Flammability of indigenous and invasive alien woody plants in coastal fynbos and thicket

By

Samukelisiwe Tholakele Msweli

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Supervisor: Dr Tineke Kraaij
Co-Supervisor: Dr Alastair J Potts

DECLARATION

I, Samukelisiwe Tholakele Msweli (214200884), hereby indicate that the dissertation for Master of Science in the Faculty of Science is my own work and that it has not previously been submitted for assessment or completion of any postgraduate qualification to another University or for another qualification.

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ABSTRACT

Globally, extreme fires have become more common in wildland-urban interface areas, and more recently, along the southern Cape coast of South Africa. The 2017 Knysna fires prompted greater understanding of the flammability of, and the fire risk posed by, different vegetation groups, which is essential to develop fire risk mitigation strategies. In this study, I experimentally assessed flammability of 30 woody plant species from the vegetation groups indigenous fynbos, thicket, and invasive alien plants (IAPs) that occur along the southern Cape coast. Live plant shoots were sampled across varying fire weather conditions and burnt experimentally to measure flammability in relation to fire weather conditions, fuel moisture, and fuel load. Flammability measures considered were: burn intensity, completeness of burn, time-to-ignition, and the likelihood of spontaneous ignition. I further assessed the flammability of partially dried plant material as a crude proxy for drought effects, to ascertain whether drying of fuels would differentially affect the flammability of the vegetation groups. I used generalized linear mixed-effects models to assess flammability measures in relation to the predictor variables: fire weather, fuel moisture, fuel load, vegetation groups, and species (as a random factor). Results showed that increasing severity of fire weather significantly increased flammability through increasing burn intensity, increasing completeness of burn, increasing the likelihood of spontaneous ignition, and also reducing time-to-ignition. Increasing fuel moisture significantly decreased burn intensity, completeness of burn, and the likelihood of spontaneous ignition. Fuel load significantly increased burn intensity and time-to-ignition. Flammability was highest in IAPs, intermediate in fynbos, and lowest in thicket. IAPs and fynbos showed significantly higher ignitability, and thus present risks under moderate and high fire weather conditions, whereas thicket presents lower risks under low and moderate fire weather conditions. The drying out of fuels considerably increased flammability equally in the three vegetation groups, and by implication, fire risk due to an increase in dead:live ratio. Flammability was furthermore assessed in relation to fuel traits, i.e. the proportion of fine fuels, coarse fuels, and dead fuels, fuel bed porosity, fuel load, and fuel moisture, using multiple regression analysis and stepwise selection of factors. This revealed that fuel moisture was the most important factor affecting flammability in terms of all the flammability measures. Results further showed that the increase in the proportions of fine fuels increased flammability by increasing completeness of burn. Lastly, vegetation groups were compared (using Kruskal Wallis) in terms of their flammability and fuel traits. I found that fynbos and IAPs exhibited greater flammability on account of higher completeness of burn and more rapid ignition than thicket species, but no clear distinction was evident between fynbos and IAPs. Fynbos' high flammability was attributed to high proportions of fine and porous fuels. Thicket's low flammability was attributed to high proportions of coarse and dense fuels. Little distinction in fuel traits could be made between fynbos and IAPs, except that fynbos had a greater proportion of fine fuels. There is a potential risk posed by the IAPs in terms of increased flammability and fire severity, on an indigenous landscape that is invaded. Fire managers need to encourage the prioritization of the management of IAPs that present high flammability as an attempt to reduce fire risk along the southern Cape coast of South Africa.

Keywords*:* wildfires, wildfire prevention, wildland-urban interface areas, southern Cape coast, South Africa

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DISSERTATION STRUCTURE AND CONFERENCE CONTRIBUTIONS

This study assessed the flammability of different vegetation groups along the southern Cape coast of South Africa to inform fire risk prevention and mitigation strategies. Chapters 2 and 3 were written in research article format, resulting in some replication of text (i.e. study area), and reference lists were provided separately for each chapter to facilitate readability. I adopted the reference style of the South African Journal of Botany throughout the dissertation for consistency purposes. The dissertation is structured as follows:

Chapter 1 provided a rationale for this study. I started with the flammability concept and its relevant measures and expand on its primary determinants. I expand on the study system, and finally study aims and objectives were introduced.

Chapter 2 assessed the flammability of live plant material of fynbos, thicket, and invasive alien plants in relation to fire weather conditions, fuel moisture, and fuel load. It further assessed the flammability of partially dried plant material as a crude proxy for drought effects. The findings of this chapter were presented at the National Symposium on Biological Invasions, 15 – 17 May 2019, Tulbagh, Western Cape, and Thicket Forum, 12 - 14 June 2019, Port Elizabeth, Eastern Cape. We intend to submit this chapter as a research paper to the journal PeerJ. Contributing authors will be Dr Alastair J Potts, Prof. Herve Fritz, and Dr Tineke Kraaij.

Chapter 3 assessed flammability of live plant material of fynbos, thicket, and invasive alien plants in terms of burn intensity, completeness of burn, and time-to-ignition in relation to various fuel traits. Structural fuel traits (i.e. the proportion of fine fuels, coarse fuels, and dead fuels, and fuel bed porosity) were considered in addition to fuel load, and fuel moisture. I further compared the vegetation groups in terms of their flammability and their fuel traits.

Chapter 4 presented a synthesis of the major findings of Chapters 2 and 3. This chapter highlighted strengths and shortcomings of these studies, and provided recommendations for management and future research.

CHAPTER 1: General introduction

Flammability

Flammability is defined as the ability of vegetation (fuel) to burn (Fernandes and Cruz, 2012; Gill and Zylstra, 2005), and is a measure of fire behaviour used in vegetation fire risk studies (Keeley, 2009). Flammability has been previously measured by considering four aspects, namely ignitability (how easily fuel ignites), sustainability (how long it continues to burn), combustibility (how rapidly it burns) and consumability (how much of it burns) (Anderson, 1970). For the purposes of this study, ignitability has been considered in terms of time-to-ignition (appearance of first flame) and spontaneous ignition (the likelihood of igniting within set time); combustibility was considered in terms of completeness of burn (proportion of the pre-burn wet mass that was consumed) (Burger and Bond, 2015; Calitz et al., 2015; Keeley, 2009) and burn intensity (maximum temperature reached by fuel) was also considered. Flammability has traditionally been experimentally assessed in laboratories through burning of relatively small components of fuels in a controlled environment (Engber and Varner, 2012; Etlinger and Beall, 2004; Fernandes and Cruz, 2012; Grootemaat et al., 2017; Guijarro et al., 2002; Ormeño et al., 2009; Varner et al., 2015, Table 1). Such experiments may not effectively represent real-world fire incidences, as flammability is primarily determined by the influences of weather conditions (Bond, 1997; Keeley and Syphard, 2017), and composite fuel traits (Davies and Nafus, 2013; van Wilgen and Richardson, 1985). Hence, this study sought to assess the flammability of whole plant shoots under various weather conditions that represent the actual context of the southern Cape coastal landscape.

Effects of weather conditions

Weather conditions that influence flammability include ambient temperature, relative humidity, and wind. These factors affect the ignitability of fuels, and thereby flammability (Archibald et al., 2008; Behm et al., 2004; Duguy et al., 2013). Large fire events often occur during extreme weather conditions (Keeley, 2009), with flammability and fire hazards increasing in dry, and warm weather (Duguy et al., 2013; Piñol et al., 1998; Wyse et al., 2016). Additionally, extended drought periods and accumulation of flammable fuels pre-fire often contribute to extreme fire events (Alcañiz et al., 2018; Kraaij et al., 2018). Under these conditions, fires readily burn through all age classes of fuels, consuming dead and live plant material (Gellie et al., 2010; Keeley et al., 1999; Viegas, 1998). Climate conditions that occurred months or years before the extreme fire events have been reported to also enhance fire severity (Archibald et al., 2008; Gellie et al., 2010; Keeley, 2009; Kraaij et al., 2018; Urbieta et al., 2015; Viegas, 1998).

Fire-proneness of weather conditions is commonly expressed in terms of fire danger indices (FDIs) based on levels of ambient temperature, relative humidity, wind speed and rainfall (Noble et al., 1980). Various FDIs are used to assess the relationship between flammability and weather conditions. Examples include the Canadian Fire Weather Index that is widely used, and is highly suitable for the Mediterranean ecosystems (Dowdy et al., 2009; Jiménez-Ruano et al., 2018; Sirca et al., 2018; Urbieta et al., 2015), the McArthur Forest Fire Danger model for Australia that is representative of forested ecosystems (Noble et al., 1980), and it also incorporates the Keetch-Byram drought index (can be used as a stand-alone index to measure the effect of seasonal drought on fire potential) (Dowdy et al., 2009; Kraaij et al., 2013b); and the Department of Agriculture, Forestry and Fisheries fire danger rating system which is generally suitable for lowveld (i.e. southern Africa vegetation types) (Madula, 2013). Some FDIs also integrate meteorological and fuel information that can be applied to regions for the issuing of fire risk warnings, or to estimate the difficulty of fire suppression (Dowdy et al., 2009; Noble et al., 1980; Sirca et al., 2018).

Effects of fuel traits

Fuel traits influencing flammability can be categorised as intrinsic and extrinsic fuel properties (Midgley, 2013; White and Zipperer, 2010). Intrinsic fuel properties affecting flammability include fuel moisture content, carbon compounds (cellulose, hemicellulose, and lignin), and volatile organic compounds (Behm et al., 2004; Calitz et al., 2015; White and Zipperer, 2010). Extrinsic fuel properties relate to the structural form of fuels such as fuel size, amount of biomass (~fuel load), and fuel bed porosity (fuel sparseness) (Burger and Bond, 2015; Calitz et al., 2015; Saura-Mas et al., 2010; Viegas, 2006). Various studies conducted in several indigenous vegetation types of the world have experimentally assessed flammability in relation to different fuel traits (Table 1). Many studies have used flammability as a composite measure (i.e. flammability index) (Alessio et al., 2008; Burger and Bond, 2015; Calitz et al., 2015; Engber and Varner, 2012; Santana and Marrs, 2014, Table 1). However, some studies have focused on specific measures such as burn intensity (~fire severity) (Grootemaat et al., 2017; Saura-Mas et al., 2010; Schwilk, 2003; Simpson et al., 2016), ease of ignition (Dimitrakopoulos, 2001; Fletcher et al., 2007; Guijarro et al., 2002; Simpson et al., 2016), completeness of burn (Burger and Bond, 2015), and rate of spread (Davies and Legg, 2011). The current study comprehensively assessed several flammability measures, i.e. burn intensity, completeness of burn, and time-to-ignition in relation to various fuel traits.

Furthermore, flammability studies have largely concentrated on fuel traits such as fuel load and fuel moisture (Table 1), whereas fuel traits such as the extent of fine fuels, dead fuels, and fuel bed porosity have been neglected. Many studies have reported the effect of large fuel loads on flammability through increasing fire intensity (Baeza et al., 2002; Calitz et al., 2015; Keeley, 2009; Saura-Mas et al., 2010; Simpson et al., 2016). However, the fuel load and fire intensity relationship has been reported to not hold in some ecosystems that generally present low fuel loads (Calitz et al., 2015; Grootemaat et al., 2017; Guijarro et al., 2002). Fuel moisture plays a critical role in ignitability and in the rate of fire spread (Alessio et al., 2008; Bianchi and Defossé, 2015; Davies and Legg, 2011; Dimitrakopoulos, 2001; Saura-Mas et al., 2010; Simpson et al., 2016). As fuel moisture content increases, more energy is required to heat fuels to combustion, translating into slower rates of fire spread (Davies and Nafus, 2013; Kane and Nuria, 2019). Although fine and dead fuels have been neglected in flammability studies, both consistently appear to enhance flammability by increasing completeness of burn and rate of spread (Burger and Bond, 2015; Calitz et al., 2015; Davies and Legg, 2011; Engber and Varner, 2012; Santana and Marrs, 2014; Schwilk, 2003, Table 1). Considering fuel bed porosity, Burger and Bond (2015) reported no effect of porosity on flammability, although it has been previously stated that sparse fuels allow oxygen supply to flames (van Wilgen et al., 1990; Ward et al., 1996), thus increasing rates of spread (Brooks et al., 2004; Davies and Nafus, 2013). However, a study conducted on moorlands reported that fuel bed porosity did not enhance the rate of fire spread (Davies and Legg, 2011).

Fuel properties of indigenous vegetation may be modified through the introduction of invasive alien plants (IAPs). Fuels of some IAPs contain volatile substances supporting fires of higher intensities (Alessio et al., 2008; Behm et al., 2004) that result in increased fire damage and difficulty of control (Murray et al., 2013). The invasion may result in significant increases in biomass due to fast growth and increased litterfall (Richardson and van Wilgen, 2004) which contributes to a build-up of excessive fuel loads (Brooks et al., 2004; Davies and Nafus, 2013). IAPs may furthermore change the arrangement of fuel particles (Brooks et al., 2004), for example, increase the vertical or horizontal continuity of fuels and as a result facilitate fire spread once ignited (Davies and Nafus, 2013; Richardson and van Wilgen, 2004). IAPs alteration of fuel characteristics may lead to additional ecological impacts in terms of the native vegetation responding to altered fire regimes (Brooks et al., 2004).

TABLE 1: Experimental flammability studies conducted in various vegetation types of the world with an indication of the scale of the experiment (i.e. litter, leaves, plots or plant shoots). Flammability measures vary from overall flammability, burn intensity, completeness of burn, ease of ignition and rate of spread. Fuel traits (explanatory variables) were fine fuels (F), coarse fuels (C), fuel load (L), fuel bed porosity (P), dead fuels (D), and fuel moisture (M). '+' denotes a positive effect, '-' a negative effect, and '0' no relationship

References	Vegetation; location	Scale of experiment	Flammability measure	Fuel traits						Notes
				F	C	L	P	D	M	
Alessio et al., 2008	Mediterranean shrubland; Barcelona	Leaves	Flammability						**-**	No clear relationship between species-specific differences in flammability and their moisture.
Burger and Bond, 2015	Cape shrublands; South Africa	Plant shoots	Flammability	**+**			**0**			Maximum temperature positively correlated with % fuel burned
			Completeness of burn	**+**				**+**		Water content was not significant but accounted for plant flammability to some extent
Calitz et al., 2015	Fynbos, Grassland, Nama-Karoo, Thicket, Forest; South Africa	Plant shoots	Flammability	**+**			**-**			Large proportion of highly and moderately flammable species
					-	**+**				Low flammability was associated with sparsely arranged leaves
Davies and Legg, 2011	Moorland (*Calluna* dominated), United Kingdoms	Plots	Rate of spread				**-**	**+**	**-**	Rate of spread negatively correlated with burn intensity
Dimitrakopoulos, 2001	Mediterranean Forest fuels;	Leaves	Ease of ignition						**-**	Most of the variation in the time-to-ignition was explained by moisture content.

References	Vegetation; location	Scale of experiment	Flammability measure	Fuel traits						Notes
				F	C	L	P	D	M	
	Mediterranean Basin									
Engber and Varner, 2012	18 oak species; USA	Litter	Flammability	+						Low-flammability cluster characterized by evergreen shrubs with small, thick leaves that burned with small flames for a short duration and little fuel consumption
(Fletcher et al., 2007)	Eight plant species native to California chaparral; Utah	Leaves	Ease of ignition						+	No consistent correlations between moisture content and the ignition behaviour of shrub leaves
Guijarro et al., 2002	*Eucalyptus, Pinus,* and grasses; South Europe	Litter	Ease of ignition			-			+	Grasses registered the lowest time-to-ignition and rate of combustion, in spite of higher values of moisture
Grootemaat et al., 2017	Closed forest, pen forest, Dry open woodland, Mallee woodland; Australia	Litter and leaves	Burn intensity		-	-				Leaves with higher packing ratios burnt at higher temperatures
Santana and Marrs, 2014	Mediterranean Basin shrublands; Spain	Plots	Flammability	+				+		Flammability was influenced by the proportion of dead fuel accumulated and their fuel moisture
Saura-Mas et al., 2010	Open pine woodlands and Coastal shrublands; Mediterranean Basin	Leaves	Burn intensity	+		+			-	Ignition depends on intrinsic plant properties such as leaf morphology, while water content, more dependent on environmental conditions

References	Vegetation; location	Scale of experiment	Flammability measure	Fuel traits						Notes
				F	C	L	P	D	M	
Schwilk, 2003	California chaparral shrub species; California	Plots	Burn intensity	+		+				Clip and leave and removal of branch treatments had significantly lower temperatures than unmanipulated or dead wood addition
Simpson et al., 2016	Grassland, Nama-Karoo; South Africa	Plant shoots	Flammability						-	Fuel moisture content exerted a strong influence on vegetation flammability
			Ease of ignition						-	
			Burn intensity			+				

Ecological significance of flammability

Fire-prone vegetation may possess traits that enhance their flammability and improve survival within fire-dependent communities (Bowman et al., 2014; Burger and Bond, 2015; Midgley, 2013). Mutch (1970) hypothesized that “fire-dependent plant communities burn more readily than non-fire dependent communities because natural selection has favored characteristics that make them more flammable”. The Mutch hypothesis faced criticism on a point of how would the ability to readily burn be beneficial to fire-dependent communities (Bowman et al., 2014; Midgley, 2013). However, the ‘kill thy neighbour’ hypothesis suggests that post-fire recruitment of an individual would be facilitated if high flammability of that individual would lead to mortality of itself and its neighbor (Bond and Midgley, 1995). In such a case, flammable individuals can injure or kill competitors and maintain favorable environments for self-perpetuation (Bond and Midgley, 1995; Engber and Varner, 2012). Hence, flammability acts as a niche-constructing trait that modifies the environment to the benefit of flammable individuals (Schwilk, 2003). Evidence showed that recurrent fires could potentially increase plant flammability (Keeley et al., 2012; Pausas and Moreira, 2012), leading to individual species developing physiological adaptations to fire. Fire adaptation traits may include resprouting, serotiny, physical dormancy, post-fire flowering, and smoke-induced germination (Bradshaw et al., 2011; Burger and Bond, 2015; Cowan and Ackerly, 2010; Schwilk, 2003), providing survival and persistence advantages in a given environment.

The relevance of flammability for fire risk management

An understanding of the relationships between weather conditions, fuel traits and flammability is not only important in fire ecological research, but it has the potential to inform fire risk management. Extreme fires are attributed to factors such as very high fire danger weather and extended droughts (Kraaij et al., 2018; Preston, 2017), and highly flammable vegetation and species (Burger and Bond, 2015; Calitz et al., 2015; White and Zipperer, 2010). Extreme fires affecting wildland-urban interface areas have become increasingly common in the shrublands of California, Australia, Europe (Montenegro et al., 2004; San-Miguel-Ayanz et al., 2013) and more recently, South Africa (Kraaij et al., 2018). These destructive fires have been accredited to the combinations of climate change (weather more conducive to fire and extended droughts) and increased ignitions linked to increased human populations (Archibald et al., 2008; Montenegro et al., 2004; Syphard et al., 2017). Furthermore, excess accumulation of fuels due to IAPs and human suppression of fires to safeguard assets, contribute to increases in fire risk (Kraaij et al., 2018; Radeloff et al., 2005; Scott et al., 1998). Fires in wildland-urban interface areas cause fatalities, loss of homes and properties (Behm et al., 2004; Kraaij et al., 2018; Williams, 2013); therefore, fire risk management in these landscapes is particularly important.

Study system

In June 2017, extreme fires occurred along the southern Cape coast of South Africa around the town of Knysna. The fires burnt through indigenous fynbos, thicket and forest vegetation and caused damage to plantations and residential properties (Kraaij et al., 2018). Large parts of the burnt area were densely invaded by IAPs and also occupied by *Pinus* or *Eucalyptus* plantation stands (Baard and Kraaij, 2014; Kraaij et al., 2018; van Wilgen et al., 2016). Fire intensities were shown to have been higher in invaded vegetation and commercial pine plantations than in uninvaded indigenous fynbos (Kraaij et al., 2018). The unprecedented 2017 Knysna fires emphasised the need for improved understanding of variation in flammability of, and the fire risk posed by, various vegetation groups. Such information could inform management efforts aimed at reducing fire risk and damage resulting from fires in southern Cape coastal landscapes.

Fynbos flammability

Fire is particularly important for maintaining plant diversity and recruitment in the Cape Floristic Region (CFR) of South Africa (Cowling et al., 1997a; Kraaij et al., 2011; van Wilgen and Richardson, 1985). The coastal vegetation of the southern Cape coast (Southern Cape Dune Fynbos) (Vlok et al., 2003) comprises fire-prone and fire-dependent fynbos shrublands approximately 3 m in height (van Wilgen et al., 1990), interspersed with smaller areas of the fire-resistant thicket and Afrotemperate forest (Pierce and Cowling, 1984). In mature mountain fynbos, the combination of ericoid, herbaceous plants and standing dead material provide vertical fuel continuity which results in crown fires (van Wilgen et al., 1990). These fine fuels make fynbos prone to burning at any time of the year (Kraaij and van Wilgen, 2014; van Wilgen, 1984), with fynbos that is five years of age already presenting sufficient biomass to sustain fire under high fire weather conditions (van Wilgen et al., 1990).

Similarly to other Mediterranean-type ecosystems, South African fynbos regenerates post-fire using two fundamental regeneration mechanisms (Duguy et al., 2013; Marais et al., 2014; Saura-Mas et al., 2010), with certain species possessing both mechanisms (Paula and Pausas, 2008; Pausas et al., 2004). Some species persist by recruiting seedlings from a fire-cued seed bank, termed reseeders (Kraaij and van Wilgen, 2014; Marais et al., 2014; van Wilgen and Forsyth, 1992). Others resprout from lignotubers or vegetative buds, termed resprouters (Paula and Pausas, 2008; Pausas et al., 2004; Pausas and Keeley, 2014). In addition, reseeders and resprouters co-occur in fynbos.

Thicket flammability

Thicket vegetation comprises assemblages of mostly evergreen broad-leaved shrubs producing a dense canopy up to 4 m in height (Brantley and Young, 2007; Pierce and Cowling, 1984). A large proportion of thicket species have low flammability, this may be attributed to medium-sized fuels that do not burn readily (Burger and Bond, 2015; Calitz et al., 2015; Kraaij and van Wilgen, 2014). Thicket has high fuel loads, but fuel consumed during a fire event is generally low due to their low flammability (Kraaij et al., 2018). Although thicket seldom burns, a recent study has indicated that under extreme weather conditions, fire intensity in coastal thicket may exceed that in fynbos (Kraaij et al., 2018).

Indigenous thicket is seen to sprout vigorously post-fire (Strydom et al., submitted) with few seedlings recruiting inter-fire periods (Cowling et al., 1997b; Le Maitre, 1992; Midgley, 1996; Midgley and Cowling, 1993). Also, fire-sensitive species in the thicket ecosystem occur in landscapes that rarely burn to escape fire in space (Cowling and Potts, 2015). Little research has been conducted considering thicket flammability and its optimum fire regime (Calitz et al., 2015; Pierce and Cowling, 1984).

Invasive alien plants flammability

Fynbos is particularly prone to invasion by IAPs (Le Maitre et al., 1996). The IAPs are regarded as one of the most significant threats to southern Cape ecosystems (Baard and Kraaij, 2014). A few common IAPs species (*Acacia*, *Eucalyptus* and *Pinus*) have invaded the fynbos extensively (Holmes et al., 2000; van Wilgen et al., 2001; Witkowski, 1991; Zietsman and Bredenkamp, 2006) with approximately 30 species occupying at least 10% of the southern Cape (van Wilgen, 2009). Interactions between IAPs and fire often occur whereby they alter fire regime variables (i.e. fire intensity, severity, type, frequency, spatial scale and seasonality) and in turn thrive in and sustain those new conditions they created (Brooks et al., 2004; van Wilgen, 2009; Williams, 2013). In such a case, a modified fire regime combined with the loss of indigenous plants create opportunities for IAPs to colonise and persist in sites where they could not previously dominate (Brooks et al., 2004; Holmes et al., 2000; Richardson and van Wilgen, 2004). Subsequently, flammability may act as a selective advantage associated with fire tolerance favouring IAPs (Bond and Midgley, 1995; Brooks et al., 2004; Calitz et al., 2015).

Information on the impacts of IAPs on fire behaviour is often lacking, specifically in the context of coastal fynbos and indigenous thicket (Richardson and van Wilgen, 2004; Zouhar et al., 2010), or knowledge is concentrated on specific species (van Wilgen et al., 2001). For example, in fynbos, *Acacia* species were found to produce more aboveground biomass subsequently increasing fire intensity and the rate of fire spread (van Wilgen, 1984; Witkowski, 1991; Yelenik et al., 2004). Overall understanding of differences in flammability among indigenous species and IAPs is inadequate, especially under varied weather conditions. The increase in IAPs on the southern Cape landscapes emphasizes the need to understand the effects they have on the environment in order to make informed decisions about the prioritization of their management.

Fire regime and fire climate

Fire regimes in fynbos have been well studied in terms of fire frequency and seasonality, but not adequately in terms of intensity (Burger and Bond, 2015; Calitz et al., 2015; Kraaij and van Wilgen, 2014). For the conservation of fynbos, moderate to high intensity fires at 10 to 20-year intervals are optimal (Kraaij et al., 2011; Kraaij and van Wilgen, 2014). In contrast to fynbos, fires in indigenous thicket are rare and fire regimes poorly understood (Helme, 2005; Liengme, 1987). It is thought that the persistence of fynbos-thicket mosaics requires fires at intervals of 15–25 years since thicket becomes dominant in the prolonged absence of fire (Kraaij and van Wilgen, 2014; Strydom et al., submitted). The climate in the southern Cape coast is moderated by the maritime influence with average minimum and maximum temperatures ranging from 7 to 19ºC in June and 15 to 26ºC in January an annual rainfall of approximately 800 mm throughout the year (Bond, 1981). The area experiences weather conditions suitable for fires at any time of the year and fires are often associated with hot, dry katabatic (‘berg’) winds (Kraaij et al., 2013b; van Wilgen, 1984). Predictions of climate change suggest that the CFR will become hotter and drier with implications for future fire regimes (Bond et al., 2003). In the southern Cape coastal region, average fire weather conditions have increased already since the 1940s (Kraaij et al., 2013; Kraaij and van Wilgen, 2014) along with the increased incidence of extreme fires (Kraaij et al., 2018; Kraaij and van Wilgen, 2014).

Study objectives

Due to increased incidence and severity of fires, the extent to which different vegetation types present fire risk in the landscape needs to be better understood in order to inform fire risk management. The main aim of the study is to compare flammability of different groups of vegetation occurring along the southern Cape coast of South Africa. Results aim to improve fire risk prevention and mitigation strategies across the coastal fynbos and thicket ecosystems. The primary objectives are therefore to:

1. Compare flammability of, and the risk posed by various vegetation groups (i.e. invasive alien plants, indigenous fynbos, and thicket) under varying fire weather conditions.
2. Compare the flammability of vegetation groups of interest in relation to their fuel traits.

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CHAPTER 2: Flammability of indigenous and invasive alien woody plants in coastal fynbos and thicket: Effects of fire weather, fuel moisture, and fuel load

Abstract

Destructive fires in the wildland-urban interface pose societal threats. Understanding the flammability of, and the fire risk posed by, different vegetation groups is essential to develop fire risk prevention and mitigation strategies. I assessed flammability of 30 woody plant species along the southern Cape coast, namely invasive alien plants, indigenous fynbos, and thicket vegetation. Plant shoots were sampled across varying fire weather conditions and burnt experimentally to measure flammability in relation to fire weather conditions, fuel moisture, and fuel load. Flammability measures considered were: burn intensity, completeness of burn, time-to-ignition, and the likelihood of spontaneous ignition. Contrary to expectations, I found no association between fire weather conditions and fuel moisture. Nonetheless, fire weather conditions significantly increased all flammability measures, whereas fuel moisture significantly reduced burn intensity and completeness of burn. Fuel load significantly increased burn intensity, while reducing ignitability. Although fire weather, fuel moisture, and fuel load had significant effects on flammability measures, species differences accounted for most of the variation in flammability. Regarding trends within vegetation groups, fynbos ignited rapidly and burnt completely (related to its low fuel moisture contents), whereas thicket was slow to ignite and burnt incompletely (due to its higher fuel moisture contents). Invasive alien plants were slow to ignite (related to their high fuel moisture contents), but they also burnt with the highest intensity (potentially due to volatile organic composition). Flammability was generally highest in invasive alien plants, intermediate in fynbos, and lowest in thicket.

Keywords*:* wildland-urban interface, burn intensity, completeness of burn, time-to-ignition, spontaneous ignition

Introduction

Flammability is the ability of vegetation (fuel) to burn (Fernandes and Cruz, 2012; Gill and Zylstra, 2005) and is a measure of fire behavior (fire intensity/severity) used in vegetation fire risk mitigation studies (Keeley, 2009). Vegetation flammability may result from climatic effects (Bond and Midgley, 1995; Calitz et al., 2015; Mutch, 1970; Snyder, 1984). For example, fires that are climate-driven may be limited when dry conditions reduce fuel production to sustain fires (Pausas and Bradstock, 2007), however dry conditions may also result in an increase in fire risk caused by the availability of dried fuels (Piñol et al., 1998). Fire-prone vegetation groups may furthermore have evolved traits that enhance their flammability and improve vegetation fitness in fire-dependent communities (Bond and Midgley, 1995). Correspondingly, species with high flammability traits would burn intensely, such that itself and the neighbour die, thereby facilitating recruitment – the 'kill thy neighbour' hypothesis (Bond and Midgley, 1995). Flammability traits may thus provide resilience associated with fire tolerance (Bond and Midgley, 1995; Calitz et al., 2015). Fire is accordingly one of the main determining factors of the ecology and distribution of ecosystems of the world, and is important for maintaining plant diversity (Bond, 1997; Bond et al., 2003; Bond and Keeley, 2005).

Flammability is also affected by weather conditions (Bond, 1997; Keeley and Syphard, 2017). To rate the fire-proneness of weather conditions, fire danger indices based on ambient temperature, relative humidity, wind speed, and rainfall are commonly used (Dowdy et al., 2009; Noble et al., 1980; Sirca et al., 2018). Ambient temperature and relative humidity also influence fuel moisture contents, thereby affecting flammability. For example, low fuel moisture facilitates the ease of ignition (Archibald et al., 2008; Baeza et al., 2002; Bond, 1997). Additionally, fuel properties such as the amount of flammable plant material (fuel load), packing ratio and chemical composition influence flammability (Brooks et al., 2004; Burger and Bond, 2015; Curran et al., 2017). For instance, greater fuel loads or volatile substances can increase fire intensity (Baeza et al., 2002; Saura-Mas et al., 2010).

Globally, extreme fires have become more common in recent years. Examples include the shrublands of California, Australia, Europe (Montenegro et al., 2004; San-Miguel-

Ayanz et al., 2013), and more recently, South Africa (Kraaij et al., 2018). These fires have been accredited to the combinations of climate change (in the form of weather conditions more conducive to fire and extended droughts), increased ignitions, expanded wildland-urban interface areas linked to increasing human populations, changes in fuels that are often human-induced. (Archibald et al., 2008; Montenegro et al., 2004; Syphard et al., 2017; Turco et al., 2017; van Wilgen, 1984). Fuels accumulate excessively when humans suppress fires to safeguard assets, and due to invasion by invasive alien plants (hereafter IAPs) (Kraaij et al., 2018; Radeloff et al., 2005; Scott et al., 1998). The IAPs may affect flammability by altering the fuel structure, fuel distribution (horizontal or vertical fuel continuity), fuel moisture, chemical contents and fuel load (Brooks et al., 2004; Davies and Nafus, 2013; Richardson and van Wilgen, 2004). Extreme fires are also known to occur in shrublands after severe droughts due to the increase of dead (~dry) to live fuel ratios (Keeley et al., 2012; Keeley and Syphard, 2017; Kraaij et al., 2018).

Along the southern Cape coast of South Africa, fynbos and thicket shrublands occur interspersed despite displaying different fire dynamics and fuel structural traits (Campbell et al., 1981; Moll et al., 1984). Fynbos ecosystems commonly support canopy fires and comprise species that readily burn to open recruitment opportunities (gaps) post-fire (Buhk et al., 2007; Deacon et al., 1992). However, thicket mostly does not exhibit high flammability traits (Calitz et al., 2015), and recruitment from seed largely occurs in inter-fire periods (Pierce and Cowling, 1984). In 2017, extreme fires occurred in this region around the town of Knysna which burnt indigenous fynbos and thicket vegetation and further caused extensive damage to commercial plantations and residential properties (Fares et al., 2017; Kraaij et al., 2018). The extreme nature of these fires has been attributed to extensive IAP fuels, an expansive wildland-urban interface area, an unprecedented regional drought preceding the fires, and very high fire danger weather conditions at the time of the fires (Kraaij et al., 2018; Preston, 2017). The 2017 Knysna fires called for improved understanding of potential differences in flammability among vegetation groups, including IAPs occurring in this region. An analysis of satellite image derived proxies for burn severity showed to be higher, but completeness of burn lower, in IAPs than in indigenous fynbos and thicket vegetation (Kraaij et al. 2018). However, the findings have not been verified with field observations (Kraaij et al., 2018). Other studies have experimentally compared the flammability of species from several biomes (both fire-prone and fire-resistant) (Burger and Bond, 2015; Calitz et al., 2015), however, no study has compared the flammability of indigenous vegetation with that of IAPs, nor under varying fire weather conditions.

In this study, the primary aim was to assess flammability of live plant material of IAPs, fynbos, and thicket in relation to fire weather conditions, fuel moisture, and fuel load. Flammability measures considered were: burn intensity, completeness of burn, and ignitability (time-to-ignition and likelihood of spontaneous ignition). I hypothesized that (H_1) fuel moisture would have negative effects on flammability; (H_2) fire weather conditions would have positive effects on flammability, and (H_3) fuel load would positively affect burn intensity. A secondary aim was to assess the flammability of partially dried plant material as a crude proxy for drought effects, to ascertain whether drying of fuels (~drought) would differentially affect the flammability of the vegetation groups of interest. Study results will inform fire risk management in the southern Cape landscapes and elsewhere with similar fuel traits and characteristics.

Materials and methods

Study area

This study was conducted along the southern Cape coast of South Africa within the Cape Floristic Region between Mossel Bay in the west and Plettenberg Bay in the east. The climate is moderated by the maritime influence with average minimum and maximum temperatures ranging from 7–19ºC in June and 15–26ºC in January an annual average rainfall of approximately 800 mm throughout the year (Bond, 1981). The area experiences weather conditions suitable for fires at any time of the year and fires are often associated with hot, dry katabatic (‘berg’) winds (Kraaij et al., 2013; van Wilgen, 1984).

The vegetation of the study area is classified as Southern Cape Dune Fynbos (Mucina and Rutherford, 2006; Pierce and Cowling, 1984) consists of medium-dense sclerophyllous fynbos (~fine-leaved) shrublands up to 2 m in height, interspersed with dense clumps of subtropical mesophyllous thicket shrubs or trees up to 4 m in height (Campbell et al., 1981; Kraaij et al., 2011; Pierce and Cowling, 1984). Both fynbos and thicket are evergreen. Fynbos shrublands are fire-prone and flammable while smaller areas of thicket vegetation seldom burn (Geldenhuys, 1994). The persistence of fynbos-thicket mosaics requires fire at appropriate intervals (15–25 years) since thicket becomes dominant in the prolonged absence of fire (Kraaij and van Wilgen, 2014; Strydom et al., submitted). The area contains extensive invasions of IAPs, commonly of the genera *Acacia, Eucalyptus,* and *Pinus* (Baard and Kraaij, 2014; van Wilgen et al., 2016).

Data collection

Live plant samples

I experimentally measured the flammability of species from three vegetation groups, namely IAPs, fynbos, and thicket. Plant shoots (hereafter samples) are generally the most flammable structures since leaves are the first fuel source to ignite during fire, subsequently spreading fire to other plant structures (Murray et al., 2013). Sampling was done over 21 occasions (February – November 2018) that were specifically selected to represent varying fire weather conditions. On each occasion, I collected two live plant samples of 30 species across three vegetation groups (10 species per vegetation group; details in Supplementary 1) common in the study area. One sample was used for flammability experiments, while the other for fuel moisture measurements. For each species, samples of approximately 70 cm in length that were representative of the fuel structure characteristic of the species were sourced. On each of the sampling occasion, samples from all 30 species were collected and burnt to ensure that flammability was measured under comparable conditions. Sample collection either started at 9h00 and subsequent burning at 12h00 or at 11h00 and 14h00 (respectively) to incorporate additional variation in fire weather conditions. For each occasion, the Canadian fire weather index was computed based on the temperature, relative humidity, rainfall (over the past 24 hours), and wind speed (Bedia et al., 2015; Dowdy et al., 2009) at the time that burning commenced. These weather measurements were obtained from a weather station located on the George Campus of Nelson Mandela University ('Saasveld NMMU CW373' on the Vital Weather online platform: www.vitalweather.co.za) where the experimental burning was conducted.

Samples used for flammability were burnt using an approach similar to that of Calitz et al. (2015) and Curran et al. (2017). Plant flammability was measured using the method and equipment described by Jaureguiberry et al. (2011), the apparatus comprises a metal barrel (85 cm x 60 cm) that is horizontally orientated with the top removable half that is used for wind protection (Baeza et al., 2002). The metal barrel is connected to a grill thermometer, removable gas cylinder and a blowtorch (Curran et al., 2017; Jaureguiberry et al., 2011). Each sample was placed on the barrel cavity grill to pre-heat at 230°C for two minutes to imitate the heating and drying effect of an approaching fire. If the samples had not spontaneously ignited within two minutes, it was ignited at the top of the shoot by exposing it to the blow torch for a period of five seconds (Calitz et al., 2015). Advantages of using this apparatus are that it preserves the architectural arrangement of plant material (Jaureguiberry et al., 2011). It further enables a more realistic comparison of relative canopy flammability among species than methods that use only smaller plant components (i.e. twigs or leaves) (Burger and Bond, 2015; Jaureguiberry et al., 2011).

Four aspects associated with species-level flammability were measured and recorded (largely after Calitz et al., 2015 and Jaureguiberry et al., 2011). Firstly, burn intensity taken as the maximum temperature (cf. Keeley, 2009) reached by a sample while burning, measured using an infrared thermometer (Major Tech 695; maximum recordable temperature: 800°C). Secondly, the completeness of burn, calculated as the proportion of the pre-burn wet mass of the samples that was consumed by the fire (mass was measured using an electronic scale). Thirdly, time-to-ignition, measured as the time elapsed between placement of the samples on the grill and spontaneous ignition (appearance of the first flame); samples that required to be ignited with the blow torch were therefore excluded from this measures' dataset. For every sample, I recorded whether it spontaneously ignited within the two minutes (pre-heating duration was consistent as there were many samples) of pre-heating or not, this binomial response comprising the fourth measure termed 'spontaneous ignition'.

Fuel moisture was calculated on a sample shoot similar in dimensions to that of flammability measurements. The fresh material was stored in sealed containers (of known mass) until these were weighed (within less than 3 hours of collection) to obtain wet fuel mass. Samples were then oven-dried at 80ºC for 48 hours and weighed again to obtain dry fuel mass (Ruffault et al., 2018; Teie, 2009). The fuel moisture was calculated as the percentage of wet mass comprised of water. Although sample size (shoot length) was standardized, samples nevertheless presented different fuel loads which is known to influence burn intensity (Keeley, 2009). Therefore, for each sample, dry plant mass (as a measure of fuel load) was estimated from pre-burn wet mass and thus provided the variable termed fuel load.

Dried plant samples

To investigate whether simulated drought conditions differentially affected the flammability of the vegetation groups, additional samples (similar to that collected for the flammability experiment’s live samples described above) were collected and left to dry under ambient conditions, out of direct sunlight, for a minimum of two weeks but not until leaf loss occurred. Sampling was conducted over five occasions (during February – March 2019) of high fire weather conditions. The drying duration was standardized for all species to avoid the loss of leaves since certain plants would drop leaves due to drought stress (Clarke and McCaig, 1982). Flammability experiments and pre-burn estimations of fuel moisture were undertaken on these dried samples as described above for live (undried) samples.

Data analysis

Live plant samples

I assessed flammability (of live samples) in terms of four response variables (burn intensity, completeness of burn, time-to-ignition, and spontaneous ignition) respectively, in relation to the predictor variables (i) fire weather (continuous), (ii) fuel moisture (continuous), (iii) fuel load (dry plant mass; continuous), (iv) vegetation groups (IAPs, fynbos, thicket; categorical) and (v) species (30 species; categorical) using generalized linear mixed-effects models (Bates, 2010; O'Hara, 2009). Detailed species-level comparisons were not the primary focus of the study and species was therefore included as a random factor, whereas the other predictor variables were included as fixed factors. To test for potential collinearity between fire weather and fuel moisture, I ran the Spearman-rank correlation test for each respective species which showed that these variables were not significantly correlated (see Results) and could both be retained in subsequent analyses. I ran generalized linear mixed-effects models using the *lme4* package (Bates, 2010) in the open-source R software version 3.6.1 (R Development Core Team 2019) with burn intensity log-transformed (to correct right-skewed distribution), completeness of burn arcsine-transformed (as it was expressed as proportions), time-to-ignition square root-transformed (to correct left-skewed distribution), and assessed spontaneous ignition using logistic regression (binomial family, `logit link` function). Subsequently, Type II Wald chi-square test (Hastie and Pregibon, 1992) was computed to determine the significance of fixed factors on the specific models. I incorporated the `scale` function to the generalized linear mixed-effects models and logistic regression model (using transformed data) to standardize variables of different scales and obtain the relative influence of fixed factors (Becker et al., 1988).

Dried plant samples

I compared the flammability (in terms of burn intensity, completeness of burn, and time-to-ignition, respectively) of the dried samples with that of live samples of the same species that was measured on five occasions under comparable fire weather conditions. I calculated the change in flammability between live and dried samples by subtracting the flammability measure of each live sample from that of its dried counterpart. I then used this derived variable as response variable and employed Kruskal Wallis to test whether the difference in flammability between live and dried samples varied among vegetation groups.

Results

Live plant samples

Fire weather and fuel moisture were not significantly correlated within any of the study species (Supplementary 1). Increasing severity of fire weather significantly increased flammability through increasing burn intensity, increasing completeness of burn, increasing the likelihood of spontaneous ignition, and reducing time-to-ignition (Table 1, Fig. 1). Increasing fuel moisture significantly decreased burn intensity, completeness of burn, and the likelihood of spontaneous ignition. Fuel load significantly increased burn intensity and time-to-ignition.

In considering vegetation groups, flammability was generally highest in IAPs, intermediate in fynbos, and lowest in thicket (Table 1, Fig. 1). IAPs burnt at significantly higher intensity than fynbos and thicket. IAPs and fynbos showed significantly higher ignitability (shorter time-to-ignition and a greater likelihood of spontaneous ignition) than thicket.

Amongst the different fixed factors, vegetation groups consistently had the largest influence (i.e. the largest scaled estimates; Table 1) on all flammability measures. Fire weather had the second largest influence on ignitability, while fuel moisture had the second largest influence on burn intensity and completeness of burn.

The total variance in the flammability measures explained by the models was generally low (24 - 40%; conditional R^2 values, Table 1). The fixed factors combined explained less variation (8 - 22%; marginal R^2 values, Table 1) than species as random factor by itself (12 - 20%), except in terms of spontaneous ignition where vegetation groups and fire weather were most influential.

TABLE 1: Output of generalized linear mixed-effects models (gaussian family, `identity` function; details in Supplementary 2) that assessed flammability in terms of the response variables; burn intensity, completeness of burn, and time-to-ignition, and the output of a logistic regression model (binomial family, `logit link` function) that assessed flammability in terms of spontaneous ignition. Fixed factors included in these models were fire weather, fuel moisture, fuel load, and vegetation groups (IAPs, invasive alien plants; Fyn, fynbos; and Thi, thicket), while species was included as a random factor.

Factors	Burn intensity			Completeness of burn			Time-to-ignition			Spontaneous ignition		
	Estimate	Chisq [a]	Scaled estimate [b]	Estimate	Chisq [a]	Scaled estimate [b]	Estimate	Chisq [a]	Scaled estimate [b]	Estimate	Chisq [a]	Scaled estimate [b]
Fire weather	0.0007	4.1 *	0.06731	0.1300	11.0 ***	0.1175	-0.0339	21.0 ***	0.19471	0.0650	23.8 ***	0.6671
Fuel moisture	-0.0015	4.4 *	0.11524	-0.1616	4.6 *	0.1225	0.0271	2.8	0.09747	-0.0379	4.5 *	0.3265
Fuel load	0.0004	5.6 *	0.10090	-0.0180	1.1	0.0477	0.0121	9.3 *	0.16529	-0.0063	2.6	0.1900
Veg group [IAP and Fyn]	-0.0427	8.1 *	0.39141	-1.1895	5.7	0.1048	-0.7575	9.6 **	0.36388	0.2156	16.3 ***	0.2156
Veg group [IAP and Thi]	-0.0648		0.59446	-5.2832		0.4657	0.8838		0.42458	-1.5563		1.5564
Conditional R^{2} [c]		0.2961			0.2442			0.3983			0.3459	
Marginal R^{2} [c]		0.0942			0.0798			0.1935			0.2258	
R^{2} (1|Species) [c]		0.2019			0.1644			0.2048			0.1201	

Significance codes: *p <0.05, **p <0.01, ***p <0.001

[a] Chisq statistics and significance levels were obtained from deviance tables (Type II Wald chi-square tests).

[b] Scaled estimates were derived from incorporating the `scale` function in the generalized linear mixed-effects models and logistic regression model.

[c] R^{2} values were derived using the `r.squaredGLMM` function, where conditional R^{2} indicates the proportion of variance explained by fixed and random factors combined, marginal R^{2} indicates the proportion of variance explained by fixed factors alone and R^{2} (1|Species) indicates variance explained by the random factor alone.

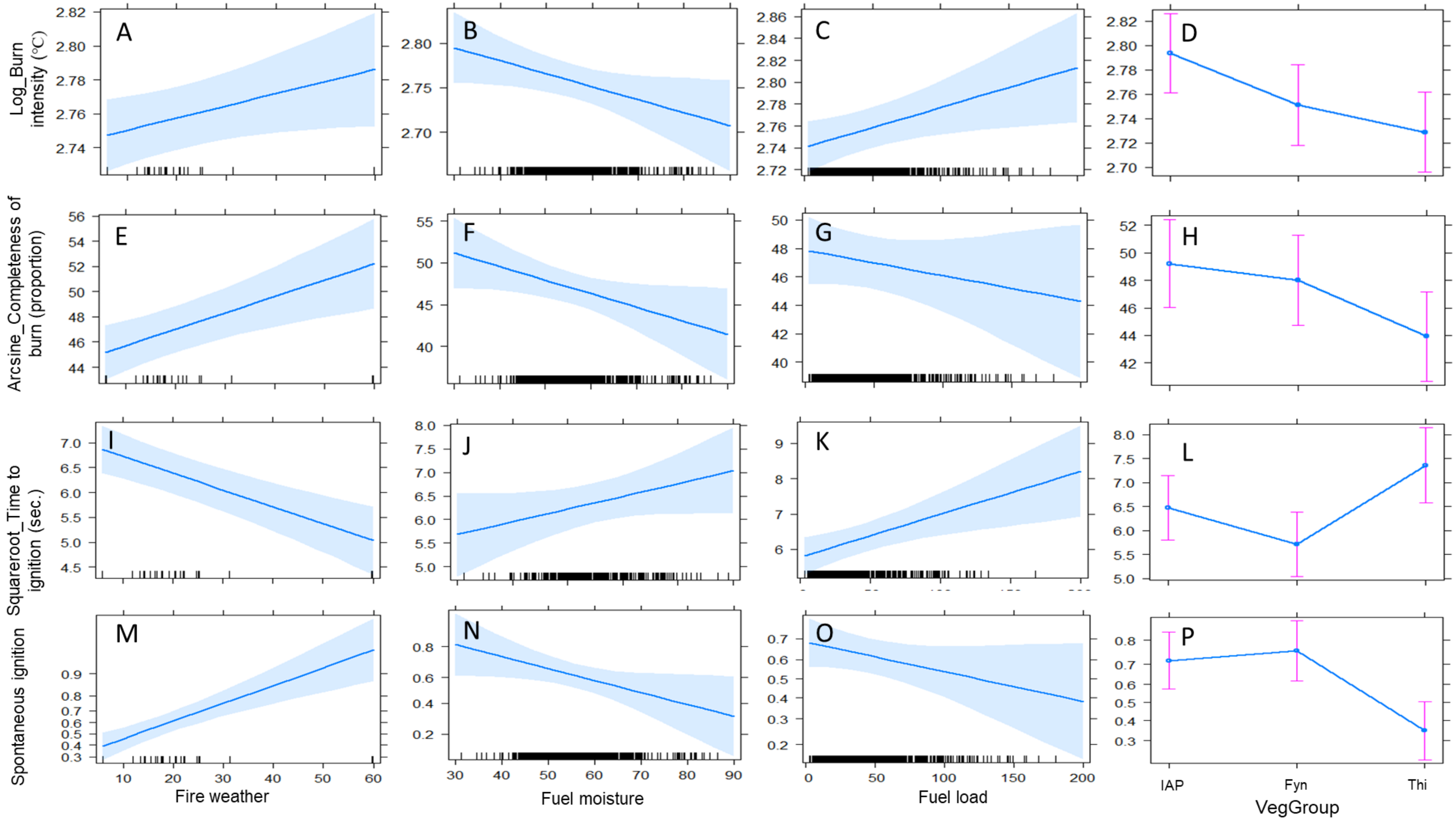

FIGURE 1: Predicted effects of fixed factors, i.e. fire weather, fuel moisture, fuel load, and vegetation group (IAPs, invasive alien plants; Fyn, fynbos; and Thi, thicket) on the flammability measures, (**A – D**) burn intensity, (**E – H**) completeness of burn, (**I – L**) time-to-ignition, and the probability of (**M – P**) spontaneous ignition. The effects shown here were based on the model outputs shown in Table 1 (shaded bands depict standard errors and whiskers show 95% confidence intervals).

Dried plant samples

Drying out of samples under ambient conditions for two weeks resulted in an average reduction in fuel moisture contents of approximately 30% (Fig. 2 A), and the extent of this reduction did not differ significantly among vegetation groups (H_2=1.4, p=0.505). Dried samples exhibited increased flammability compared to their live counterparts, i.e. an average increase in burn intensity of 115°C; an 11% increase in completeness of burn; and a 46 seconds reduction in time-to-ignition (Fig. 2 B - D). However, this differential response in flammability between dried and live samples was comparable among the vegetation groups in terms of burn intensity (H_2=0.8, p=0.666), completeness of burn (H_2=1.8, p=0.410), and time-to-ignition (H_2=0.6, p=0.741).

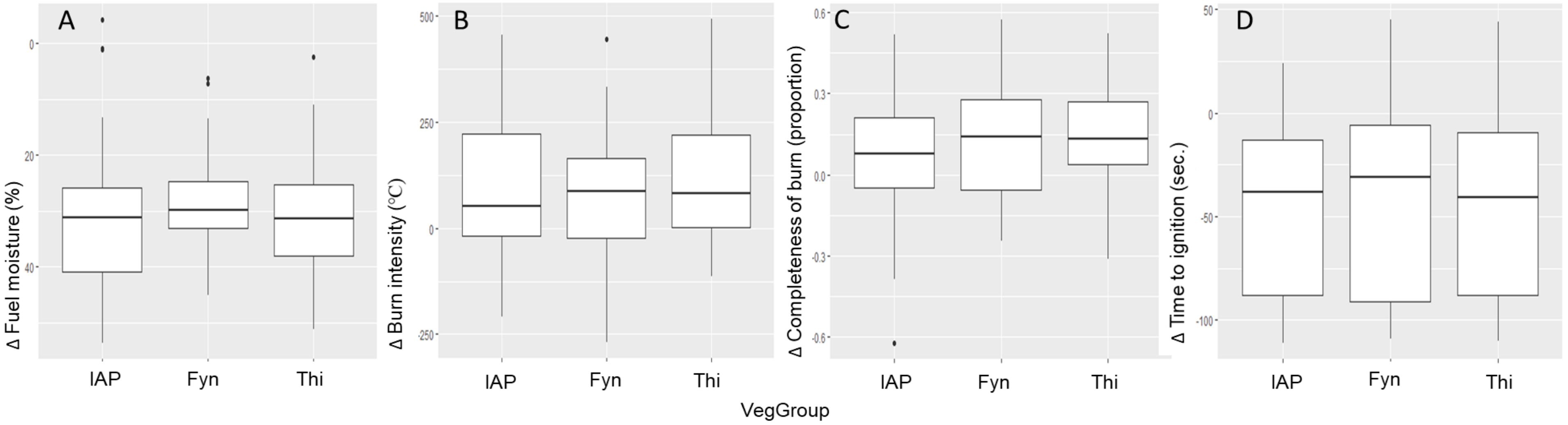

FIGURE 2: The change (Δ) between live and dried samples (of the same species under comparable fire weather conditions) in (**A**) fuel moisture, and flammability in terms of (**B**) burn intensity, (**C**) completeness of burn, and (**D**) time-to-ignition, compared among vegetation groups (IAPs, invasive alien plants; Fyn, fynbos; and Thi, thicket). Medians (lines), 25 – 75 quantile ranges (boxes), 1.5 * interquartile ranges (whiskers), and outliers (dots) are shown.

Discussion

Effects of fuel moisture, fire weather, and fuel load on live fuels

Fuel moisture content is widely regarded to be a major determinant of flammability in grassland, shrubland and forested ecosystems with sufficient evidence of its dampening effects on fire behaviour and flammability (Bianchi and Defossé, 2015; Fares et al., 2017; Pausas and Paula, 2012). Live fuel moisture has furthermore been shown to respond closely to fire weather, particularly in grassland ecosystems (Bianchi and Defossé, 2015; Bowman et al., 2014; Chuvieco et al., 2004). That is why several fire danger indices attempt to account for fuel moisture to improve fire danger forecasting (Madula, 2013; Rothermel, 1983; Ruffault et al., 2018; Sirca et al., 2018). This concept assumes that the mechanism behind the enhancing effects of fire weather on flammability is through short-term (i.e. daily) variation in fuel moisture in response to weather conditions. However, contrary to expectation, fuel moisture in this study was not significantly correlated with fire weather in any of the study species. Fuel moisture did significantly correlate to burn intensity and completeness of burn as hypothesized (H_1), but the magnitude of its influence on flammability relative to the other factors investigated was generally low.

Fire weather significantly enhanced all measures of flammability as hypothesized (H_2), however the lack of response of live plant moisture contents to fire weather suggests that the mechanism through which fire weather enhances flammability may not be fuel moisture. Instead, the mechanism may involve the effect of fire weather on fuel temperature in relation to ignition temperature (Bedia et al., 2015; Pausas and Paula, 2012; Piñol et al., 1998). Other studies that have investigated fuel moisture–flammability relations (e.g., Bianchi et al., 2018) have not evidently assessed the effects of fire weather or have manipulated fuel moisture through drying out of fuels beyond natural levels of fluctuation in live fuels (Dimitrakopoulos and Papaioannou, 2001). I argue that the importance of live fuel moisture for flammability of evergreen shrublands rests on inter-specific and inter-vegetation type differences in fuel moisture contents (cf. Chuvieco et al., 2004), rather than short-term intra-specific fluctuation in live fuel moisture in response to weather conditions. The incorporation of satellite-derived proxies for live fuel moisture into fire danger indices is therefore unlikely to be useful in these systems. Although fire weather increased all measures of flammability (and particularly ignitability), it was less influential than vegetation groups. The contribution of short-term weather conditions to the severity of the 2017 Knysna fires was regarded to have been secondary to that of the long-term drought preceding these fires that would have caused a buildup of dead fuels (Kraaij et al., 2018). Fire weather is expected to increase in importance in its effects on flammability if cognizance is taken of dry or dead fuels (see below) and when considering stand level fire behaviour. Although plant shoot flammability experiments were an improvement on laboratory assessments of the flammability of excised leaves, the scale of experimentation relative to stand or landscape level fire was still inadequate. For instance, particular aspects of fire weather, such as wind speed, greatly influence wildfire spread and spotting behavior (Forsyth et al., 2019). Such dynamics could not be considered in the current study thereby likely leading to an underestimation of the importance of fire weather on flammability and, by implication, fire behavior.

Fuel load had varying effects on flammability, depending on the measure considered; it increased burn intensity as hypothesized (H_3), but reduced ignitability. These findings support other evidence for positive correlations between the amount of biomass (~fuel load) that vegetation presents and fire intensity or severity (Baeza et al., 2002; Keeley, 2009; Saura-Mas et al., 2010), but negative correlations between fuel load and completeness of burn (Kraaij et al., 2018; van Wilgen et al., 1990). Such contrasting effects on the different aspects of flammability emphasize the need to consider flammability in terms of its constituent measures rather than treating it as a composite measure (Engber and Varner, 2012; Pausas et al., 2012; Santana and Marrs, 2014).

Although fuel moisture content, fire weather conditions, and fuel load had significant effects on some of the flammability measures, these factors did not explain a large portion of variability in the flammability response. Species, which was assessed as a random factor, often accounted for more variation in flammability than the fixed factors combined. This suggests important species effects on flammability, which warrant more detailed investigation (see Chapter 4).

Vegetation group effects in relation to fire risk

Vegetation group comparisons showed that the flammability of IAPs exceeded that of thicket in terms of all flammability measures and exceeded that of fynbos in terms of burn intensity. These findings support claims (Forsyth et al., 2019; Stander, 2019) and other evidence (Brooks et al., 2004; Kraaij et al., 2018; Richardson and Rejmánek, 2011) that invasions by alien plants can add to the severity, intensity, and difficulty of control of wildfires. Fynbos and IAPs were more ignitable than thicket, and thus present higher risks under moderate and high fire weather conditions, whereas thicket presents lower risks under low and moderate fire weather conditions. Accordingly observations from the 2017 Knysna fires indicated that thicket only becomes ignitable under very high or extreme fire weather conditions but may then burn at intensities exceeding that in fynbos but not that of IAPs (Kraaij et al., 2018) presumably on account of disparate fuel loads (Keeley, 2009; Mandle et al., 2011). There were no significant differences between the flammability of fynbos and IAPs but completeness of burn appeared to be the highest in fynbos which suggests that the risk of recurring fire in fynbos will be almost zero for some period post-fire, whereas incomplete burning of IAPs and thicket will not afford the same level of risk reduction shortly post-fire.

Simulated drought conditions

Extremely large and severe fires, including the 2017 Knysna fires, are often associated with preceding droughts (Kraaij et al., 2018; Quinn, 1994; San-Miguel-Ayanz et al., 2013; Williams, 2013) and the resultant increase in dead fuels (Keeley, 2009). The extent and severity to which thicket, normally regarded as a fire-resistant (~poorly ignitable) vegetation (Calitz et al., 2015; Cowling and Potts, 2015), burnt in the 2017 Knysna fires, was attributed to extreme fire weather conditions and to the preceding severe drought (Kraaij et al., 2018). In this study, I confirmed that the drying of fuels as a crude proxy for severe drought effects considerably increased flammability. However, the magnitude of the increase in flammability in response to drying of fuels was consistent across vegetation groups. Flammability, and by implication fire risk, is thus unlikely to increase disproportionately in one vegetation group compared to another under extended drought unless the production of dead fuels due to drought would be disproportionate among the vegetation groups. I concede that the proxy for drought conditions could not realistically simulate all potential effects of drought on fuel modification and flammability, and in particular on the dying off of fuels and resultant increase in litter component. Detailed consideration of this aspect was beyond the scope of this study and warrants further investigation. Given that dead fuels respond more rapidly to weather conditions than live fuels, the ratio of dead:live fuels are likely to be a useful indicator of fire risk in evergreen shrublands (Keeley, 2009). Proxies for this ratio should, therefore, be sought for incorporation into fire danger indices.

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SUPPLEMENTARY 1

Spearman's rank correlation (rho) tests between predictor variables; fire weather and fuel moisture results on each respective species. Nomenclature follows The Plant List (2013).

No.	Species names	Slope	rho	p
Fynbos				
1	*Passerina rigida* Wikstr.	negative	0.003	0.993
2	*Erica discolor* Andrews	negative	0.174	0.460
3	*Erica canaliculata* Andrews	positive	0.181	0.432
4	*Cliffortia ericifolia* E.Mey. ex Harv	positive	0.114	0.621
5	*Cliffortia ilicifolia* L.	negative	0.051	0.828
6	*Agathosma ovata* (Thunb.) Pillans	negative	0.210	0.358
7	*Metalasia muricata* (L.) D.Don	positive	0.419	0.060
8	*Phylica axillaris* Lam.	positive	0.353	0.117
9	*Aspalathus spinosa* L.	negative	0.370	0.099
10	*Leucadendron eucalyptifolium* H. Buek ex Meisn.	positive	0.070	0.763
Thicket				
11	*Pterocelastrus tricuspidatus* Walp.	negative	0.097	0.674
12	*Searsia lucida* (L.) F.A.Barkley	negative	0.134	0.562
13	*Tarchonanthus littoralis* P.P.J.Herman	negative	0.078	0.737
14	*Diospyros dichrophylla (*Gand.) De Winter	negative	0.084	0.716
15	*Osteospermum moniliferum* L.	positive	0.103	0.657
16	*Sideroxylon inerme* L.	positive	0.334	0.139
17	*Cassine peragua* L.	positive	0.086	0.711
18	*Gymnosporia buxifolia* (L.) Szyszył.	positive	0.349	0.121
19	*Scolopia zeyheri* (Nees) Szyszył.	positive	0.326	0.149
20	*Osyris compressa* A.DC.	positive	0.256	0.262
Alien invasive plats				
21	*Pinus pinaster* Aiton	negative	0.308	0.174
22	*Pinus radiata* D.Don	negative	0.255	0.264
23	*Cestrum laevigatum* Schltdl.	positive	0.138	0.550
24	*Acacia cyclops* G.Don	negative	0.179	0.435
25	*Acacia melanoxylon* R.Br.	positive	0.009	0.972
26	*Acacia saligna* (Labill.) Wendl	positive	0.003	0.993
27	*Acacia mearnsii* De Wild.	positive	0.229	0.318
28	*Eucalyptus camaldulensis* Dehnh.	negative	0.001	0.998
29	*Callistemon viminalis* (Sol. ex Gaertn.) G.Don	negative	0.217	0.343
30	*Leptospermum laevigatum* (Gaertn.) F.Muell.	positive	0.310	0.171

SUPPLEMENTARY 2

Formulae used in R software version 3.6.1 (R Development Core Team 2019) that assessed flammability in terms of the response variables (burn intensity, completeness of burn and time-to-ignition) respectively, in relation to the predictor variables (i) fire weather (ii) fuel moisture, (iii) fuel load, (iv) vegetation groups (IAPs, invasive alien plants; Fyn, fynbos; and Thi, thicket).and (v) species as random factor. Burn intensity, completeness of burn and time-to-ignition were run using generalized linear mixed-effects models (gaussian family and `identity` function) and spontaneous ignition (binomial family and `logit link` function) using *lme4* package.

```
Response variables            Linear mixed model ['lmerMod']
```

`Log_BurnIntensity`

```
> GLMM.1 <- glmer (Log_BurnIntensity ~
FireWeather + FuelMoisture + FuelLoad + VegGroup
+ (1|Species), family = gaussian (identity),
data = Dataset)
> summary (GLM.1)
```

`Arcsine_Completenessofburn`

```
> GLMM.2 <- glmer (Arcsine_Completeness.of.burn
~ FireWeather + FuelMoisture + FuelLoad +
VegGroup + (1|Species), family = gaussian
(identity), data = Dataset)
> summary (GLM.2)
```

`Squareroot_TimeToIgnition`

```
> GLMM.3 <- glmer (Sqrt_TimeToIgnition ~
FireWeather + FuelMoisture + FuelLoad +
VegGroup + (1|Species), family = gaussian
(identity), data = Dataset)
> summary (GLM.3)
```

`SpontaneousIgnition`

```
> GLMM.4 <- glmer (SpontaneousIgnition ~
FireWeather + FuelMoisture + FuelLoad +
VegGroup + (1|Species), family = binomial
(logit), data = Dataset)
> summary (GLM.4)
```

Analysis of Deviance Table (Type II Wald chi-square tests) of the generalized linear mixed-effects models and logistic regression fitted above.

```
Log_BurnIntensity                              Chisq Df Pr(>Chisq)
                                  FireWeather  4.1168  1    0.04246 *
                                  FuelMoisture 4.3764  1    0.03644 *
                                  FuelLoad     5.6331  1    0.01762 *
                                  VegGroup     8.0701  2    0.01768 *
```

```
Arcsine_Completenessofburn                    Chisq Df Pr(>Chisq)
                              FireWeather  11.0550  1  0.0008845 ***
                              FuelMoisture  4.6153  1  0.0316873 *
                              FuelLoad      1.1265  1  0.2885249
                              VegGroup      5.7229  2  0.0571855

Squareroot_TimeToIgnition                     Chisq Df Pr(>Chisq)
                              FireWeather  20.9586  1  4.693e-06 ***
                              FuelMoisture  2.7578  1   0.096779
                              FuelLoad      9.2720  1   0.002327 **
                              VegGroup      9.5618  2   0.008388 **

SpontaneousIgnition                           Chisq Df Pr(>Chisq)
                              FireWeather  23.8176  1  1.059e-06 ***
                              FuelMoisture  4.4745  1  0.0344038 *
                              FuelLoad      2.6076  1  0.1063494
                              VegGroup     16.3775  2  0.0002778 ***
```

Significance codes: *p<0.05, **p <0.01, ***p <0.001

CHAPTER 3: Flammability and fuel traits of indigenous and invasive alien woody plants in coastal fynbos and thicket

Abstract

The southern Cape coast has both fire-prone fynbos and fire-resistant thicket vegetation interspersed with invasive alien plants (IAPs). Recently, destructive wildfires occurred in this region. I aimed at informing fire risk management in these landscapes by experimentally assessing the flammability of vegetation groups (10 woody plant species each of IAPs, indigenous fynbos, and thicket) in relation to their fuel traits. Flammability measures considered were burn intensity, completeness of burn, and time-to-ignition, assessed respectively in relation to fuel traits. I used multiple regression models and stepwise selection of factors to identify fuel traits affecting flammability. Fuel load significantly enhanced, and fuel moisture significantly reduced, burn intensity, whereas the proportion of fine fuels significantly increased completeness of burn. The proportion of dead fuels and fuel bed porosity were not retained by any of the models to account for variation in flammability. Fynbos and IAPs generally exhibited greater flammability in the form of higher completeness of burn and more rapid ignition than thicket. Little distinction in flammability and fuel traits could be made between fynbos and IAPs, except that fynbos had a greater proportion of fine fuels. Thicket had higher fuel loads than fynbos and IAPs. The trend of higher burn intensity in IAPs than in indigenous vegetation suggested potential increases in fire intensity or severity if indigenous vegetation was to be invaded by IAPs. Fuel moisture did not differ among vegetation groups, despite differences in flammability often having been ascribed to effects of fuel moisture in the literature. The fuel traits investigated only explained 21-53% of the variation in flammability and large variation was evident within vegetation groups suggesting that species-specific investigations are warranted.

Keywords: Cape Floristic Region, fire risk, ignitability, fine fuels, fuel load, fuel moisture

Introduction

Flammability is the ability of vegetation (fuel) to burn (Fernandes and Cruz, 2012; Gill and Zylstra, 2005; Jaureguiberry et al., 2011). At the vegetation community scale, flammability can be assessed in terms of fire behaviour characteristics, for example, the rate of fire spread (Anderson, 1970). However, at the level of the individual plant, flammability may be measured in terms of burn intensity, completeness of burn and time-to-ignition (~ignitability). These measures of flammability are mainly affected by fuel properties such as moisture contents and volatile substances, fuel load, fuel size and dead:live ratio (Bianchi and Defossé, 2015; Santana et al., 2011; Saura-Mas et al., 2010). Flammability is commonly assessed by burning fuels experimentally, either in the form of leaf litter, or plant shoots (Chapter 1).

Most flammability studies assessed flammability as a fire-adaptive trait (Cowan and Ackerly, 2010; Saura-Mas et al., 2010; Scarff and Westoby, 2006; Schwilk, 2003), but studies focused on small plant components fail to represent whole plant flammability (Fernandes and Cruz, 2012). In this study, larger plant components were used, which enabled a more realistic assessment of canopy flammability. Flammability studies have largely concentrated on burn intensity (~fire intensity) and ease of ignition as measures of flammability, and on fuel traits such as fuel load and fuel moisture (Grootemaat et al., 2017; Guijarro et al., 2002), whereas other traits like fuel bed porosity and the extent of fine and dead fuels have been neglected. Although fine and dead fuels have been neglected, both consistently appear to enhance flammability by increasing completeness of burn and rate of spread (Burger and Bond, 2015; Calitz et al., 2015; Davies and Legg, 2011; Engber and Varner, 2012; Santana and Marrs, 2014; Schwilk, 2003, Chapter 1). Great fuel loads have been reported to increase fire intensity (Baeza et al., 2002; Keeley, 2009; Saura-Mas et al., 2010; Simpson et al., 2016). Furthermore, an increase in fuel moisture generally delays plant ignition as more energy is required to heat fuels to combustion, translating into slower rates of spread (Alessio et al., 2008; Davies and Legg, 2011; Dimitrakopoulos and Papaioannou, 2001; Kane and Nuria, 2019; Saura-Mas et al., 2010). Understanding of the relations between some fuel traits and plant flammability is limited and thus require further assessments.

Fire plays an important role in structuring plant communities worldwide (Bond and Keeley, 2005), particularly along the southern Cape coast of South Africa (Bond, 1997; Bond et al., 2003; Moll et al., 1984). Fire is a natural process and vegetation persistence and regeneration occur after recurrent fires (Kraaij and van Wilgen, 2014; Pausas et al., 2004). However, extreme fires occurring around the world have resulted in severe damages to the wildland-urban interface areas (Kraaij et al., 2018; Montenegro et al., 2004; Quinn, 1994; San-Miguel-Ayanz et al., 2013; Syphard et al., 2017; Williams, 2013). Such extreme fires are attributed to various factors, including increased sources of ignition linked to the expansion of wildland-urban interface areas; high fire weather conditions (sometimes attributed to global climate change), and a buildup of fuel often resulting from extended periods of fire suppression (Fernandes et al., 2016; García-Llamas et al., 2019; Radeloff et al., 2005; San-Miguel-Ayanz et al., 2013; Scott et al., 1998; Silva et al., 2011; Storey et al., 2016; Syphard et al., 2017). The combination of the above factors were also reported in relation to very destructive fires occurring along the southern Cape coast of South Africa during 2017 (Kraaij et al., 2018). These fires were preceded by an; unprecedented regional drought, while very high fire danger weather conditions prevailed at the time of the fires (Kraaij et al., 2018; Preston, 2017). Large parts of the southern Cape are extensively invaded by IAPs (Baard and Kraaij, 2014; Richardson and van Wilgen, 2004) which are associated with excessive accumulation of fuels and deemed to greatly increase flammability and alter natural fire regimes (Baard and Kraaij, 2014; Brooks et al., 2004; Holmes et al., 1987; Kraaij et al., 2018; Milton and Dean, 2010).

In this study, the primary aim was to assess the flammability in relation to respective fuel traits. Here I assessed flammability in terms of burn intensity, completeness of burn, and time-to-ignition, whilst the fuel traits considered were: fine fuels, coarse fuels, dead fuels, fuel bed porosity, fuel load, and fuel moisture. I hypothesized that (H_1) burn intensity would be enhanced by high fuel load, and low fuel moisture content; (H_2) completeness of burn would increase with increased fine fuels and reduced fuel moisture; and (H_3) time-to-ignition will decrease with increased fine fuels, increased dead fuels and reduced fuel moisture. A secondary aim was to compare the vegetation groups (IAPs, indigenous fynbos, and thicket) in terms of their flammability and fuel traits. Results were aimed at informing fire risk management in the southern Cape landscapes and elsewhere with similar fuel characteristics.

Materials and methods

Study area

This study was conducted along the southern Cape coast of South Africa within the Cape Floristic Region between Mossel Bay in the west and Plettenberg Bay in the east. The climate is moderated by the maritime influence with average minimum and maximum temperatures ranging from 7–19ºC in June and 15–26ºC in January an annual average rainfall of approximately 800 mm throughout the year (Bond, 1981). The area experiences weather conditions suitable for fires at any time of the year and fires are often associated with hot, dry katabatic (‘berg’) winds (Kraaij et al., 2013; van Wilgen, 1984).

The vegetation of the study area is classified as Southern Cape Dune Fynbos (Mucina and Rutherford, 2006; Pierce and Cowling, 1984) which consists of medium-dense sclerophyllous fynbos (~fine-leaved) shrublands up to 2 m in height, interspersed with dense clumps of subtropical mesophyllous thicket shrubs or trees up to 4 m in height (Campbell et al., 1981; Kraaij et al., 2011; Pierce and Cowling, 1984). Both fynbos and thicket are evergreen. Fynbos shrublands are fire-prone and flammable while smaller areas of thicket vegetation seldom burn (Geldenhuys, 1994). The persistence of fynbos-thicket mosaics requires fire at appropriate intervals (15–25 years) since thicket becomes dominant in the prolonged absence of fire (Kraaij and van Wilgen, 2014; Strydom et al., submitted). The area contains extensive invasions of IAPs, commonly of the genera *Acacia, Eucalyptus,* and *Pinus* (Baard and Kraaij, 2014; van Wilgen et al., 2016).

Data collection

Flammability was assessed in relation to the fuel traits of 30 woody plant species, ten from each of the three vegetation groups: IAPs, fynbos, and thicket. Flammability of plant shoots (hereafter samples) of the different species was experimentally measured using the method and equipment described by Jaureguiberry et al. (2011). Samples comprised sun-exposed branch tips that were approximately 70 cm in length. The flammability experiments were conducted on 21 different occasions across a range of weather conditions as detailed in Chapter 2. Flammability measures recorded were (i) burn intensity taken as the maximum temperature (cf. Keeley, 2009) reached by a sample during burning; (ii) completeness of burn, calculated as the proportion of the pre-burn wet mass of the samples that was consumed by the fire; and (iii) time-to-ignition, measured as the time elapsed between placement of the samples on the grill and spontaneous ignition (appearance of the first flame); samples that did not spontaneously ignite within 120 seconds of pre-heating were ignited with a blow torch and assigned an arbitrary time-to-ignition of 200 seconds. The wet mass of samples was recorded prior to conducting the flammability experiments. On each of the 21 occasions that the flammability experiments were performed, a duplicate set of plant samples were collected and oven-dried at 80ºC for 48 hours and weighed again to obtain dry fuel mass (Ruffault et al., 2018; Teie, 2009). The fuel moisture content was calculated as the percentage of wet mass comprised water. The dry mass of samples was regarded to be a proxy for the fuel load that samples presented. Seeing that those samples subjected to flammability experiments could not be dried beforehand, I estimated the dry mass of burnt samples from their wet mass prior to being burnt and the fuel moisture content measured for the duplicate set of plant samples [where dry mass = pre-burn wet mass – (pre-burn wet mass x proportion of fuel moisture)]. For the flammability response variables, and for the fuel traits, moisture, and fuel load, I thus had 21 replicate values per species.

Other fuel traits of interest were the proportion of fine fuels, coarse fuels, dead fuels, and fuel bed porosity. To measure these fuel structural traits, a once-off collection of six samples per species was conducted, similar to those collected for the flammability experiments and following the approach by Burger and Bond (2015). The six samples provided three replicate values per fuel trait per species. Three samples were used to measure the mass of live material in different fuel size classes. Each sample was separated based on stem diameter into the following size classes; < 3 mm (hereafter fine fuels), and > 6 mm (hereafter coarse fuels). This study did not consider 3–6 mm fuel size class as in Burger and Bond (2015), since it included both classes. Leaves were included in the stem diameter class to which they were attached and the plant mass in each size class was weighed. The same samples from each species were separated into live and dead fuel material (twigs, branches, and leaves) and subsequently weighed. The remaining three samples of each species were used to determine fuel bed porosity, calculated as the canopy volume (based on the formula for the volume of a cone) divided by the fuel volume. The latter was the volume occupied by the samples and measured through means of volume displacement in a 5 Litre measuring bucket.

Data analysis

The response variables (burn intensity, completeness of burn and time-to-ignition) and fixed factors, namely fuel moisture and fuel load, were derived from the flammability experiments using averages of the 21 replicates of each of the 30 sample species. The response variables did not violate assumptions of normality (burn intensity W = 0.97, p = 0.66; completeness of burn W = 0.96, p = 0.38; and time-to-ignition W = 0.96, p = 0.27) in accordance with Shapiro-Wilk test. For the fuel structural trait variables, namely the proportion of fine fuels, coarse fuels, and dead fuels, and fuel bed porosity (ratio), I used averages of the three replicates measured per species. A combined dataset was created for further analyses containing, for all of the variables, the averages per species, with the 30 species thus comprising replicates.

Multiple regression models were used to assess the relationships between flammability responses (respectively) and the following fuel traits as fixed (explanatory) factors: (i) proportion of fine fuels, (ii) proportion of coarse fuels, (iii) proportion of dead fuels, (iv) fuel load, (v) fuel bed porosity (ratio), and (vi) fuel moisture (percentage). Stepwise model selection based on the lowest Akaike information criterion (AIC) (Sakamoto et al., 1986) was used to choose the best combination of fixed factors that could potentially predict flammability. The `scale` function (Becker et al., 1988; Hastie and Pregibon, 1992) was incorporated to the multiple regression models in order to standardize variables of different scales and obtain the relative influence of each fixed factor. To test if the flammability measures and fuel traits differed among vegetation groups (IAPs, fynbos, and thicket), I employed Kruskal Wallis (as most of the fuel trait variables did not conform to normality) and thereafter Dunn’s test for multiple comparisons if significant differences occurred (Dunn, 1964). All statistical analyses were performed in the open-source R software version 3.6.1 (R Development Core Team 2019).

Results

Effects of fuel traits

The stepwise selection procedure retained different combinations of fixed factors for the respective flammability responses, but the proportion of dead fuels and fuel bed porosity were not retained by any of the preferred models (Table 1; detailed outputs in Supplementary 1). Fuel moisture was retained in the preferred models for all of the respective flammability measures, and lower fuel moisture significantly increased burn intensity (Table 1, Fig. 1). No significant relations were found between fuel moisture and completeness of burn; fuel moisture and time to ignition; and fine fuels and time-to-ignition. Greater fuel loads increased flammability by significantly increasing burn intensity. Amongst the assessed fixed factors, fuel load had the largest influence (i.e. the largest scaled estimates; Table 1) on burn intensity. Fine fuels had the largest influence on completeness of burn.

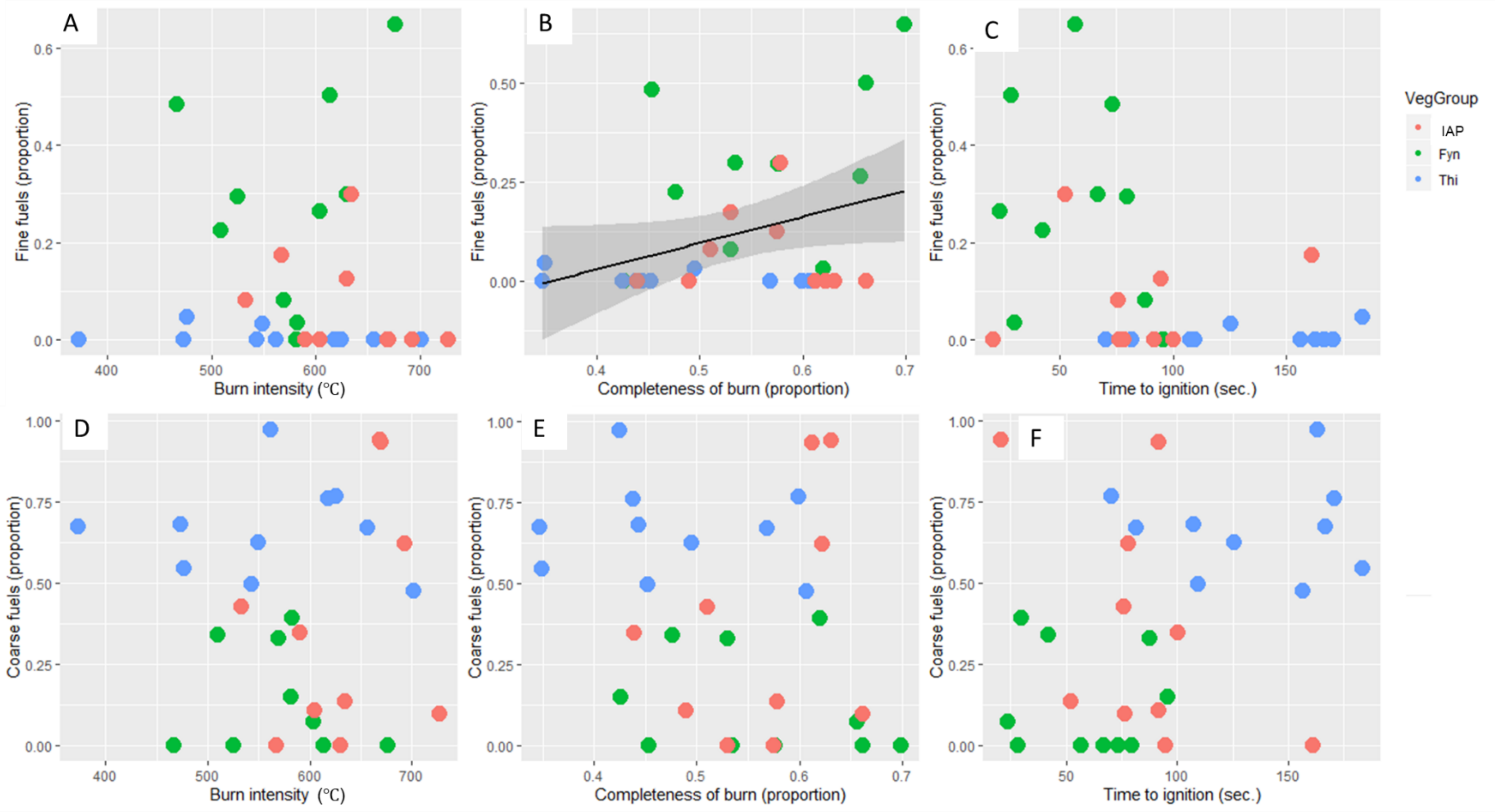
TABLE 1: Output of multiple regression models that assessed flammability (in terms of burn intensity, completeness of burn, and time-to-ignition, respectively) in relation to fuel traits as fixed factors, i.e. proportion of fine fuels, coarse fuels, and fuel load, and fuel moisture (percentage). Results shown are for the preferred models after stepwise selection (details in Supplementary 1).

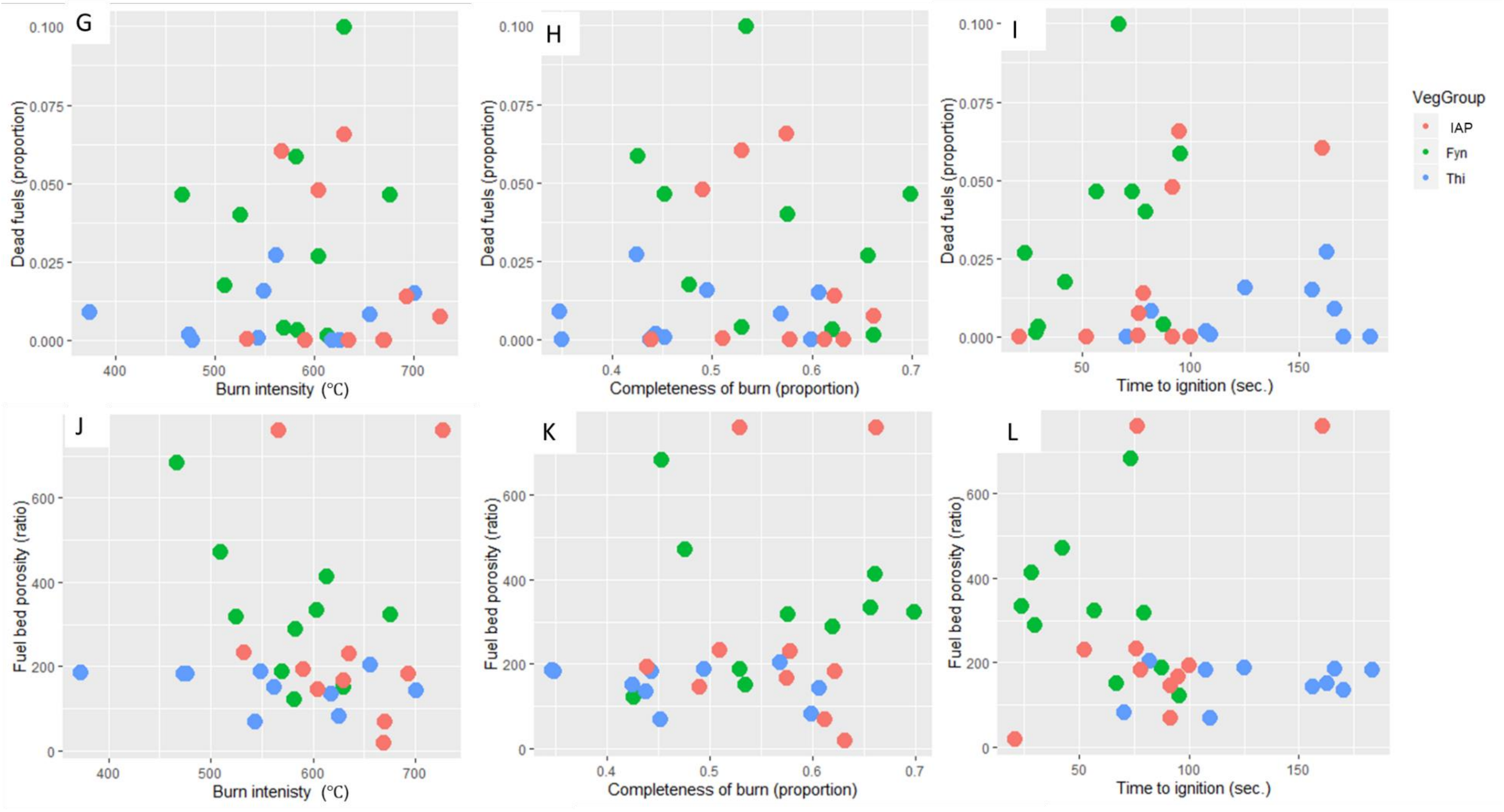
Factors	Burn intensity		Completeness of burn		Time-to-ignition	
	t [a]	Scaled estimate [b]	t [a]	Scaled estimate [b]	t [a]	Scaled estimate [b]
Fine fuels			2.2 *	0.45	-1.9	-0.33
Coarse fuels	-1.7	-0.32				
Fuel load	3.8 ***	0.68	1.9	0.37		
Fuel moisture	- 2.4 *	-0.36	-1.5	-0.27	1.7	0.30
Model statistics	$F^{a}_{3,26} = 11.87$		$F^{a}_{3,26} = 4.54$		$F^{a}_{2,27}. = 4.87$	
	$R^{2\,a}$ adj. = 0.53		$R^{2\,a}$ adj. = 0.27		$R^{2\,a}$ adj. = 0.21	

Significance codes: *p <0.05, **p <0.01, ***p <0.001

[a] t statistic, F statistic, and R^2 adjusted (adj.) obtained from the multiple regression model output

[b] Scaled estimates were derived from incorporating the `scale` function in the multiple regression model


A
Fine fuels (proportion)
0.0
0.2
0.4
0.6
Burn intensity (°C)
400
500
600
700
B
Fine fuels (proportion)
0.00
0.25
0.50
Completeness of burn (proportion)
0.4
0.5
0.6
0.7
C
Fine fuels (proportion)
0.0
0.2
0.4
0.6
Time to ignition (sec.)
50
100
150
VegGroup
IAP
Fyn
Thi
D
Coarse fuels (proportion)
0.00
0.25
0.50
0.75
1.00
Burn intensity (°C)
400
500
600
700
E
Coarse fuels (proportion)
0.00
0.25
0.50
0.75
1.00
Completeness of burn (proportion)
0.4
0.5
0.6
0.7
F
Coarse fuels (proportion)
0.00
0.25
0.50
0.75
1.00
Time to ignition (sec.)
50
100
150


G
H
I
J
K
L
Dead fuels (proportion)
0.100
0.075
0.050
0.025
0.000
Burn intensity (°C)
400
500
600
700
Completeness of burn (proportion)
0.4
0.5
0.6
0.7
Time to ignition (sec.)
50
100
150
VegGroup
IAP
Fyn
Thi
Fuel bed porosity (ratio)
600
400
200
0
Burn intenisty (°C)

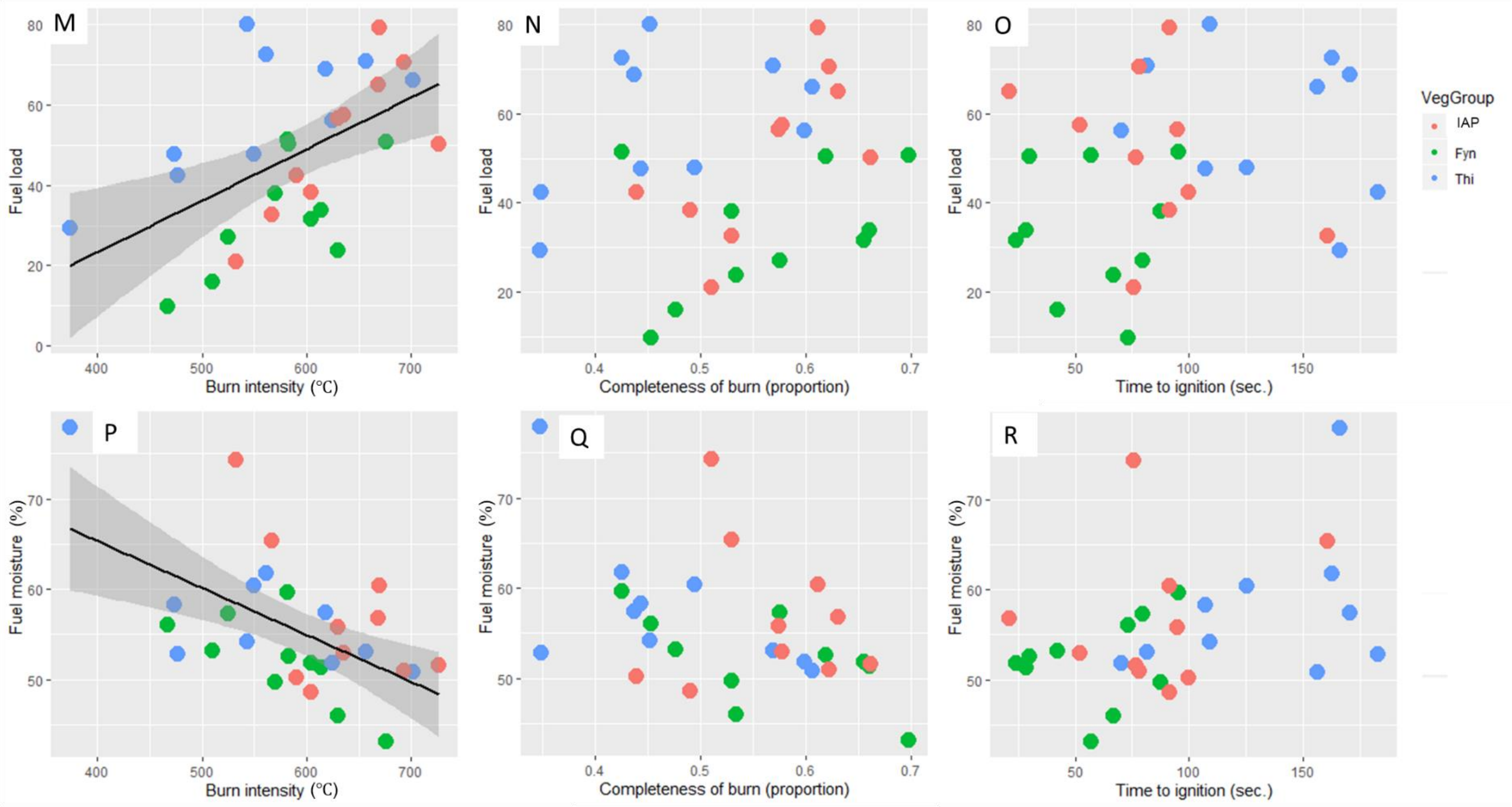


FIGURE 1: Relationships between flammability measures, i.e. burn intensity (left column of panels), completeness of burn (middle column), and time-to-ignition (right column), and fuel traits (**A – C**) fine fuels, (**D – F**) coarse fuels, (**G – I**) dead fuels, (**J – L**) fuel bed porosity, (**M – O**) fuel load, and (**P – R**) fuel moisture, respectively. Each point represents the average value for each of the 30 species. Lines and shaded confidence interval bands are indicated for relationships shown to be statistically significant in multiple regression models (details in Table 1 and Supplementary 1).

Vegetation group comparisons

Burn intensity and fuel moisture did not differ significantly among the vegetation groups, whereas completeness of burn, time-to-ignition, proportion of fine fuels, proportion of coarse fuels, fuel bed porosity, and fuel load differed significantly (Fig. 2; see details in Supplementary 2). Completeness of burn did not differ between IAPs and fynbos but was significantly higher in these vegetation groups than in thicket. Time-to-ignition did not differ between IAPs and fynbos but was significantly shorter than in thicket. Fynbos had a significantly higher proportion of fine fuels than IAPs and thicket, whereas thicket had a significantly higher proportion of coarse fuels than IAPs and fynbos. Fuel bed porosity was significantly higher in fynbos than in thicket, while IAPs did not differ from fynbos or thicket. Fuel load was significantly lower in fynbos than in thicket, while IAPs did not differ from the other vegetation groups.

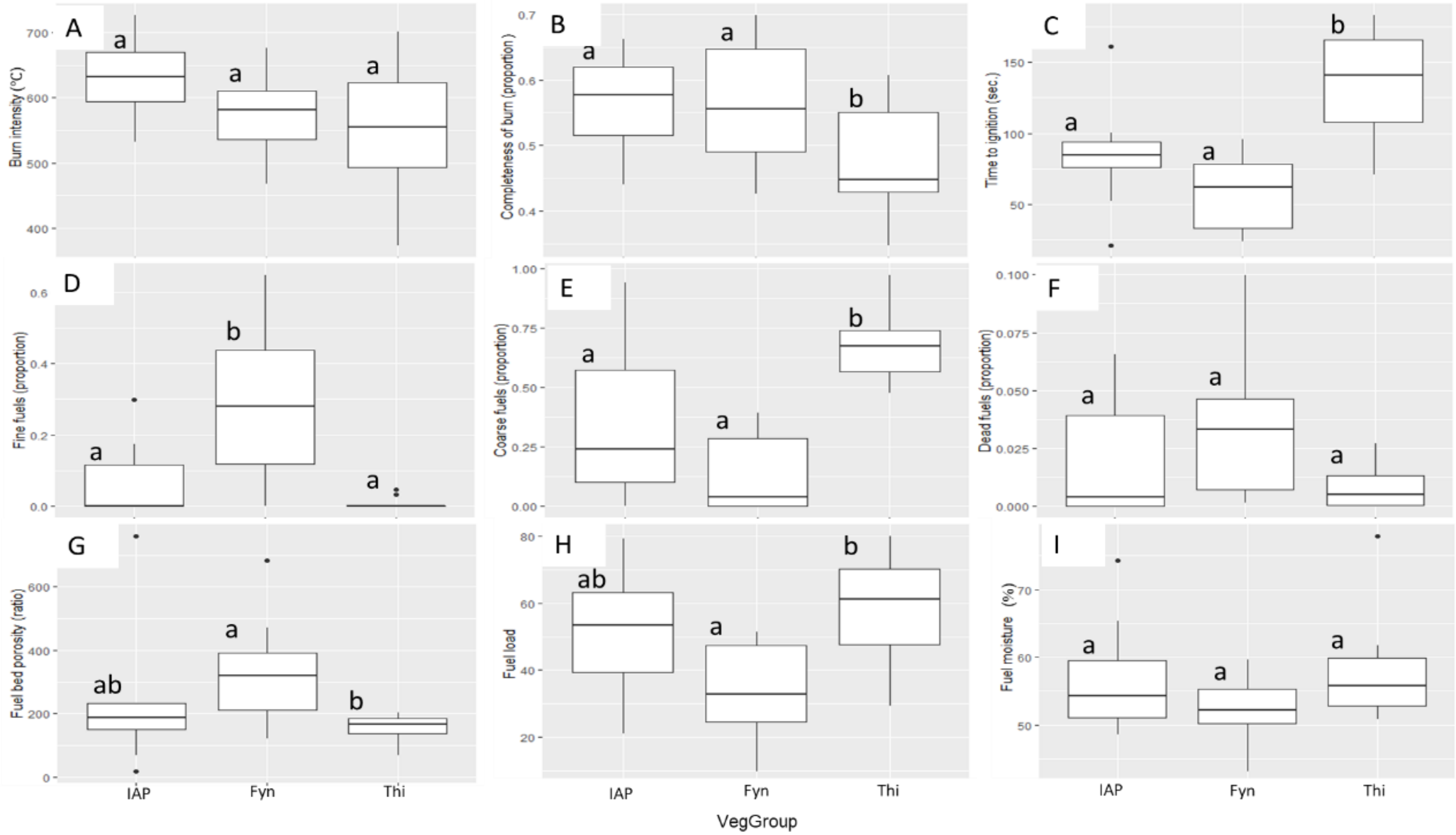


FIGURE 2: (**A – C**) Flammability measures and (**D – I**) fuel traits compared among vegetation groups (IAPs, invasive alien plants; Fyn, fynbos; Thi, thicket). Boxes show 25 – 75 quantile ranges, middle lines show medians, dots show outliers and whiskers show 1.5*interquartile ranges). Disparate small letters denote significant differences among vegetation groups based on Kruskal Wallis test results (details in Supplementary 2) and Dunn’s multiple comparisons.

Discussion

Effects of fuel traits

The flammability of ten species each of IAPs, indigenous fynbos, and thicket was assessed in relation to their respective fuel traits. Burn intensity was significantly enhanced by increased fuel load and reduced fuel moisture as hypothesized (H_1). A positive relationship between fire intensity and the amount of biomass (~fuel load) that vegetation presents was also observed in other studies (Calitz et al., 2015; Keeley, 2009; Saura-Mas et al., 2010; Simpson et al., 2016).

The impeding effects of fuel moisture on flammability and fire behaviour are well recognized in different ecosystems such as shrublands and forests (Alessio et al., 2008; Bianchi and Defossé, 2015; Davies and Legg, 2011; Dimitrakopoulos and Papaioannou, 2001; Pausas and Paula, 2012; Saura-Mas et al., 2010). However, flammability experiments that have been conducted at a small scale (litter or leaves) showed conflicting results (Fletcher et al., 2007; Guijarro et al., 2002). For example, grasses have been found to ignite despite high moisture contents (Guijarro et al., 2002) on account of small leaf surface area that allows quick moisture evaporation to enable fuel ignition (Simpson et al., 2016). In the current study fuel moisture significantly reduced burn intensity and was retained by the preferred models for all three flammability measures. Despite the strong relationship between fuel moisture and flammability measures (i.e. rate of spread and ease of ignition) presented in other studies (Alessio et al., 2008; Davies and Legg, 2011; Dimitrakopoulos and Papaioannou, 2001; Saura-Mas et al., 2010; Simpson et al., 2016), only a weak and non-significant relationship was found in this study between fuel moisture and completeness of burn. The latter is in line with Burger and Bond (2015) findings for a selection of fynbos and forest species, where the magnitude of water contents did not significantly influence flammability in any of the vegetation groups.

The proportion of fine fuels in this study significantly enhanced completeness of burn (as hypothesized, H_2), and was retained by the model for time-to-ignition, exhibiting a weak and negative relationship (as hypothesized, H_3). However, the proportion of fine fuels did not influence burn intensity. Flammability experiments conducted at different scales on various vegetation types unanimously showed that fine fuels enhanced flammability (Burger and Bond, 2015; Calitz et al., 2015; Engber and Varner, 2012; Santana and Marrs, 2014; Schwilk, 2003). Burger and Bond (2015) found that the proportion of fine fuels and of dead fuels were the most important factors governing completeness of burn in fynbos and forest species, while dead fuel retention also enhanced completeness of burn in other systems (Davies and Legg, 2011; Santana and Marrs, 2014). In contrast to the findings of Burger and Bond (2015), I found that the proportion of dead fuels did not affect any of the flammability measures; this may be due to the sampling of sun-exposed branch tips that had very little dead material. The other factor that had no effect on flammability in this study was fuel bed porosity. Burger and Bond (2015) likewise observed no effect of fuel porosity, while the other study that assessed this trait found that it negatively affected the rate of fire spread in moorlands (Davies and Legg, 2011).

Vegetation group comparisons

This study presented the first experimental comparison of the flammability of indigenous and IAP vegetation groups. Vegetation comparisons showed that fynbos and IAPs exhibited greater flammability on account of higher completeness of burn and more rapid ignition than thicket species. There was no apparent distinction between fynbos and IAPs in terms of their flammability. Nevertheless, there was a weak trend of IAPs burning at higher intensities than fynbos and thicket. The trend of higher burn intensity in IAPs than in indigenous vegetation suggests potential increases in fire intensity or severity if indigenous vegetation was to be invaded by IAPs (Brooks et al., 2004; Keeley, 2001; Key and Benson, 2006).

Correspondingly, fynbos and IAPs did not differ in terms of most fuel traits either, except for the proportion of fine fuels. In accordance with other studies (Burger and Bond, 2015; Calitz et al., 2015; Campbell et al., 1981; García-Llamas et al., 2019; van Wilgen et al., 1990), fynbos had large proportions of fine fuels, high porosity and low fuel loads, which likely accounted for high flammability, and in particular, ease of ignition. IAPs displayed high flammability in the form of high burn intensity, high completeness of burn and short time-to-ignition time but did not exhibit any particular fuel traits that could account for high flammability. IAPs presented a combination of fire-prone (i.e. high fuel load) and fire-resistant (i.e. low fine fuel proportion and low porosity) fuel traits which suggests that other fuel traits not accounted for, such as volatile organic compounds (Dimitrakopoulos and Papaioannou, 2001; Van Vuuren and Viljoen, 2009), likely increased the flammability of IAPs. The ten sample species of IAPs furthermore reflected a random set of species rather than a community that evolved collectively under a particular fire regime, which likely introduced variability in fuel traits and flammability response. These results prompt for further investigation of IAPs at a species-specific level and of chemical contents that may enhance flammability.

Thicket had high proportions of coarse and dense fuels, which accounted for its low flammability, also previously observed (Burger and Bond, 2015; Calitz et al., 2015; Pierce and Cowling, 1984; Vlok et al., 2003). Although continuous (~dense) fuels generally facilitate fire spread (Guijarro et al., 2002; Keeley, 2001), high fuel density and coarse fuels can limit oxygen supply to the fire and therefore reduce the rate of fire spread (Scarff and Westoby, 2006). Thicket had greater fuel loads but lower completeness of burn; this corresponds with the study at landscape level that indicated high fuel biomass, but small areas burnt of thicket compared to fynbos vegetation (Kraaij et al., 2018).

Conclusions

This study of flammability in relation to fuel traits showed that increases in fuel load and reductions in fuel moisture enhanced burn intensity, whereas increases in fine fuels enhanced completeness of burn. Fuel moisture appeared to be the most important factor affecting flammability as it was retained by all best models. Fuel moisture was, however, not distinguishable among vegetation groups (cf. Chapter 2) but appeared to vary among species within vegetation groups. Fuel moisture warrants further investigation at species-level. IAPs potentially pose a high fire risk in terms of increased flammability, and fire severity compared to indigenous vegetation. Therefore, IAP clearing should be regarded a priority on the southern Cape coast landscapes. Species-level investigation of IAPs is necessary to specifically assess more fuel traits that may influence their flammability.

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SUPPLEMENTARY 1

Results of multiple regression models ran on the response variables burn intensity, completeness of burn, and time-to-ignition using stepwise model selection based on the lowest Akaike information criterion (AIC). Fixed factors included in these models were fine fuels (F), coarse fuels (C), fuel load (L), fuel bed porosity (P), dead fuels (D), and fuel moisture (M).

Response variables	Fixed factors	AIC
Burn intensity	F + C + L + P + D + M	-14.54
Burn intensity	C + L + P + D + M	-16.50
Burn intensity	C + L + P + M	-18.21
Burn intensity	C + L + M	-18.89
Completeness of burn	F + C + L + P + D + M	-2.68
Completeness of burn	F + L + P + D + M	-4.05
Completeness of burn	F + L + P + M	-5.75
Completeness of burn	F + L + M	-5.82
Time-to-ignition	F + C + L + P + D + M	0.72
Time-to-ignition	F + L + P + D + M	-0.88
Time-to-ignition	F + L + D + M	-2.54
Time-to-ignition	F + D + M	-3.69
Time-to-ignition	F + M	-4.34

SUPPLEMENTARY 2

Kruskal Wallis results of the comparison of flammability measures and fuel traits (respectively) among the vegetation groups (IAPs, fynbos, and thicket).

Factors	H_2	p
Burn intensity	4.50	0.11
Completeness of burn	6.29	0.04
Time-to-ignition	13.43	0.00
Fine fuels	13.52	0.00
Coarse fuels	14.89	0.00
Dead fuels	5.07	0.08
Fuel bed porosity	6.20	0.04
Fuel load	8.30	0.02
Fuel moisture	3.38	0.18

CHAPTER 4: Synthesis and conclusions

Summary of major findings

Fire is a natural phenomenon in various ecosystems, including in the Cape Floristic Region of South Africa (Cowling et al., 1997; Kraaij and van Wilgen, 2014; van Wilgen et al., 1992). However, extreme fires have caused damages in the form of human casualties and economic losses in regions such as California, Australia, and Europe (Montenegro et al., 2004; Quinn, 1994; San-Miguel-Ayanz et al., 2013; Williams, 2013), and recently South Africa around the town of Knysna (Kraaij et al., 2018). The 2017 Knysna firesburnt through indigenous fynbos, thicket and forest vegetation and caused damage to plantations and residential properties (Kraaij et al., 2018). Fire intensities were shown to have been higher in invaded vegetation and pine plantation stands than in uninvaded indigenous fynbos (Kraaij et al., 2018). It was thus essential to understand the variation in flammability of, and the fire risk posed by, various vegetation groups. Such information could inform management efforts aimed at reducing fire risk and damage resulting from fires in the southern Cape coastal landscapes. The flammability of fire-prone (fynbos) and fire-resistant (thicket) indigenous vegetation compared to IAPs have not been studied apart from select species-specific investigations such as *Pinus* and *Eucalyptus* (Forsyth et al., 2004; Kraaij et al., 2011; Preston et al., 2018; van Wilgen, 2009; van Wilgen et al., 2016, 1990). This study presented the first experimental comparison of the flammability of indigenous and IAPs vegetation groups in the context of the southern Cape coast.

In Chapter 2 I assessed the flammability of live plant material of fynbos, thicket, and IAPs in relation to fire weather conditions, fuel moisture, and fuel load. Secondly, I assessed the flammability of partially dried plant material as a crude proxy for drought effects. This was to ascertain whether drying of fuels (~drought) would differentially affect the flammability of the vegetation groups of interest. In the live plant material investigation, results indicated that fire weather influenced all flammability measures (i.e. burn intensity, completeness of burn, time-to-ignition and spontaneous ignition), although live plant moisture contents did not respond to fire weather. Increased live fuel moisture decreased burn intensity, completeness of burn, and the likelihood of spontaneous ignition. Likewise, the depressing effects of fuel moisture on flammability and fire behaviour have been widely reported in various systems (Bianchi and Defossé, 2015; Fares et al., 2017; Kane and Nuria, 2019; Pausas and Paula, 2012). Fuel load enhanced burn intensity but increased time-to-ignition. In terms of burn intensity, findings of this study were in line with evidence for a positive relationship between fire intensity and the amount of biomass (~fuel load) that vegetation presents, also observed in thicket, forest, shrubland, and grassland ecosystems (Calitz et al., 2015; Keeley, 2009; Kraaij et al., 2018; Saura-Mas et al., 2010; Simpson et al., 2016). Fuel load, however, had contrasting effects on different measures of flammability as fuel load negatively affected completeness of burn, also shown in other studies (Kraaij et al., 2018; van Wilgen et al., 1990).

Considering vegetation groups in relation to fire risk, the flammability of IAPs exceeded that of thicket in terms of all flammability measures and exceeded that of fynbos in terms of burn intensity. This suggested potential increases in fire risk and severity posed by IAPs invading natural systems (Brooks et al., 2004; Keeley, 2001; Key and Benson, 2006). Completeness of burn appeared to be the highest in fynbos which suggests that the risk of recurring fire in fynbos will be the lowest for some period post-fire, whereas incomplete burning of IAPs and thicket will not afford the same level of risk reduction post-fire. Extreme fires, including the 2017 Knysna fires, are often associated with preceding droughts (Kraaij et al., 2018; Quinn, 1994; San-Miguel-Ayanz et al., 2013; Williams, 2013), as the resultant increases in dead fuels commonly enhance fire severity (Keeley, 2009). When the flammability of partially dried plant material was assessed, I observed a decrease in fuel moisture and time-to-ignition, an increase in burn intensity and completeness of burn, thereby increasing overall flammability. The drying out of fuels considerably increased flammability equally in the three vegetation groups, and by implication, fire risk due to fuel moisture decrease in fuels.

In Chapter 3 I assessed flammability in terms of burn intensity, completeness of burn, and time-to-ignition in relation to respective fuel traits. Fuel traits considered were the proportion of fine fuels, coarse fuels, and dead fuels, fuel bed porosity, fuel load, and fuel moisture. I further compared the vegetation groups (IAPs, indigenous fynbos, and thicket) in terms of their flammability and fuel traits. I found that burn intensity was enhanced by increased fuel load and reduced fuel moisture. Greater fuel load effects on burn intensity were also reported in Chapter 2, and other studies (Calitz et al., 2015; Keeley, 2009; Kraaij et al., 2018; Saura-Mas et al., 2010; Simpson et al., 2016). Also similar to Chapter 2 results, increased fuel moisture decreased burn intensity, and was in line with studies supporting the impeding effects of fuel moisture on flammability and fire behaviour (Alessio et al., 2008; Bianchi and Defossé, 2015; Davies and Legg, 2011; Dimitrakopoulos and Papaioannou, 2001; Pausas and Paula, 2012; Saura-Mas et al., 2010; Simpson et al., 2016). I found that greater proportions of fine fuels increased flammability by increasing completeness of burn, similarly to flammability experiments conducted at different scales on various vegetation types which showed that fine fuels enhanced flammability (Burger and Bond, 2015; Calitz et al., 2015; Engber and Varner, 2012; Santana and Marrs, 2014; Schwilk, 2003, Chapter 1). The extent of dead fuels did not affect any of the flammability measures, this contradicted findings of Burger and Bond (2015). Furthermore, fuel bed porosity had no effect on flammability measures, and Burger and Bond (2015) obtained similar results.

Vegetation comparisons showed that fynbos and IAPs exhibited greater flammability on account of higher completeness of burn and a rapid ignition than thicket species. These results were consistent with the findings in Chapter 2, but no clear distinctions were made between fynbos and IAPs. The trend of higher burn intensity in IAPs than in indigenous vegetation suggested potential increases in fire intensity or severity if indigenous vegetation was to be invaded by IAPs, formerly validated by some studies (Brooks et al., 2004; Keeley, 2001; Key and Benson, 2006). Interestingly, fynbos and IAPs did not differ in terms of most fuel traits, except for the proportion of fine fuels. This result pointed out that increased flammability in IAPs could not be attributed to fine fuels. Therefore, there is a probability that other fuel traits such as volatile organic compounds (not investigated in this study) may influence the flammability of some IAPs (Behm et al., 2004; Keeley, 2004). Thicket had high proportions of coarse and dense fuels, which accounted for its low flammability, also documented in previous studies (Burger and Bond, 2015; Calitz et al., 2015; Pierce and Cowling, 1984; Vlok et al., 2003).

Study limitations and recommendations for future research

Flammability has been experimentally assessed in laboratories through burning of relatively small components of fuels in a controlled environment (Engber and Varner, 2012; Etlinger and Beall, 2004; Grootemaat et al., 2017; Guijarro et al., 2002; Ormeño et al., 2009; Pausas and Moreira, 2012; Varner et al., 2015). Such experiments may not effectively represent the real-world fire incidences and plant flammability, as flammability is primarily determined by the influences of weather conditions (Bond, 1997; Keeley and Syphard, 2017), and composite fuel traits (Davies and Nafus, 2013; van Wilgen and Richardson, 1985). A novel contribution of this study was that flammability was assessed under a relatively wide range of weather conditions representative of the study area's climate. Furthermore,larger plant components, which enabled a more realistic comparison of canopy flammability, were used. However, this study still could not effectively represent fire behaviour at a landscape level. To apply flammability experiments to landscape level, a more detailed characterization of fuels and species complexes, followed by field-based experiments will be necessary (Bianchi et al., 2018; Wyse et al., 2016).

For the purpose of assessing flammability in relation to fire weather conditions, sampling was conducted from February – November 2018 to obtain a range of fire weather conditions, although high fire danger conditions were rare. Hot, dry katabatic winds (locally known as 'berg' winds) associated with high fire weather conditions occur in autumn and winter (May – August) in the study area (Kraaij et al., 2013; Southey, 2009). The occurrence of high fire weather conditions in this region is brief (Kraaij et al., 2018, 2013). To obtain more high fire weather conditions, sampling may need to be concentrated in autumn and winter, as indicated by Kraaij et al. (2013) and Southey (2009).

Essentially, droughts reduce moisture contents in vegetation (Dimitrakopoulos and Bemmerzouk, 2003), hence prolonged droughts preceding fires are considered a factor greatly contributing to fire spread and severity (Baeza et al., 2002; Duguy et al., 2013; Kane and Nuria, 2019; Kraaij et al., 2018). In this study, drought conditions were simulated by drying plant material for a period of approximately two weeks. The brief drying duration was to avoid the loss of leaves since certain plants would drop leaves due to drought stress (Clarke and McCaig, 1982). Without leaves, I would not have been able to efficiently conduct flammability experiments given the apparatus used (Jaureguiberry et al., 2011; Chapter 2). Therefore, the drying component of the study provided a first indication of potential drought effects on plant flammability, albeit not a perfect proxy for drought conditions.

In this study (both Chapters 2 and 3) the need to investigate species-specific differences in flammability responses was apparent given that species accounted for substantial variation within vegetation groups. However, species-specific investigation was beyond the scope of this study. Species-specific flammability assessments should inform recommendations for fire-wise landscaping. This may be achieved by identifying plant species that are highly flammable and thus high risk, as well as those that display low flammability, and therefore suitable for fire-wise landscaping. Given the challenges associated with potential future extreme fires in South Africa and around the world, there is a significant need to further improve and understand wildfires and fire ecology research to tackle obstacles that future fire regimes will place on society.

Study contributions and implications for management

The findings that live fuel moisture did not vary in relation to weather conditions and was not distinguishable among vegetation groups, indicated that the incorporation of live fuel moisture into fire danger indices is unlikely to be useful particularly in fynbos, thicket, and IAPs systems. Therefore, the use of dead:live fuel ratio will likely be useful in indicating fire risk in evergreen shrublands (Keeley, 2009).

In terms of vegetation groups and potential fire risks, fynbos and IAPs presented high fire risks under moderate and high fire weather conditions, whereas thicket presented lower risks under low and moderate fire weather conditions. However, observations from the 2017 Knysna fires indicated that thicket becomes ignitable under very high or extreme fire weather conditions, and may burn at intensities exceeding that in fynbos but not that of IAPs (Kraaij et al., 2018), presumably on account of fuel loads (Keeley, 2009; Mandle et al., 2011). Therefore, prescribed burns aiming at reducing fuels (Cowell and Cheney, 2017; Kraaij et al., 2011) may be necessary for thicket adjacent to the wildland-urban interface areas.

Assertions regarding the impacts of IAPs on indigenous ecosystems have been documented (Baard and Kraaij, 2014; Brooks et al., 2004; Milton and Dean, 2010; van Wilgen et al., 2008, 2001); however, quantifiable assessments of these impacts are not common (Xanthopoulos et al., 2012; Zouhar et al., 2010). This study laid a foundation in attempting to understand the flammability and fire risk posed by the various vegetation groups occurring on the southern Cape coast. In this study, I highlighted the fire risk posed by IAPs in terms of increased flammability, and fire severity compared to uninvaded indigenous vegetation. Additionally, IAPs and thicket showed to burn incompletely which may potentially result in lingering risk post-fire. Fire managers need to encourage the prioritization of the management of IAPs that present high flammability as an attempt to reduce fire risk along the southern Cape coast of South Africa.

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