2	1058.17
	BD, LI	2	1052.13
	BD, FMC	2	1067.84
	Vol., LI	2	1050.64
	Vol., FMC	2	1061.14
	LI, FMC	2	1052.13
	BD, Vol., LI	3	1054.55
	BD, Vol., FMC	3	1062.57
	BD, LI, FMC	3	1056.81
	Vol., LI, FMC	3	1055.31
	BD, Vol., LI, FMC	4	1059.22
nF	BD	1	198.52
	Vol.	1	198.92
	LI	1	199.38
	FMC	1	198.34
	BD, Vol.	2	203.12
	BD, LI	2	203
	BD, FMC	2	202.23
	Vol., LI	2	203.59
	Vol., FMC	2	202.57
	LI, FMC	2	202.75
	BD, Vol., LI	3	207.68

	BD, Vol., FMC	3	206.86
	BD, LI, FMC	3	206.61
	Vol., LI, FMC	3	207.17
	BD, Vol., LI, FMC	4	211.29
FT	BD	1	1385.08
	Vol.	1	1385.54
	LI	1	1380.97
	FMC	1	1388.57
	BD, Vol.	2	1376.26
	BD, LI	2	1381.93
	BD, FMC	2	1389.6
	Vol., LI	2	1384.87
	Vol., FMC	2	1389.51
	LI, FMC	2	1385.54
	BD, Vol., LI	3	1379.34
	BD, Vol., FMC	3	1380.55
	BD, LI, FMC	3	1386.6
	Vol., LI, FMC	3	1389.31
	BD, Vol., LI, FMC	4	1383.82

Appendix B.3 Models of shoot traits using species as an explanatory term.

Response	Terms	SS	DF	F	P
Leafing intensity	species	157.152	11	30.5	< 0.001
	residuals	44.968	96		
Bulk density	species	27.654	11	18.011	< 0.001
	residuals	13.4	96		
Volume	species	0.055	11	7.989	< 0.001
	residuals	0.06	96		

Appendix B.4 Models of flammability attributes by status.

Response	Terms	χ^2	DF	P
TTF	status	5.224	1	0.022
FD	status	0.838	1	0.36
nF	status	0.224	1	0.64
FT	status	0.553	1	0.46

Appendix B.5 Models of shoot traits by plant status.

Response	Terms	χ^2	DF	P
Leafing intensity	status	0.121	1	0.73
Bulk density	status	1.495	1	0.22
Volume	status	0.133	1	0.72

Appendix C – Chapter 4, Relationship between shoot traits and ambient temperature on the flammability attributes

For street trees, temperature alone remained the significant correlate of nF (Appendix C.1) and FD (Appendix C.2). Temperature was also a significant correlate of TTF, however, leafing intensity emerged as a significant correlate of TTF irrespective of temperature (partial r = -0.264, F1,83 = 6.22,P = 0.015) (Appendix C.1). In the case of FT, temperature became a non-significant correlate, yet shoot mass (partial r = 0.272, F1,83 = 6.653, P = 0.012), branching intensity (partial r = 0.242, F1,83 = 5.158, P = 0.026), and leafing intensity (partial r = 0.218, F1,83 = 4.154, P = 0.045) were all significant correlates of TTF (Appendix C.1). Both leafing intensity and temperature were significant correlates of TTF (Appendix C.1).

Appendix C.1 Models of the flammability attributes TTF, nF, and FT for street trees, which had a significant main effect of ambient temperature, but no significant species x ambient temperature interaction, with each of the six shoot traits added in separate models.

Response	Term	SS	DF	F	P
TTF	**Species**	5.103	4	4.381	**0.003**
	Ambient temp.	4.341	1	14.91	< **0.001**
	Mass	0.01	1	0.035	0.85
	Residuals	24.165	83		
TTF	**Species**	6.682	4	5.847	< **0.001**
	Ambient temp.	5.855	1	20.495	< **0.001**
	Bulk density	0.463	1	1.622	0.21
	Residuals	23.712	83		
TTF	**Species**	7.07	4	6.094	< **0.001**
	Ambient temp.	5.516	1	19.018	< **0.001**
	Volume	0.102	1	0.351	0.56
	Residuals	24.074	83		
TTF	**Species**	6.709	4	5.799	< **0.001**
	Ambient temp.	4.213	1	14.566	< **0.001**
	Branching intensity	0.166	1	0.574	0.45
	Residuals	24.01	83		
TTF	**Species**	8.966	4	8.273	< **0.001**
	Ambient temp.	2.454	1	9.055	**0.003**
	Leafing intensity	1.685	1	6.22	**0.015**
	Residuals	22.49	83		
TTF	**Species**	7.436	4	6.427	< **0.001**
	Ambient temp.	4.869	1	16.833	< **0.001**
	Fuel moisture content	0.167	1	0.576	0.45
	Residuals	24.009	83		
nF	**Species**	5.057	4	8.024	< **0.001**
	Ambient temp.	5.628	1	35.713	< **0.001**
	Mass	0.003	1	0.019	0.89
	Residuals	13.079	83		
nF	**Species**	5.025	4	8.037	< **0.001**
	Ambient temp.	6.26	1	40.045	< **0.001**

	Bulk density	0.108	1	0.689	0.41
	Residuals	12.975	83		
nF	**Species**	4.921	4	7.809	**< 0.001**
	Ambient temp.	6.713	1	42.611	**< 0.001**
	Volume	0.006	1	0.04	0.84
	Residuals	13.076	83		
nF	**Species**	4.128	4	6.554	**< 0.001**
	Ambient temp.	6.079	1	38.604	**< 0.001**
	Branching intensity	0.013	1	0.082	0.77
	Residuals	13.069	83		
nF	**Species**	5.023	4	7.967	**< 0.001**
	Ambient temp.	5.529	1	35.077	**< 0.001**
	Leafing intensity	0	1	0.003	0.96
	Residuals	13.082	83		
nF	**Species**	3.739	4	6.047	**< 0.001**
	Ambient temp.	5.888	1	38.097	**< 0.001**
	Fuel moisture content	0.253	1	1.64	0.20
	Residuals	12.829	83		
FT	**Species**	26495.182	4	0.733	0.57
	Ambient temp.	6187.516	1	0.684	0.41
	Mass	60140.421	1	6.653	**0.012**
	Residuals	750295.61	83		
FT	**Species**	24266.672	4	0.623	0.65
	Ambient temp.	27285.789	1	2.802	0.10
	Bulk density	2076.257	1	0.213	0.65
	Residuals	808359.775	83		
FT	**Species**	37962.21	4	0.989	0.42
	Ambient temp.	40884.474	1	4.259	**0.042**
	Volume	13588.496	1	1.415	0.24
	Residuals	796847.536	83		
FT	**Species**	65031.789	4	1.769	0.14
	Ambient temp.	12444.383	1	1.354	0.25
	Branching intensity	47416.469	1	5.158	**0.026**
	Residuals	763019.563	83		
FT	**Species**	57060.352	4	1.534	0.20
	Ambient temp.	9533.396	1	1.025	0.31
	Leafing intensity	38626.063	1	4.154	**0.045**
	Residuals	771809.969	83		
FT	**Species**	42143.194	4	1.089	0.37
	Ambient temp.	45932.878	1	4.748	**0.032**
	Fuel moisture content	7419.769	1	0.767	0.38
	Residuals	803016.263	83		

Appendix C.2 Models of the flammability attribute FD for street trees, which had a significant species x ambient temperature interaction, with each of the six shoot traits added in separate models.

Response	Term	SS	DF	F	P
FD	**Species**	32096.402	4	11.389	**< 0.001**
	Ambient temp.	21004.332	1	29.814	**< 0.001**
	Mass	1643.09	1	2.332	0.13
	Species x ambient temp.	7144.504	4	2.535	**0.047**
	Residuals	55657.259	79		
FD	**Species**	29648.704	4	10.225	**< 0.001**
	Ambient temp.	28469.288	1	39.273	**< 0.001**
	Bulk density	33.261	1	0.046	0.83
	Species x ambient temp.	7822.012	4	2.698	**0.037**
	Residuals	57267.088	79		
FD	**Species**	30350.25	4	10.491	**< 0.001**
	Ambient temp.	33292.516	1	46.034	**< 0.001**
	Volume	165.745	1	0.229	0.63
	Species x ambient temp.	7413.739	4	2.563	**0.045**
	Residuals	57134.604	79		
FD	**Species**	30222.906	4	10.536	**< 0.001**
	Ambient temp.	25517.681	1	35.582	**< 0.001**
	Branching intensity	644.853	1	0.899	0.35
	Species x ambient temp.	7504.26	4	2.616	**0.041**
	Residuals	56655.495	79		
FD	**Species**	25574.682	4	8.865	**< 0.001**
	Ambient temp.	24135.449	1	33.466	**< 0.001**
	Leafing intensity	325.899	1	0.452	0.50
	Species x ambient temp.	7657.047	4	2.654	**0.039**
	Residuals	56974.45	79		
FD	**Species**	29676.124	4	10.343	**< 0.001**
	Ambient temp.	31438.946	1	43.829	**< 0.001**
	Fuel moisture content	632.646	1	0.882	0.35
	Species x ambient temp.	8433.85	4	2.939	**0.025**
	Residuals	56667.703	79		

For garden plants, shoot traits were only added to new models for TTF and FT, as the original models showed no significant effect of temperature on either FD (Fig. 4.3) or nF (Fig. 4.4). After the addition of the shoot traits, temperature remained a significant correlate of both FT (Appendix C.3) and TTF (Appendix C.4). In addition, shoot mass (partial r = 0.476, F1,100 = 29.322, P < 0.001), volume (partial r = 0.412, F1,100 = 16.326,P < 0.001), branching intensity (partial r = 0.375, F1,100 = 16.326, P < 0.001), and leafing intensity (partial r = 0.402, F1,100 = 19.284, P < 0.001) emerged as significant correlates of FT (Appendix C.3), and shoot volume (partial r = 0.222, F1,95 = 4.931,P = 0.029) and branching intensity (partial r = -0.273, F1,95 = 7.638,P = 0.007 emerged as significant correlates of TTF (Appendix C.4).

Appendix C.3 Models of the flammability attribute FT for garden plants, which had a significant main effect of ambient temperature, but no significant species x ambient temperature interaction, with each of the six shoot traits added in separate models.

Response	Term	SS	DF	F	P
FT	**Species**	320442.688	5	4.397	**0.001**
	Ambient temp.	105994.686	1	7.272	**0.008**
	Mass	427409.697	1	29.322	**< 0.001**
	Residuals	1457658.947	100		
FT	**Species**	279304.163	5	2.966	**0.015**
	Ambient temp.	239867.147	1	12.736	**< 0.001**
	Bulk density	1646.537	1	0.087	0.77
	Residuals	1883422.107	100		
FT	**Species**	171907.11	5	2.197	0.06
	Ambient temp.	173903.759	1	11.113	**0.001**
	Volume	320139.424	1	20.457	**< 0.001**
	Residuals	1564929.22	100		
FT	**Species**	541712.085	5	6.686	**< 0.001**
	Ambient temp.	66064.716	1	4.077	**0.046**
	Branching intensity	264557.553	1	16.326	**< 0.001**
	Residuals	1620511.091	100		
FT	**Species**	596163.417	5	7.545	**< 0.001**
	Ambient temp.	116409.457	1	7.366	**0.008**
	Leafing intensity	304752.406	1	19.284	**< 0.001**
	Residuals	1580316.238	100		
FT	**Species**	260458.232	5	2.767	**0.022**
	Ambient temp.	245222.138	1	13.027	**< 0.001**
	Fuel moisture content	2599.908	1	0.138	0.71
	Residuals	1882468.736	100		

Appendix C.4 Models of the flammability attribute TTF for garden plants, which had a significant species x ambient temperature interaction, with each of the six shoot traits added in separate models.

Response	Term	SS	DF	F	P
TTF	**Species**	6.610	5	8.438	**< 0.001**
	Ambient temp.	1.015	1	6.480	**0.013**
	Mass	0.187	1	1.194	0.28
	Species x ambient temp.	4.032	5	5.147	**< 0.001**
	Residuals	14.884	95		
TTF	**Species**	7.218	5	9.248	**< 0.001**
	Ambient temp.	1.209	1	7.743	**0.007**
	Bulk density	0.243	1	1.558	0.21
	Species x ambient temp.	3.495	5	4.479	**0.001**
	Residuals	14.828	95		
TTF	**Species**	7.441	5	9.867	**< 0.001**
	Ambient temp.	0.881	1	5.843	**0.018**
	Volume	0.744	1	4.931	**0.029**
	Species x ambient temp.	3.856	5	5.113	**< 0.001**
	Residuals	14.327	95		
TTF	**Species**	7.072	5	9.633	**< 0.001**
	Ambient temp.	0.279	1	1.898	0.17
	Branching intensity	1.122	1	7.638	**0.007**
	Species x ambient temp.	3.622	5	4.934	**< 0.001**
	Residuals	13.95	95		
TTF	**Species**	5.056	5	6.405	**< 0.001**
	Ambient temp.	0.855	1	5.413	**0.022**
	Leafing intensity	0.073	1	0.459	0.50
	Species x ambient temp.	3.762	5	4.766	**< 0.001**
	Residuals	14.999	95		
TTF	**Species**	6.593	5	8.314	**< 0.001**
	Ambient temp.	1.144	1	7.214	**0.009**
	Fuel moisture content	0.003	1	0.020	0.89
	Species x ambient temp.	3.826	5	4.825	**< 0.001**
	Residuals	15.068	95		

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