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Wildfire ignition potential from cigarettes

Literature Review

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A literature review was conducted to summarize research reports available on the wildfire ignition potential of cigarettes. Articles from 1933 to 2021 were compiled and analyzed. The search included publications on cigarette physical characteristics, ignition thresholds, cigarette behavioral response to variable environmental conditions and statistical studies regarding impact on wildfire in Canada.

According to the information gathered during the review, a cigarette can start a fire in wildland fuels but requires very specific physical and environmental conditions. However, this review also highlighted many gaps in the literature on the subject. Articles published are limited; experimental methods are often not scientifically sound and lack standardization. Furthermore, there are inconsistencies around the definition of the term “ignition”. A couple of factors are of the utmost importance in cigarette-caused fires according to research: wind and fuel moisture content (FMC). There is plenty of evidence showing that air flow is necessary up to a certain level to obtain ignition. Data also show that the FMC must remain below a certain fuel-dependent threshold.

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Table of contents

List of figures

List of tables

INTRODUCTION

A wildfire is a natural or human-caused fire that consumes natural fuels such as forests, brush, tundra, grasses, etc. (Canadian Interagency Forest Fire Centre Inc. 2021).

It is a necessary ecological process as certain plant species require fire to germinate. Fire also opens landscapes by burning shrubs and underbrush and giving room for new grass that wildlife depends on. Because of human encroachment, fire is managed intensively to prevent burning inhabited areas. Consequently, it has not occurred at its natural rate.

Despite keeping ecosystems healthy, fires can be very destructive. Between 1970 and 2017, an average of 8000 wildland fires burned about 2.25 million hectares per year in Canada, costing lives (premature deaths due to wildfire smoke, firefighting accidents, people trapped, etc., Matz *et al*. 2020) and billions of dollars in property damage, insurance, and suppression costs (Canadian Interagency Forest Fire Centre n.d., Government of Canada n.d.). In 2016, the Horse River wildfire in Fort McMurray, Alberta, resulted in the highest costs in Canadian history, totaling 3.84 billion dollars. Note that this amount accounted only for insurance claims and did not include suppression costs (Tymstra 2020).

Wildfires have either natural (lightning) or human causes. Out of 989 wildfires in Alberta in 2019, 71% were caused by human activity and 28% were caused by lightning. The most common human fire causes were incendiary at 22%, recreation at 22% (e.g., off highway vehicles (OHV), campfires), residents at 19% (e.g. brush piles, burning barrels), power lines for 11%, and under 1% for the agriculture industry (Alberta Government 2019).

One category of human-caused fires which has been debated for decades are cigarettes. It is a widely accepted notion that cigarettes can ignite fires when discarded in flammable fuels. However, the number of wildfires caused by cigarettes may be largely overestimated. Countless studies have shown that cigarettes are capable of igniting furniture and cause residential fires, even if the new Reduced Intensity Propensity (RIP) cigarettes have greatly lessened their occurrence (Government of Canada 2020, Government of Canada 2007, Butry *et al*. 2017, Garis & Biantoro 2019). However, cigarette ignitions in a wildland setting have not been studied as thoroughly despite the increased need for wildfire management and prevention (Butry *et al*. 2014).

There are few studies on cigarette ignition in wildlands and they are often informal and dated. This review compiles information from 69 documents and discusses results from 16 articles directly related to the topic of cigarette ignition. A few of these documents are often cited and used as standard references in the investigation of wildfires. However, since their publication, the characteristics of commercial cigarettes have evolved including RIP capacities. The understanding of fire patterns and behavior has also increased drastically. Table 1 lists all 16 papers in chronological order and outlines relevant concerns with each one.

This literature review was undertaken as part of a collaborative effort to highlight what is known about cigarettes as a wildfire cause and identify knowledge gaps. This technical report summarizes the information available on the subject, identifies inconsistencies and future research opportunities.

Table 1. Summary of relevant publications on wildland fuels ignition potential from cigarettes

YEAR	TITLE	AUTHOR(S)	SOURCE	LIMITATIONS
1933	Fire hazards tests with cigarettes	F.M. Hoffheins	Journal of the Franklin Institute	Very little detail on experimental design; no statistical analysis; sample size not recorded
1964	Xerometer and relative humidity test	C. Carlson & L. Gerlinger	California Division of Forestry	Missing page(s); small sample size; very little information on the experimental process; did not record a lot of variables or isolate key variables
1979	Cigarette burn time test	T.G. Harper	California Department of Forestry	Results were not analyzed or interpreted unless pages are missing
1983	Ignition of grass fuels by cigarettes	C. Countryman	Fire Management Notes	No statistical analysis; small sample size; relative humidity (RH) values during testing were not recorded and neither was the time between the end of fuel conditioning and testing. If this time was short, it can be assumed that the FMC was not or seldom affected. Did not test correlation between RH and FMC
1984	Laboratory experiments on the role of burning cigarette-ends as ignition cause of forest fires	S. Markalas	Allgemeine Forstund Jaddzeitung	Only had access to English and French summaries. Rest of the article is written in German. English and French translation did not match. Part of the English translation was wrong.
2003	Can cigarette butts start (bush) fires?	J. Dainer	Honour thesis; University of Technology Sydney	Never published or peer-reviewed; no statistical analysis
2003	Study of forest fire initiation due to lighted cigarette – measurement and observation of flaming probability of dried leaves	K. Satoh, Y.L Zhong, K.T. Yang	6th ASME-JSME Thermal Engineering Joint Conference	Did not conduct all tests using cigarettes
2003	The ease of ignition of 13 landscape mulches	L.G. Steward, T.D. Sydnor, B. Bishop	Journal of Arboriculture	Small sample size; no statistical analysis
2006	Quantifying the propensity of cigarettes to initiate wildland fire in Mediterranean environment	J.F. Galtié	Forest and Ecology Management	Only had access to a summary of the research; missing many details on the experimental design and statistical analysis

2009	Ignition of surface fuels by cigarette in forest fire	D.H. Kim, M.B. Lee, D. X. Viegas	Unknown	No statistical analysis; did not account for temperature or RH
2010	Vulnerability of *Pinus densiflora* to forest fire based on ignition characteristics	H. Seo & Y. Choung	Journal of Ecology and Field Biology	Did not test many factors; focused on effect FMC; small sample size; lacking details on experimental design and ignition rate
2015	Study on probability of *Pinus koraiensis* needles fire lighted by burning cigarette end based on logistic regression	Y.L. Zhang, H. Zhang, S. Jin	Journal of Central South University of Forestry and Technology	Article is written in Chinese apart from abstract written in English. Information was gathered from the English abstract.
2018	Influence of fuel moisture content, packing ratio and wind velocity on the ignition probability of fuel beds composed of Mongolian oak leaves via cigarette butts	P. Sun, Y.L. Zhang, L. Sun, H. Hu, F. Guo, G. Wang, H. Zhang	Forests	-
2020	Moisture content thresholds for ignition and rate of fire spread for various dead fuels in northeast forest ecosystems of China	M.M. Masinda, L. Sun, G. Wang, T. Hu	Journal of Forestry Research	-
Not dated	Relative humidity and wildland fire ignition by cigarettes	T.L. Henriksen, C. Warren, K.H. Lewis	CASE Forensics Corp.	Very small sample size; no statistical analysis; did not control variables
2021	Ignition of fuel beds by cigarettes: a conceptual model to assess fuel bed moisture content and wind velocity effect on the ignition time and probability	D.X. Viegas, R. Oliveira, M. Almeida, D. Kim	Fire	-

1 IGNITION PROPENSITY

Since the 1930's, scientists from around the world have been studying the flammability of wildland fuels from burning cigarettes. A variety of independent experiments have been conducted to determine the main factors that influence ignition from cigarettes. Most studies were conducted in a laboratory to control variables. Field experiments results were generally not peer-reviewed.

Redsicker and O'Connor (1996) identified that cigarette-caused fires were dependent on three factors:

1. The burning cigarette must be in contact with the fuel
2. Fuel must be flammable
3. The cigarette's ignition capacity

In this chapter, the factors known to influence the ignitability of wildland fuels by cigarettes are discussed. Table 2 summarizes the values used for each of these variables in the most relevant publications on the subject. Table 3 lists the key results and optimum conditions found to increase ignitability of wildland fuels under the influence of a burning cigarette.

Table 2. Key variables measured in the most relevant publications (NA: Not available; NR: Not Recorded; NC: Not controlled but measured)

Reference							Cigarette			
	Sample Size	Fuels	Temp (°C)	RH (%)	Wind (km/h)[1]	FMC (%)	Length	Position	Definition of “ignition”	Ignition?
Hoffheins (1933)	NR	Grass Forest floor materials Duff	NR	25–50	NR	NR	Half length	45° horizontal	NR	Yes
Harper (1979)	13	Grass	37.8 dry bulb 21.1 wet bulb	21	0-3.6	NR	Full length	On the fuel +/- 30° of the horizontal	NR	No
Countryman (1983)	77	Cheat grass o Fine o Medium o Coarse	26.6	14-85	1.4, 4.7	1.9–14.7	Burnt 2” before placed	0° = Into wind 90° = Right angle 180° = Away	Fuel burnt to the edge of the fuel bed at one or more points	Yes
Markalas (1984)	NA	Pine needles Dried grasses Ferns Oak and beech leaves Evergreen shrubs	25-26	38-42	1.8-14.4	4.5-6.5	Butts with / without filters	On and into fuel	NA	Yes
Dainer (2003) Lab	240	Oven-dried hay	38-43	NC	0, 3.6	2-4, 5-7, 8-10	42 mm and drawn once	On fuel Coal buried into fuel	Self-sustained glowing combustion 30 seconds after cigarette extinguishment	Yes

Dainer (2003) Field	75	Grass	NR	14	~ 40	~ 12	Full length	On fuel	Self-sustained glowing combustion of 30 seconds after cigarette extinguishment	Yes
Satoh *et al.* (2003)	NR	Dried broad-leafed Japanese oak leaves	NR	35-85	0, 3.6	15-Oct	83 mm	Between leaves - dense Buried in leaves - loose 0° = Into wind	Flaming	Yes
Steward (2003)	104[2]	13 different untreated mulches	NC	NC	NC	NR	Full length	NR	NR	Yes
Galtié (2006)	NA	Forest litter Grass	NA	NA	NA	NA	NA	NA	NA	Yes
Kim *et al.* (2009)	11520	*Pinus densiflora* *Quercus variabilis*	NR	NR	0, 1.8, 3.6, 5.4, 7.2, 9	*densiflora*: 15, 23, 37, 42 *variabilis*: 8, 13, 17, 29	Full length 8 mm & 5 mm diameters	On, middle and bottom of the fuel 0° = Into wind 180° = Away	Flaming	Yes
Seo & Choung (2010)	15[3]	*Pinus densiflora* *Quercus variabilis*	21.5-23.9	54.6-63.1	0-4.3	0, 5, 10	Full length	1 cm into the fuel	Flaming	Yes
Zhang *et al.* (2015)	1440	*Pinus koraiensis*	NA	NA	NA	NA	1 cm	NA	Flaming	Yes
Sun *et al.* (2018)	2520	Mongolian oak leaves	Constant but NR	NR	0, 3.6, 7.2, 10.8, 14.4,	0, 5, 10, 15	50 mm (no filter) 20 mm (filter)	Random	Flaming that can spread	Yes

					18, 21.6					
Masinda *et al.* (2020)	NA	Dead fuel representative of Chinese forests	15	NR	10, 12, 14	Focus of the experiment variable	Butt	NR	Sustained flaming that extended beyond initial point of ignition	Yes
Henriksen *et al.* (n.d.)	7	Cheat grass	21.1-29.4	17-53.5	3.2, 4.7, 6.1	Focus of the experiment variable	Puffed three times before placement	On the fuel	Self-sustained flaming and/or smoldering with incandescence and smoke	Yes
Viegas *et al.* (2021)	>40	Straw	NR	NR	0-18	0 - 25	40 mm (butt), 82 mm (full length)	On the fuel Burning end of cigarette in contact with the fuel bed	Sustained flaming combustion	Yes

Table 3. Summary of optimum conditions required to obtain ignition (NR: Not recorded; NC: Not controlled but measured; ?: Information is unavailable)

Reference	Fuels	Lab/Field	Ignition definition	Sample Size	% Ignition	Summary
Hoffheins (1933)	Grass Forest floor materials Duff	Lab	NR	NR	50-90%	• Need wind • Wind speed = 4.8–6.4 km/h if cigarette angle of 45° • Wind speed = 9.7-12.1 km/h if horizontal • With best wind, best RH = 25%
Countryman (1983)	Cheat grass o Fine o Medium o Coarse	Lab	Fuel burned to edge of the fuel bed at one or more points	77	48% positive ignitions 22% marginal ignitions	• Ignition increased with finer fuels • Ignition increased with fuel bed depth • Ignition increased with wind speed • Ignition increased when tip into the wind • FMC >14% = No ignition
Markalas (1984)	Pine needles	Lab	NA	NA	0%	• Cigarettes with filter = No ignition • No wind = No ignition
	Dried grasses				0%	
	Ferns				0%	
	Oak and beech leaves				6.6–30%	
	Evergreen shrubs >10 cm thickness				10-33.3%	

Dainer (2003)	Oven-dried hay	Lab	Self-sustained glowing combustion of 30 seconds after cigarette extinguishment	240	33% (average of all trials)	• No wind = < 0.2% ignition • Increased ignition with 3.6 km/h wind • Increased ignition with increased contact – if ventilation • FMC 8-10% and no wind = No ignition • FMC < 10% and 3.6 km/h wind Ignition • 70% ignition with 2-4% FMC • 63% ignition with 5-7% FMC • 55% ignition with 8-10% FMC
Dainer (2003)	Grass	Field	Self-sustained glowing combustion of 30 seconds after cigarette extinguishment	75	4%	• ~ 40 km/h • 14% RH • 12% FMC
Satoh *et al.* (2003)	Dried broad-leafed Japanese oak leaves	Lab	Flaming	NR	NA	• No wind = No ignition • 20% FMC = No ignition • 14.4 km/h wind = Extinguished • More heat input with loose fuel • Denser fuel heated faster but did not ignite unless ventilated • Sudden wind is effective • Model calculated probability of ignition - Wind + loosely packed = 23% - Wind + densely packed = 50%

Steward (2003)	13 different untreated mulches	Field	NR	8/mulch Total = 104	Yard waste 50% Recycled pallets 50% (July)	
Galtié (2006)	Forest litter Herbaceous formation	Lab	NA	NA	NA	
Kim *et al.* (2009)	*Pinus densiflora* *Quercus variabilis*	Lab	Flaming	11520	1.70%	• Ignition increased with finer fuels • Ignition increased with wind speed > 7.2 km/h • Ignition increased when buried in fuel • Ignition increased when FMC < 15% • Ignition increased with 8 mm cigarette
Seo & Choung (2010)	*Pinus densiflora* *Quercus variabilis*	Field	Flaming	15	NR	
Zhang *et al.* (2015)	*Pinus koraiensis*	Lab	Flaming	1440	NA	• Ignition increased when FMC ≤ 10% • Ignition increased with wind ≥ 7.2 km/h
Sun *et al.* (2018)	Mongolian Oak leaves	Lab	Flaming that can spread	2520	2.90%	• No wind = No ignition • 18 km/h wind = Extinguished • Highest ignition probability at 14.4 km/h wind • Ignition increased when FMC < 15% • Packing ratio = No impact
Masinda *et al.* (2020)	Dead fuel representative of Chinese	Lab	Sustained flaming that can spread	NA	NA	NA

	forest ecosystems					
Henriksen *et al.* (n.d.)	Cheat grass	Lab	Self-sustained flaming and/or smoldering with incandescence and smoke	7	71%	NA
Viegas *et al.* (2021)	Straw	Lab	Sustained flaming combustion	>40	NR	• Time to ignition decreases when wind speed increases • Time to ignition increases with higher FMC • Probability of ignition decreases with increased time to ignition • No difference in the probability of ignition between regular cigarettes and low propensity cigarettes • Wind speed, tobacco moisture content and fuel moisture content are the main parameters influencing ignition according to the model

2 PHYSICAL CHARACTERISTICS

2.1 Cigarette length

The United States Forest Service (USFS) determined that fuels require constant heat for an average of 9 to 13 seconds to ignite (Henriksen *et al*., n.d., as cited in Stocksdad 1975). A full-length cigarette can take as long as 20 minutes and 12 seconds to burn entirely (Kim et *al*. 2009), meaning if the fuel is flammable and the cigarette releases enough energy, it could easily be a *competent source of ignition*. In the National Fires Protection Association (NFPA) 921, a *competent ignition source* is defined as having sufficient energy and the capacity of transferring that energy to a fuel long enough to raise it to its ignition temperature.

The length of a discarded cigarette influences the likelihood of ignition. Longer cigarettes are more likely to start a fire as they burn for a longer time (Markalas 1984). Because of their reduced length, cigarette butts have less tobacco to burn and thus a shorter time to ignite fuels (Krasny 1987). During field trials, Dainer (2003) used whole cigarettes and obtained ignitions in 4% of tests. The cigarettes either ignited the grass within a minute or two, or not at all. In practice, smokers seldom discard full-length lit cigarettes which means that the ignition rate is likely lower than 4%, in the conditions experienced by Dainer.

The length of a cigarette also influences its aerodynamics and the probability of contacting flammable fuels. When examining the movement of discarded cigarettes on the road, Xanthopoulos *et al*. (2006) found that full-length cigarettes require higher wind speeds to move off asphalt, cement and dirt compared to cigarette butts.

2.2 Burning rate and temperature

Satoh *et al*. (2003) measured the heat released by a cigarette at 15 Watts (W) in still conditions and up to 25 W in windy conditions. The amount of heat produced did not surpass 25 W even with stronger winds up to 12.6 km/h, but the cigarette did extinguish with velocities over 14.4 km/h.

Cigarette temperatures reported in the literature are variable. These differences might be in part due to various methods of measurement (thermal camera, thermocouples, indirect calculations, etc.). It is also important to keep in mind that burning rates and temperatures vary amongst cigarette brands and sometimes even amongst cigarettes of the same brand (Harper 1979). Markalas (1984) compared the temperature of a cigarette's outer layer with the temperature of its coal. The results showed that the center of the cigarette was significantly hotter than the surrounding ashes. The amount of ash produced depends on the brand of cigarette and its physical properties. The more ash produced, the lower the heating capacity of a cigarette as the cooler ash protects the fuel from the coal's heat (Countryman 1980).

Smoldering cigarettes can reach temperatures up to 600-700^{o}C, depending on the brand (Redsicker & O'Connor 1997, Steensland 2005), and reach an average maximum of 584^{o}C ± 15^{o}C at the surface of the coal (Lyman *et al*. 2003). Steensland (2005) reports results from a variety of studies finding the cigarette core temperature to average 713.33ºC – 838.33ºC, while the surface average temperature ranged from 359.44ºC to 646.67ºC. In one study by Countryman (1982, as referenced in Krasny 1987), the center of the coal was found to be around 780ºC and the outer layer to average 442ºC). In his 2021 book, Babrauskas cites the work of Baker (1974) and Holleyhead (1996) which report coal temperature values between 700ºC and 750ºC at rest and up to 850ºC - 950ºC when puffed. Another study conducted in 2002 further divided cigarette temperature into three categories (Liu & Woodcock 2002, as cited in Baker 1977):

1. <u>Solid-phase temperature</u>: temperature of the tobacco during burning, inside the cigarette coal. It was found to vary between 790ºC during smoldering and 900ºC during puffing.
2. <u>Gas-phase temperature</u>: temperature of the gas in and around the cigarette coal. Temperatures range from 790ºC during smoldering and 860ºC during puffing.
3. <u>Surface temperature</u>: temperature of the surface, varying between 675ºC during smoldering and 930ºC during puffing (Fig 1.).

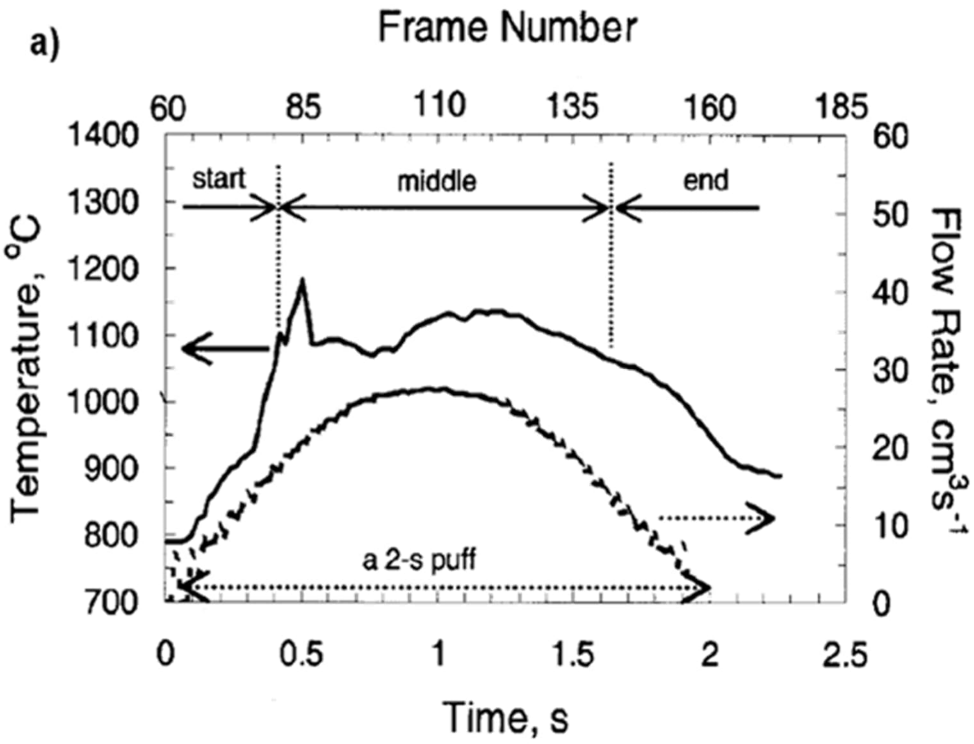

Figure 1. Diagram showing the temperature and flow rate profile versus time during a 2-second puff (Liu & Woodcock 2002, Figure 5(a) p.260).

Despite the discrepancies between studies, a common trend was noticeable: the surface of the burning cigarette is colder than its core. Furthermore, cigarette surface temperatures can vary during puffing episodes and occasional hotter burning events occur during the combustion of tobacco shreds (Liu & Woodcock 2002). When looking at the ignitability of a cigarette, the temperature at the point of contact between the cigarette and substrate is key. The higher the temperature, the more energy the cigarette will emit.

Ultimately, the burning rate of a cigarette will affect its length and the time the burning ember contacts the substrate. The longer the cigarette, the higher the chance of ignition will be (Markalas 1984, Krasny 1987). Carlson and Gerlinger (1964) found that a cigarette took between 4 and 5.5 minutes to burn entirely. However, similarly to cigarette temperatures, reported full-length burn times vary, and likely depend on the type of cigarette.

2.3 Diameter

Cigarettes come in various sizes and scientists noticed that their diameter could impact the probability of ignition (Mehta 2012). Kim *et al*. (2009) found that slim cigarettes (5 mm) were not as prone to ignite wildland fuels compared to thicker cigarettes (8 mm). Thicker cigarettes have more area in contact with the fuel and contain more tobacco, which can increase the amount of heat released on the fuel (Krasny 1987). Five-mm cigarettes are capable of igniting fuels but require very specific conditions (Kim *et al*. 2009).

2.4 Porosity

The permeability of the cigarette paper can change the amount of oxygen flowing in and around a cigarette. Air flow is a key factor in combustion and the amount of oxygen moving through a cigarette impacts the heat it produces and combustion speed (Krasny 1987). More permeability tends to facilitate airflow which increases the cigarette's potential to start fires (Mehta 2012, as cited in Gann *et al*. 1987). More information is given on ventilation in section 3.1.

2.5 Type of cigarette

Cigarettes came in all shapes and sizes until 2005 when the Canadian government made Reduced Ignition Propensity (RIP[1]) cigarettes mandatory (Government of Canada 2020, Seidenberg *et al*. 2011, Garis & Biantoro 2019). In the Canadian legislation, a cigarette is now defined as "*any roll or tubular construction that contains tobacco, has a wrapper or cover made of paper and is consumed through the inhalation of the products of combustion"* (Cigarette Ignition Propensity (Consumer Products) Regulations 2016).

According to section 3(1) of the *Cigarette Ignition Propensity (Consumer Products) Regulations*, all cigarettes manufactured or imported to Canada must successfully pass the *Standard test method for assessing the ignition propensity of cigarettes (ISO 12863).* In this test, no more than 25% of 40 tested cigarettes can burn entirely when resting on 10 layers of filter paper (Cigarette Ignition Propensity (Consumer Products) Regulations 2016):

"*Cigarettes of every size of each brand must burn their full length no more than 25% of the time when tested on 10 layers of filter paper using the International Organization for Standardization standard ISO*

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[1] *Also known as Low Ignition Propensity (LIP), Reduced Fire Risk (RFR), Fire Safe Cigarette (FSC), depending on the country.*

12863, entitled Standard test method for assessing the ignition propensity of cigarettes (ISO 12863), as amended from time to time".

Based on this, the question becomes whether RIP cigarettes have less ignitability and reduce the number of smoking-caused fires in Canada's wilderness. A study conducted by Seidenberg *et al*. (2011) compared RIP and non-RIP cigarettes to calculate a percentage of full-length burn (FLB). Researchers found that non-RIP cigarettes achieved FLB over 75% of the time while RIP cigarettes did not exceed 10% and thus could greatly reduce the risk of ignition. Conversely, Viegas *et al*. (2021) found no difference in the probability of ignition between Low Ignition Propensity (LIP[2]) and regular cigarettes. Of note, the LIP/RIP cigarettes were tested without the effect of wind and may respond similarly to regular cigarettes under its influence. Anecdotal evidence and personal observations suggest that Canadian RIP cigarettes may not behave the same on wildland fuels.

Since 2005, manufacturers have modified the physical characteristics of their cigarettes to reduce their ignitability. Chapman and Balmain (2004) describe the four most common alterations to cigarettes:

1. Reduced tobacco density
2. Reduced paper porosity
3. Reduced circumference
4. Removal and/or reduction of additives.

Ultimately, these cigarettes should have a lower ignition potential or self-extinguish when not puffed.

Despite the standardization of Canadian cigarettes, brands remain unique and cigarettes may display a variety of characteristics. For example, the amount of heat released and the burning rate of a cigarette may vary with tobacco density (Alpert 2010, as cited in Yi *et al*. 2001).

Tobacco may vary in its composition (additives, flavoring, proportions), influencing the amount of energy released during combustion (Krasny 1987). Depending on their composition, cigarettes also produce variable amounts of ash (Countryman 1980). Ash is naturally colder and can lower the surface temperature and insulate the hot coal from the substrate (Krasny 1987).

Hand-rolled cigarettes have not been studied as extensively as regular manufactured cigarettes. An experiment conducted by Laugesen *et al*. (2003) suggested that this type of cigarette was unlikely to ignite wildland fuels as they extinguish if not puffed. Out of the 40 hand-rolled cigarettes tested, none burnt entirely when placed on filter paper. Conversely, manufactured cigarettes burnt to full length 100% of the time. Note that this study was conducted prior to the implementation of RIP cigarette legislation. Babrauskas (2021, p 25) mentions results from Schudel and Hazell (2014) showing that both marijuana joints and hand rolled cigarettes are unlikely to ignite fuels if discarded as they usually self-extinguish when they are not puffed.

Certain cigarettes come without filters. However, the influence of filters has not been extensively studied. Markalas (1984) suggests that filter-less cigarettes were more likely to ignite flammable fuels.

The results from the reviewed literature show that the type of cigarette can affect its flammability. However, most of the research findings are now obsolete with the implementation of RIP cigarettes.

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[2] Portugal

2.6 Conclusion

The information available on cigarette characteristics and their impact on ignitability of wildland fuels is summarized in Table 4.

Table 4. Summary of the individual effect of key physical variables on cigarette potential to ignite wildland fuels (TBD: To Be Determined)

Variable	Change in variable	Expected effect on ignitability
Length	Increase	Increase
Temperature	Increase	Increase
Burning Rate	Increase	Decrease - up to threshold
Diameter	Increase	Increase
Porosity	Increase	Increase – up to threshold
Type of Cigarette	Presence of RIP cigarette	Decrease on furniture – TBD on wildland fuels

3 ENVIRONMENTAL CONDITIONS

Specific environmental conditions can affect cigarette ignition potential. Often however, it is a combination of factors that affects the outcome. In this section, the influence of several environmental factors is discussed.

3.1 Wind

All studies found airflow to be a critical cigarette flammability factor in igniting wildland fuels. Some studies considered wind to be the most important factor in the ignition process.

In 1933, Hoffheins was first to determine that fuels need wind to ignite under the influence of a cigarette. In 2015, Ellis concluded that airflow increased the chance of ignition of eucalyptus forest litter by firebrands. Sun *et al*. (2018) found that wind was always necessary to obtain ignition, regardless of the FMC levels. In 1983, Countryman reported that ignition potential increases with the wind. These observations were later corroborated by Kim *et al*. (2009) and more recently by Masinda *et al*. (2020). In their experiments, Satoh *et al.* (2003) found that sudden winds of 3.6 km/h triggered quicker ignitions. It is important to note that these tests were not done with cigarettes but a small coiled heater (0 to 140 W). However, Markalas (1984) obtained comparable results finding that without ventilation, fuels did not ignite from cigarettes.

Ventilation allows for increased oxygenation of the glowing ember, accelerating the transition from smoldering to flaming (Babrauskas 2021). It also helps fire spread (Markalas 1984, Dainer 2003, Sun *et al*. 2018). Wind gusts create more airflow and increase the potential of ignition by raising the coal temperature, removing the insulated ash layer around the coal or by moving the cigarette in contact with more flammable fuels (Dainer 2003).

There is an optimum wind speed for which the probability of fuel ignition is the highest. Beyond this threshold, the probability of ignition decreases. Research has shown optimal wind speeds to be 3.6-7.2 km/h (Dainer 2003, Sun *et al*. 2018). In Dainer (2003), without wind, the ignition probability of the driest fuels (2%-4% FMC) was as low as 0.1% but jumped to 70% with 3.6 km/h winds. Sun *et al*. (2018) reported that winds higher than 18 km/h did not ignite fuels, regardless of the FMC, because cigarettes were blown off the fuel bed. In another study, cigarettes became extinguished with wind speeds over 14.4 km/h (Satoh *et al*. 2003). This study indicated that a cigarette does not release enough heat in still conditions. Without wind, a cigarette released 15 W of heat whereas up to 25 W with winds of 3.6, 7.2 and 10.8 km/h. Over 14.4 km/h, the cigarettes extinguished and stopped emitting heat. Strong winds can shorten the time to ignition (Kim *et al*. 2009) until they reach an upper threshold where they start to cool down the fuel and the cigarette coal's temperature (Satoh *et al*. 2003).

Dainer (2003) found that in a natural environment with 39.6 km/h average winds, 14% RH and FMC of 12%, ignitions were possible 4% of the time. It is possible that optimum and maximum wind speeds are fuel-dependent. Moreover, during her field tests, Dainer used full-length cigarettes, which are rarely discarded by smokers.

Many cigarette butts are littered along the road. At the fuel level, a steady line of passing cars on the highway creates a wind draft of 10.1-14.8 km/h, gusting to 25.2-39.6 km/h with large trucks (Dainer 2003). Based on these values, vehicle-caused drafts could increase ignitability or on the contrary extinguish cigarettes, depending on their intensity. Anecdotal evidence and personal observations indicate that the wind draft created by moving vehicles tends to draw a cigarette towards the vehicle rather than away from it (Steensland 2005, Xanthopoulos *et al*. 2006). Steensland (2005) further observed that the effects of the draft were stronger with higher vehicle speeds and shorter cigarettes. The author also noted that cigarettes rolled closer to the shoulder when affected by consecutive vehicles. Xanthopoulos *et al*. (2006) determined that a cigarette is most likely to move when it is orientated at a 90° angle to the incoming wind. To move a cigarette, it took minimum winds of 3.2 km/h on asphalt, 5.9 km/h on cement and 8.4 km/h on dirt. The higher values recorded by Sun *et al*. (2018) are likely due to the rough surface of the oak leaves offering more resistance, and the orientation of the cigarette in comparison to the wind and the fuel bed.

The interactive effect of FMC and wind speed is significant and can impact the ignition threshold (Masinda *et al*. 2020). This is discussed further in section 3.3.

3.2 Fuel Moisture Content (FMC)

Ignition probability is closely linked to FMC. Galtié (2006) and Possell & Bell (2013) considered it to be the *most critical* factor of fire ignition. Ellis (2015) demonstrated that FMC is not only a critical factor of vegetation ignition risk by firebrands but also the best indicator of its probability.

When the FMC decreases, the ignition probability increases (Dainer 2003) and the time needed to attain ignition is reduced (Kim *et al*. 2009, Seo & Choung 2010). Beyond a certain moisture content, Galtié (2003) found ignition to be impossible unless influenced by wind and with direct contact between the burning cigarette and the fuel. Ignition probability is a function of moisture in the fuel because higher moisture requires more energy to evaporate the water and allow the fuel to heat up and combust (Sun *et al*. 2018).

Steensland (2005) suggests a “rule of thumb” that the FMC needs to be less than 14% - 15% to allow for combustion. It has been documented that ignitability is closely linked to the type of fuel and its composition (Henriksen *et al*. n.d.). Each fuel is susceptible to ignition at different ranges of moisture content, meaning it has a threshold below which it may ignite but not readily spread and an upper threshold over which it cannot easily ignite and/or spread (Anderson & Anderson 2010). In 1978, Luke noticed that fuels rarely ignited when the FMC was higher than 35%[3]. Looking specifically at Mongolian oak leaves, Sun *et al*. (2018) found that ignition did not occur beyond 15% FMC. Kim *et al*. (2009) found that *Pinus densiflora* needles could not ignite when the FMC was higher than 42%, could marginally ignite at 23%, and ignited at a rate of 6.9% with an FMC of 15%. On the contrary, *Quercus variabilis* leaves had a much lower threshold. There was no ignition over 17% FMC, marginal ignition at 13% FMC and 5.23% chance of ignition at 8% FMC. Seo and Choung (2010) observed that *Pinus densiflora* ignited 1.8 times faster and sustained a longer combustion than *Quercus variabilis* when the FMC was at 10%. These results suggest that FMC greatly influences ignitability, along with other fuel characteristics. For example, *Pinus densiflora* needles have a higher concentration of volatile substances such as resins and oils, which are highly flammable (Seo & Choung 2010, as cited in Song & Kim 1994). The effect of the fuel nature is discussed in more details in section 3.5.

3.3 Wind speed x FMC

Already back in 1941, Keetch had found that ignition from cigarettes required low FMC (below 15%) and wind. Dainer (2003) found that beyond 10% FMC, ignitions were almost impossible without wind although they did not test the impact of FMC greater than 10%. With a wind of 3.6 km/h, the rate of ignition dramatically increased.

Using data from Markalas (1984), Dainer (2003) and Satoh *et al*. (2003), Xanthopoulos *et al*. (2006) created a cigarette ignition prediction model. This model indicated that there was no ignition possible without wind, while the reverse was true with winds over 14.4 km/h and FMC from 2%-8%.

Sun *et al*. (2018) found that the interaction between the wind speed and the FMC had a statistically significant effect on the probability of ignition of Mongolian oak leaves by a cigarette. Wind velocities of 21.6 km/h or calm conditions could not ignite the fuel, regardless of the moisture content. However, for winds of 3.6, 7.2, 10.8, 14.4 and 18 km/h, increased moisture content reduced the ignition probability. A wind speed of 14.4 km/h had the highest probability of flames when FMC was measured at 5%, 10% and 15%. Taken individually, both the wind speed and the FMC had significant impacts on the probability of ignition. For all moisture content levels except the 0% FMC, the ignition probability peaked with wind velocity of 14.4 km/h. The authors suggested that an increase in wind speed beyond a certain threshold can lower the fuel temperature.

3.4 Relative Humidity (RH)

Steensland (2005) presents relative humidity (RH) as the most critical factor of cigarette ignition. However, it has not been extensively studied in recent years. Certain studies recorded a correlation between the RH and the FMC, but few considered it.

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[3] *As cited in Sun et al. (2018).*

According to Steensland (2005) and based on the research of Carlson and Gerlinger (1964), wildland fuel combustion is impossible when the RH is higher than 22%. The 2021 NFPA 921 manual mentions that when the RH is above 25%, ignition becomes difficult (Section 27.8.2.2.2). However, a series of seven informal experiments undertaken by Henriksen *et al*. (n.d.) showed that ignition of cheat grass by a cigarette was possible even with a RH just over 50% without modifying the fuel structure and with the application of wind. Out of 7 tests, 5 reached ignition with RH values ranging between 17% and 53.5%.

Most studies focusing on cigarette ignition of wildland fuels used FMC over RH as a measurable variable. Yet, RH has been linked to FMC. Satoh *et al*. (2003) presented a linear regression between RH and FMC. When the relative humidity of the air increases, so does the moisture content in the fuels. However, there is a lag during which the FMC changes relative to a change in air humidity. During this time, the relationship between RH and FMC may be affected.

The inconclusive results presented in the literature regarding the effects of RH on ignitability suggest that further research is required and that the 22% RH standard currently used by investigators may be obsolete.

3.5 Fuel type, size and density

The physical properties of a fuel greatly influence its capacity to ignite. Masinda *et al*. (2020) tested the ignitability of 40 common species found in Chinese forests, in contact with a burning cigarette. Overall, they found that ignition thresholds ranged from 10.5% ± 1.1% to 27.5% ± 1.7%, depending on the species. Based on these results, they further categorized fuels into three groups (over 25% FMC, between 20% and 25% FMC and below 20% FMC). This study further highlights how ignition probability is fuel-dependent and investigators should not solely rely on results obtained with one specific fuel.

Satoh *et al*. (2003) focused on the ignition potential of dried oak leaves and found that they needed wind under 14.4 km/h to ignite. They conducted similar tests with other common Japanese forest fuels and found that bamboo leaves and dried weeds had similar ignition responses to cigarettes. However, they discovered that dried pine needles were extremely flammable and even ignited in still wind. The higher concentration of resin in the needles is likely to increase its flammability. According to Satoh *et al*., the probability of ignition from a cigarette can be extremely high with this type of fuel.

Markalas (1984) experimented ignition from cigarettes on 12 different fuels[4]. Three types of fuels (pine needles, dried grasses, ferns) did not ignite, regardless of the amount of wind or their size. The study showed that ignition was possible for oak and beech leaves 6.6% to 30% of the time, but only after they had been cut into small pieces and compressed. Finally, the author found that *Quercus coccifera* L. leaves were most flammable (10% to 33.3% of the time) when they were organized in 10-cm thick layers. These findings do not match those of Satoh *et al*. (2003). The difference in ignitability is difficult to explain, as very little information is available from Markalas (1984). It is possible that the nature of the fuels varied between the two experiments, or that other factors were not well controlled.

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[4] Pine needles (*Pinus halepensis*, *Pinus brutia*, *Pinus nigra*), dried grasses, eagle fern leaves (*Pteridium aquilinum*), oak leaves (*Quercus conferta*, *Quercus coccifera*), beech leaves (*Fagus* sp.), mastic tree leaves (*Pistacia lentiscus* L.), olive tree leaves (*Phillyrea media* L.), dry grass, straw and evergreen shrubs.

Steward *et al*. (2003) led a study that looked at the ignition potential of 13 different types of mulches. They found that shredded pine bark did not ignite regardless of the weather conditions whereas composted yard waste ignited 50% of the time.

Fuel characteristics can greatly influence its ignition capacities and the ability of the fire to spread. Other than its composition, the size and load of the fuel can also influence combustibility. Finer fuels are more likely to ignite, due to a higher surface to volume ratio and a faster drying capacity (Countryman 1983, Kim *et al*. 2009). Moreover, to evolve from a smoldering to a flaming fire and be able to spread, a fire requires enough fuel to be sustained (Finney *et al*. 2010, Masinda *et al*. 2020). Sun *et al*. (2018) reported that fuel packing ratio did not have a significant effect on ignition probability. The packing ratio was measured using this equation:

$$\frac{\text{bulk density of the fuel bed } \left(\frac{\text{mass}}{\text{volume}}\right)}{\text{density of the fuel bed particles}}$$

Other studies found that fuel structure had an impact on ignition. Satoh *et al*. (2003) determined that temperatures were higher and fuels required less time to heat up to ignition with densely packed fuels as the heat was concentrated and did not disperse easily. Conversely, loose leaves are more ventilated which increases ignition potential by providing more oxygen. However, when the fuel is too loose, it loses heat through the gaps between its components. Fuel configuration must allow a certain amount of airflow to obtain combustion. Yet, if the ventilation is too high, there can be excessive radiative heat loss (Babrauskas 2014). Steensland (2005) mentions how looser fuels may allow a cigarette to fall in or to the bottom of the fuel bed. Being light, a cigarette will naturally land on top of a substrate, unless it is loosely organized (Dainer 2003, as cited in Ford 1971). The impact of fuel density is further discussed in section 3.6.

What can be learned from all this research is that the potential for cigarettes to ignite wildland fuels cannot be established based on the study of one type of fuel only. Fuels are highly variable in their composition, size, structure, etc. and thus in their sensitivity to heat.

3.6 Orientation to the fuel

Ford stated in 1971 that a third of a burning cigarette needed to be in contact with the substrate to generate ignition. Fuels can heat up through three types of transfers: conduction, convection and radiation. Conduction requires direct contact while radiation does not (Christiansen 2014). In the case of a cigarette, there is no research specifically measuring the amount of direct and indirect contact required between the wildland fuel and the burning cigarette. However, some studies have looked at the effects of the cigarette's general orientation to the fuel.

Dainer (2003) determined that cigarettes placed directly on the fuel without wind created more ignitions than cigarettes placed into the fuel in still wind. The results were opposite when 3.6 km/h winds were added to the experiment. These results indicate that when a cigarette is trapped within the fuel, it needs more oxygen to reach combustion. This is consistent with the behavior of densely packed fuels, as per the findings of Satoh *et al*. (2003). The same authors conducted 20 tests during which they placed a lit cigarette on a dry oak leaf. With or without wind, they did not obtain an ignition. In a second trial, they buried a cigarette in a dense leaf structure and found a probability of ignition of 50% with wind of 3.6 km/h but no ignition in still wind. With loosely packed fuels, they calculated an ignition probability of 23% with 3.6 km/h winds and again no ignition in still wind. In optimum conditions, they concluded that cigarettes have a higher ignition potential when they land in densely organized dried oak leaves.

Kim et *al*. (2009) conducted experiments with cigarettes placed on top, in the middle and underneath the fuel. They found that the ignition rate was 1.5 to 2 times higher when the cigarette was positioned in the middle or underneath the fuel compared to on top of the fuel, with the middle position being optimal. However, there were no statistical analyses done to test the significance of these differences and the values obtained were close, particularly between the middle and bottom positions. When the cigarette is buried in the fuel, its coal not only contacts more fuel, but it also continues to receive enough airflow to fuel the combustion and there is less heat loss (Fig. 2). The fuel is preheated by the trapped radiating heat (Steensland 2005). When the cigarette is placed underneath the fuel, it receives less oxygen. With the cigarette in the middle of the fuel, the right balance between fuel surfaces available, airflow and heat transfer is created to generate ignition.

In summary, denser fuels can better trap heat and increase ignition rates, as long as enough ventilation is allowed.

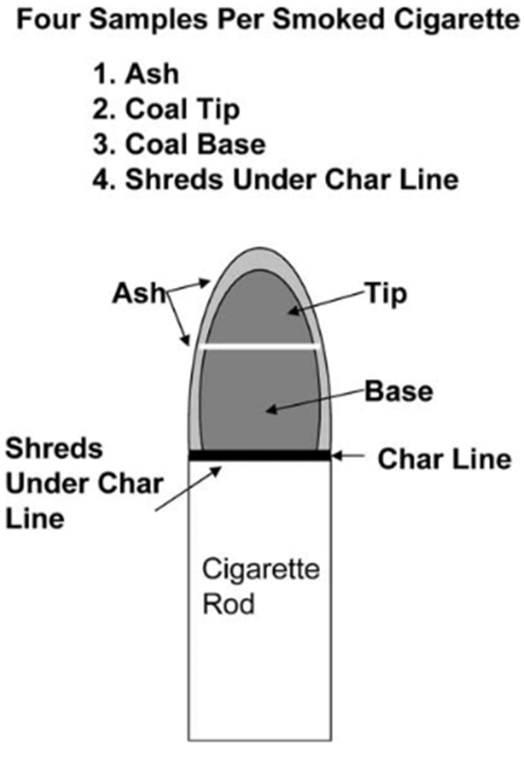

Figure 2. Diagram showing the morphology of a cigarette (Baliga *et al*. 2003, Figure 5(a) p.260).

Unpublished field experiments showed that cigarettes placed in loose fuels have a higher chance of igniting if the coal is facing down (Steensland 2005).

3.7 Orientation to the wind

Countryman (1983) tested three cigarette tip orientations to the wind and measured the impact on ignition potential. He found that cigarettes directly facing into the wind burnt more readily and rapidly and released more heat. Countryman hypothesized that there must be a threshold wind speed above which cigarettes will likely extinguish due to the cooling effect of the wind (too much heat loss). Contrary to Countryman, Kim *et al*. (2009) did not notice huge differences, if any, between the ignition rates of cigarettes facing the wind or placed against the wind. However, they noticed a difference in ignition time. When the cigarette faced the wind, the ignition time was shorter.

3.8 Slope

Topography is a well-known factor in fire behavior. The degree of slope can greatly influence fire spread and intensity. To determine the influence of slope on cigarette ignition, Kim *et al*. (2009) conducted tests on flat ground and with a 20° slope. The results showed that ignition rates were higher when the terrain was inclined. Steensland (2005) conducted a similar experiment and found that ignition happened faster on a steeper slope.

3.9 Conclusion

Table 5 summarizes the general influence of key environmental factors on the ignitability of a glowing cigarette in a field setting. Note that no research focusing on the effect of air temperature was found. Yet, it is common knowledge that increased air temperature is favorable to fuel drying, and consequently to ignitability.

Table 5. Summary of the individual effect of increasing values of key environmental variables on cigarette potential to ignite wildland fuels

Environmental variable	Expected effect on ignitability
Wind	Increase – up to threshold
Air temperature	Increase
Relative humidity	Decrease
Fuel moisture content	Decrease
Fuel size	Decrease
Fuel density	Increase – up to threshold
Contact with substrate	Increase
Slope	Increase

4 RESEARCH GAPS

This literature review summarized the research done on cigarette ignition potential. It also highlighted gaps in the knowledge of this debatable topic:

- Outdated research
- Small sample sizes
- Unclear experimental conditions
- Lack of consensus in the terminology
- Anecdotal evidence
- Many laboratory experiments but very little field testing
- Results are rarely comparable due to discrepancies in methodology

4.1 Outdated research

One of the recurring issues encountered throughout the review process was the age of the studies, with 75% of the most relevant research being over 10 years old. Some of the articles commonly cited and used as standards in wildfire investigation are based on informal experiments, small sample sizes, non-isolated factors and non-scientific methodology. Since there has been little research done on the subject in recent years, investigators have had to use these older publications as guidelines in their decision-making process. However, cigarettes have changed and now need to pass the RIP test, so results based on non-RIP cigarettes have become less relevant. Because fire science has also made great progress, tools to collect strong and sound data are now available to scientists and investigators. The debate about cigarette ignition potential could be settled with additional research.

4.2 Terminology

Ignition is a complex process influenced by several variables. When studying the ignition capacity of a cigarette, one must understand the term “ignition”. Unfortunately, as shown in Table 2, there is no consensus in the various studies on what ignition really is. Some studies did not define it (Hoffheins 1933, Harper 1979, Steward 2003), others defined it as “flaming combustion” (Kim *et al*. 2009, Seo & Choung 2010, Zhang *et al*. 2015), or even as “flaming combustion capable of spreading” (Sun *et al*. 2018, Masinda *et al*. 2020). Dainer (2003) and Countryman (1983) had their own definitions, respectively: glowing combustion and fire that can spread to the edge of the fuel bed. Neither of these two publications specified if flames were required or if a smoldering fire was also considered a positive ignition. Newer articles have been better at precisely defining the term (Sun *et al*. 2018, Masinda *et al*. 2020). To successfully draw conclusions on cigarette ignition, the first step for researchers should be to clearly define the object of their research. Results will only be comparable if scientists harmonize the terminology, which is true when studying any ignition source.

4.3 Methodology

Because of the large number of littered cigarettes, it is not uncommon to find a butt in or around a Specific Origin Area, during an investigation. Therefore, wildfire investigators must be able to explain why they eliminate or chose “smoking” as a fire cause. Presently, investigations are presumed to be based on forensics results, backed by a scientific approach. The mere experience of an investigator may not be as valuable as it once was, particularly when dealing with high-profile cases. Senior investigators may be able to sustain a theory based on their field experience, but junior investigators require data to gain credibility. A defense lawyer can exploit this weakness in the system to discredit a wildfire expert. The current research on cigarette potential has limited weight, mostly due to methodology faults and subjective interpretation of findings.

Weather measurements work well in a controlled laboratory setting. However, it can be more difficult to do when undertaking field experiments, or when investigating several hours after the initial ignition. Temperature, wind speed, wind direction and RH vary over the course of the day and can be different at the surface of the fuel compared to higher levels. Terrain, exposure, obstructions may all contribute to the creation of microclimates. Consequently, investigators should not solely rely on weather station data when determining the origin and cause of a fire. The proximity of a weather station to a wildfire ignition area varies. Further, they do not measure wind speed at ground level (Christiansen 2014). The weather data obtained post-ignition is not always representative of the microclimate within the ignition source, at the time of ignition. Investigators should not rule out the hypothesis of a smoking-caused fire exclusively based on weather readings.

Wildfire investigators have been trained that cigarettes are not likely to start a fire if the RH is over 22%, the FMC over 14% and the air temperature below 26.7ºC (Canadian Interagency Forest Fire Centre 2018, *FI-210*). In practice, these values are conservative and the ignitability of a cigarette varies over a range of values. Cigarette ignitions are overestimated but they cannot be ruled out based on threshold values established in a few dated studies. This review emphasized the many factors that influence the likelihood of cigarette ignitions and how they are interrelated. Satoh *et al*. (2003) conducted ignition tests with an assortment of common Japanese forest fuels. They found that bamboo leaves and dried weeds had comparable reactions to cigarettes. However, they found that dried pine needles were extremely flammable and even ignited in still wind. In addition to low FMC, the needles were more flammable because of their higher concentration in resins and oils. This information is crucial when implementing fire prevention programs. Western Canadian provinces are currently battling the devastation of pine trees by mountain pine beetles (*Dendroctonus ponderosae*). Vast areas are decimated, and dry needles cover the ground. According to observations from Satoh *et al*. (2003), the probability of ignition from a cigarette could be extremely high in this type of fuel. Because of the current climate conditions surrounding these devastated areas, research focusing on the response of dried pine needles to a variety of ignition sources (including cigarettes) would be highly beneficial.

5 CONCLUSION

Cigarettes have long been designated as one of the most common causes of wildland fires. In fact, they only have limited capability of igniting wildland fuels. Already back in 1941, Keetch conducted a literature review on cigarette ignition of fires and concluded that they may not start as many fires as what was commonly believed.

It is surprising how few articles are available on the topic despite its key significance to wildfire investigation. When reviewing the most relevant publications, the answer to the question “*can a* *cigarette start a wildfire*" remains unclear. Some articles report high ignition rates (Hoffheins 1933, Countryman 1983, Markalas 1984, Dainer 2003, Steward 2003, Henriksen *et al*. n.d.) whereas others show an ignition probability of less than 5% (Markalas 1984, Dainer 2003, Kim *et al*. 2009, Sun *et al*. 2018). Interestingly, the lowest rates are associated with higher sample sizes, showing how crucial it is to repeat a test to obtain statistical significance. As of now, there is evidence supporting both hypotheses that cigarettes can be a significant ignition source or a marginal ignition source.

In 2017, 15% of Canadians (4.6 million people) smoked and 11% smoked daily, averaging 13.7 cigarettes/day (Government of Canada 2019). Additionally, the cigarette continues to be the most discarded waste item in the world. In 2012, 6.3 trillion cigarettes were consumed worldwide, and one to two thirds of the butts were discarded in the smokers' direct surroundings or buried in landfills. In 2015, the Litter Reduction Taskforce estimated that Canadians discard on average 8,000 tons of cigarette butts annually (Zero Waste Canada 2016), and in 2020, the city of Hamilton estimated that 65% of the cigarettes consumed were tossed on the ground (City of Hamilton 2020). Dainer (2003) undertook a cigarette road survey along a major Australian highway and found that a daily average of 7 cigarettes were littered at the survey areas (35.28 m^2 and 22.25 m^2). These results are likely underestimated as strong wind gusts or vehicle drafts could easily have blown butts further away. Overall, cigarettes ignition rates may be high simply because of the large number of littered butts.

Despite the decrease in the number of smokers in Canada and the implementation of legal standards for the manufacture of RIP cigarettes, the National Fire Information Database (NFID) of Statistics Canada found that smoking materials and open flames remained the leading causes of residential fires between 2005 and 2014 (As cited in Garis & Biotoro 2019). In Alberta, between 2005 and 2009, there was no significant change in the number of cigarette fires and only a small decrease in smoking related residential injuries (Krasovsky 2015). For wildfires, Butry *et al*. (2014) reviewed United States wildfire reports from 2000 to 2011 and found a 10% decrease in the number of cigarette-caused fires. Their models show that the decrease was due to weather conditions, a drop in the number of U.S. smokers, the establishment of RIP cigarettes and the improvement in training of wildfire investigators (fewer misidentification of fire causes).

A variety of factors influence the likelihood of smoking-caused wildfires. According to the published studies, the conditions that favor ignition from cigarettes are the following:

- Optimum wind speed (minimum 3.6 km/h)
- Wind gusts
- Low FMC
- Low RH
- High air temperature
- Fine fuels
- Thick fuel bed/high fuel load
- Direct contact between the cigarette coal and the fuel
- Dense fuel (but loose enough to allow for airflow)
- Steep slope
- Long cigarette
- Large cigarette diameter
- High tobacco content

- High additive content
- Permeable cigarette paper

Many studies have shown that ventilation, FMC and the type of fuel are the most critical factors. Other elements appear to be of lesser importance or require further research.

It is crucial to the fields of wildfire investigation and prevention that more scientific research be done to identify the most common competent ignition sources of wildland fires. In the future, fire research should focus on defining threshold values for all physical and environmental factors influencing cigarette ignition and use these values to develop mathematical models (standard fuels can be established based on representative Canadian forest ecosystems and areas of greater human activity or follow the standard fuel types used in fire behavior systems). As with the Forest Fire Behavior Prediction and Fire Weather Index systems, investigators could benefit from a model capable of calculating the probability of cigarette ignition based on data collected at the fire scene.

It is key for investigators to present strong evidence in court. Because so many cigarettes are discarded every year, it is necessary to determine the role they have in starting wildfires. Currently, the literature remains scarce on the subject and further work is required to identify the optimum conditions for cigarette ignition in the wildlands. As discussed earlier in this document, this knowledge is critical in preventing wildfires. For example, if it is found that dry dead pine needles can be ignited by a discarded cigarette butt under common fire hazard conditions, preventative measures could be implemented in high beetle-kill areas during vulnerable times (area closure, restricted public access, fire bans and advisories, no smoking zone, etc.).

Overall, there are gaps in the research on cigarette potential to start wildfires. Caution should be used when reviewing older research findings as more recent research has provided new insights. Future experiments should focus on properly defining the research, follow clear and controlled processes that can be shared and standardized, and create an ignition probability model.

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