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ORIGINAL PAPER

# Moisture content thresholds for ignition and rate of fire spread for various dead fuels in northeast forest ecosystems of China

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**Abstract** Fuel moisture content is one of the important factors that determine ignition probability and fire behaviour in forest ecosystems. In this study, ignition and fire spread moisture content thresholds of 40 dead fuel were performed in laboratory experiments, with a focus on the source of ignition and wind speed. Variability in fuel moisture content at time of ignition and during fire spread was observed for different fuels. Matches were more efficient to result in ignition and spread fire with high values of fuel moisture content compared to the use of cigarette butts. Some fuels did not ignite at 15% moisture content, whereas others ignited at 40% moisture content and fire spread at 38% moisture content in the case of matches, or ignited at 27% moisture content and spread fire at 25% moisture content using cigarette butts. A two-way ANOVA showed that both the source of ignition and the wind speed affected ignition and fire spread threshold significantly, but there was no interaction between these factors. The relationship between ignition and fire spread was strong, with $R^2=98\%$ for cigarette butts, and 92% for matches. Further information is needed, especially on the density of fuels, fuel proportion (case of mixed fuels), fuel age, and fuel combustibility.

**Keywords** Dead fuel · Ignition source · Wind speed · Ignition moisture threshold · Propagation moisture threshold

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## Introduction

Understanding the appropriate forest policy and how it should be implemented is crucial for protecting fragile ecosystems and preserving ecosystem services (Alessio et al. 2008). In this respect, forest fires have been extensively studied at specific spatial scales at which climate conditions interact with the fuel load and moisture content, composition, and spatial distribution to affect ignition and fire behaviour (Allen et al. 2016). However, indices that determine whether a fire can be controlled or whether it will expand

and have disastrous impacts have not been measured in some forest areas. Thus, identifying and quantifying the critical thresholds of determinant factors of forest fire behavior is crucial for fuel management, fire prevention, and suppression (Liu et al. 2013).

Anthropogenic activities have significantly increased the occurrence and extent of wildland fires (Ying et al. 2018), and over the last five decades, wildland fires have become a major danger to many countries and regions such as Canada, the United States, central Chile, South Africa, Russia, Southern Australia, the Mediterranean Basin (Figueroa et al. 2019), the northeast and southeast of China (Wu et al. 2011), and most recently in Brazil (August 2019) and Australia (December 2019). Fire ignition and spread are a process of various interdependent components, including fuel moisture content (Madrigal et al. 2009). (Nelson 2001) identified three effects of fuel moisture content levels on reducing the rate of fuel combustion—increasing the time for ignition, reducing fuel consumption, and raising the residence time of burning particles. Finney et al. (2010) and Syphard et al. (2019) demonstrated that fuel moisture content, wind speed, and fuel load are the main factors that control fire behaviour, and Possell and Bell (2013) reported that fuel moisture content is the most critical factor affecting fire ignition. However, McAllister and Weise (2017) showed that this alone cannot explain the ignition behaviour of fuels. In addition to these findings, Rossa (2018) provided several more determinants considered as key variables for measuring the risk of ignition and fire spread, including fuel load and its moisture content, topography, wind speed and direction, relative humidity, and air temperature.

Plucinski et al. (2010) noted that information on ignition moisture threshold of fuels is important for scheduling and implementing prescribed burning. In the same study, they showed that many attempts at prescribed burning of shrubland vegetation resulted in ignition failures due to the narrow window for successful controlled burning. In addition, Nolan et al. (2016) advocated that, during prescribed burning, fire managers should ensure that the moisture content of the dead fuels are sufficient for the fuels to be burned and that the moisture content of live fuel is sufficiently high so that the fire cannot ignite and spread into the crown. Therefore, an understanding of the relationship between fuel moisture content (FMC), ignition and fire spread is needed to improve current understanding of forest fire behavior, in particular by estimating the FMC threshold at which ignition can occur and fire can spread in forest ecosystems (Fletcher et al. 2007).

Forest fire management requires prevention and fire risk assessment systems by providing accurate and timely information on fire potential for all basic fuel types (Allen et al. 2016). In this context, ignitability and combustibility ranking of forest species, the most significant fuel types, are essential components in fire prevention and fire risk management (Dimitrakopoulos 2001; Plucinski et al. 2010). Each fuel species has its own narrow and distinct threshold, below which it may ignite but will not spread, but beyond which ignition develops into fire spread with high intensity (Anderson and Anderson 2010). For this reason, knowledge on fuel conditions in forest ecosystems may constitute an effective means of preventing or managing forest fires (Ganteaume et al. 2011).

Studies on the moisture content of ignition fuels started about five decades ago (Dimitrakopoulos 2001). Since the 1970s, U.S. researchers have been developing a measurement of the flammability of various types of forest fuels (Anderson 1970). Other studies have been conducted in Australia and the Mediterranean region. For example, Alessio et al. (2008), Anderson and Anderson (2010), and Dimitrakopoulos and Papaioannou (2001) focused on estimating the ignition moisture content threshold of several mixed species of fuels. In China, forest fires are reported from the subtropics through temperate zones to the boreal zone (Li et al. 2015; Guo et al. 2017; Su et al. 2019). Daxing'anling is the largest area of boreal forests in China, which is sensitive to climate change. From 2004–2014, 240 fire occurrences were recorded at Daxing'anling, burning over 385,725 ha of forest (Su et al. 2019). Yang et al. (2011) hypothesized that the number of days with extremely high fire danger in Daxing'anling would increase from 44 days (in the 1980s) to 53–75 days by the end of the 21st century due to climate change. Xiaoxing'anling Forest is a forested area in northeast China, famous for ecotourism. Like many forested tourist areas in China, numerous wildfires occur in Xiaoxing'anling, mainly caused by human factors (Su et al. 2018). Therefore, research is needed to improve understanding of the effect of fuel moisture levels on the flammability and combustibility of forest floor fuels in fire risk management, and to provide sustainable silvicultural interventions against wildfires.

The spread of fire is uncertain when moisture content of dead fuels is between 10–40% (Rothermel 1972). Similarly, U.S., Canadian, and Austrian forest management researchers have developed indices used in several studies to assess their validity in fire risk and management. However, there are inconsistencies in some areas, given the particularities of different forest ecosystems (Nelson and Hiers 2008). In China, there is no documentation on fuel moisture ignition thresholds and rate of fire spread and therefore, this study extended its scope to several fuel types in the northeast of the country where fires have been reported and still occur.

The main objective was to determine the maximum fuel moisture threshold that could trigger ignition through lite cigarette butts and matches (human action), and spread the fire. The specific objectives were: (1) to define the moisture content thresholds for ignition and fire spread of various dead fuels of Daxing'anling and Xiaoxing'anling forest ecosystems; (2) to determine the influence of wind speed and source of ignition on ignition and fire spread; and, (3) to establish the relationship between ignition and fire spread in forest ecosystems.

## Materials and methods

### Study locations

This study was conducted in the Daxing'anling and Xiaoxing'anling forests in Heilongjiang province in the northeast of China (Fig. 1).

The first site, Daxing'anling (Tahe), is located at 123°56′ E, 52°27′ N and is characterised as a continental monsoon climate, with long, cold dry winters due to the Siberian cold air mass; a fresh and short spring and autumn; and a short summer with significant variations in temperature and rainfall (Hu et al. 2019). The yearly average precipitation and temperature are 463 mm and –2.3 °C, respectively, and the frost-free period is less than 100 days. Daxing'anling vegetation is a mixed formation of boreal forest species (southern extension of boreal forests of eastern Siberia) and temperate forest species (Chang et al. 2008). Between 1965 and 2010, 1614 wildfires were recorded in the Daxing'anling forests, making the region first in terms of forest fire incidences in China (Hu et al. 2017). The Xiaoxing'anling area is located at Liangshui (128°02′E, 47°12′ N) and at Fenglin (129°15′ E, 48°07′ N). These sites are also characterised by a continental monsoon climate, with a yearly average temperature and precipitation of –0.3 °C and 676 mm, respectively. Summers are rainy, hot, and short. The growing season is relatively short, with 100–120 frost-free days and soils that are frozen from December to April for about 130–150 days. Xiaoxing'anling is temperate forest with evergreen and deciduous species, the latter dominant (Liu et al. 2015).

### Field sampling

Dead fuel material was collected during the autumn fire season (September 2014) in 45 quadrats in Daxing'anling and in Liangshui (September 2015) and Fenglin (September 2016) of Xiaoxing'anling. Fifteen representative forest ecosystems were selected from sampling site. In each ecosystem, three plots were randomly set out and five 16 $m^2$ subplots installed for fuel sample collection. The samples were moved to the laboratory kept in a climate chamber at 25 °C and 50% relative humidity and away from direct sunlight. A total of 40 samples were recorded instead of 45 (from 15

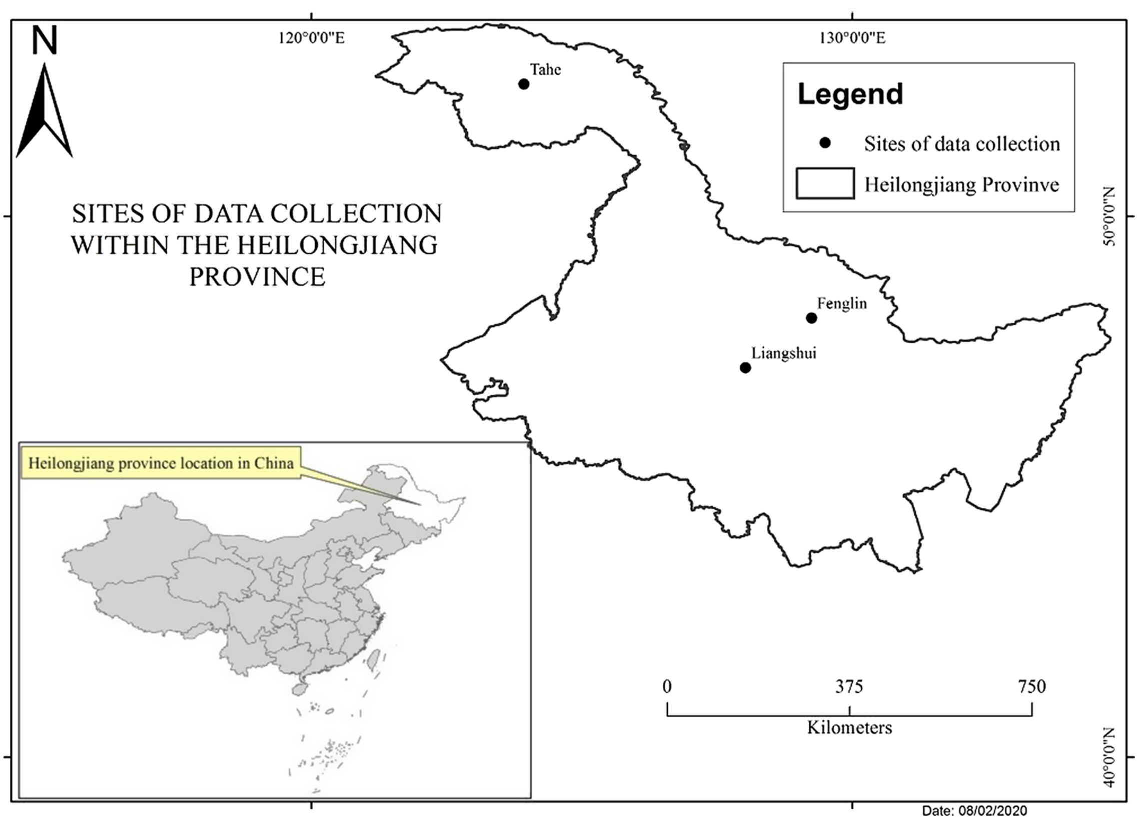


**Fig. 1** Study location

forest ecosystems × 3 sampling sites), as some ecosystems were common to two or three sites (Daxing'anling and Tahe; Xiaoxing'anling, Liangshui and Fenglin).

### Experimental design and laboratory tests

Fuel moisture content was calculated in the laboratory as measurement under field conditions is difficult to evaluate due to the presence of live fuel on the ground surface (Davies and Legg 2011). In the laboratory, before the burning process, for each fuel sample, three 100 g sub-samples were oven dried at 105 °C for 48 h to determine dry mass. Samples were placed on experimental trays enclosed in a burning unit. The fuel moisture content (FMC) was calculated by the gravimetric method:

$$FMC = \frac{W_w - W_d}{W_d} \times 100 \quad (1);)$$

where $W_w$ is the wet weight and $W_d$ the dry weight of fuel

Each test was repeated five times for each combination of variables (source of ignition and wind speed) in order to reduce uncertainties and obtain a valid dataset (Jervis and Rein 2016). Before each ignition, steady-state conditions of the air-flow angle and wind speed were checked. The burning process was carried out for 40 dead fuel samples using matches as in Larjavaara et al. (2004), and cigarette butts as in Sun et al. (2018). Two independent variables were considered: source of ignition, and wind speed. The source of ignition had two variants, matches and cigarette butts.

During autumn, wind speed in the region does not exceed 15 km/h. Therefore, three wind speeds between 10 and 15 km/h, corresponding to the intervals of maximum wind speeds in the region during the fall season, were considered. The speeds selected were 10 km/h (2.77 m·s$^{-1}$), 12 km/h (3.33 m·s$^{-1}$), and 14 km/h (3.89 m·s$^{-1}$). A fan was used to simulate wind speed and was installed 1.5 m from the experimental tray. The air-flow to the tray was adjusted to 45° to prevent fuel particles from blowing away (Marino et al. 2010). The highest slope in the study region is 45° and was considered the critical slope. High wind speed and slope values were considered according to the site's configuration to measure impact on fire ignition and spread. The dependent variables were the maximum fuel moisture content at ignition and rate of spread of the fire.

Ignition of fuel samples was considered successful when the flame was sustained and extended beyond the initial point of ignition, and unsuccessful when the flame was extinguished at the contact point or in a short time (Anderson 1970). The ignition source was applied for 2–3 min at 15 and 25°C but relative humidity was not measured. In addition, fire spread was regarded as successful if the flames spread more than 20 cm from the contact point. The average time for each test was 17.5 min. The ignition potential was not taken into account because, if after 5–20 tests the fuel did not ignite, it was discarded.

### Statistical analysis

The Student *t* test was used to compare the moisture content at ignition and fire spread using both source of ignition and wind speed. The test was considered significant at $p < 0.05$. Data distribution was normalised using log-transformation, and the effect of the ignition source and wind speed were analysed by two-way ANOVA. Tukey's test in STATISTICA 12.5.192.7 (StatSoft Inc., Tulsa, OK, USA) was used to investigate differences in ignition when calibrating different wind speeds (2.77, 3.33, or 3.89 m·s$^{-1}$). Spearman correlations for wind speed, ignition source, and moisture content thresholds were calculated. Statistical analyses were carried out with RStudio (RStudio Team 2018; Integrated Development for RStudio, Inc., Boston, MA), and the ignition and fire spread relationship graph was built with Origin software (Origin 2018; Origin 9.5. OriginLab Corp., Northampton, MA, USA) (Fig. 2).

## Results

Fuel moisture content varied at the point of ignition and in rate of fire spread for different species (Table 1). The moisture content of fuels ignited by matches ranged from 13.7% ± 2.2% (*Syringa reticulana*) to 40.4 ± 2.5% (*Betula costata*), and 10.5 ± 1.1% to 27.5 ± 1.7% for cigarette butts. For rate of fire spread, moisture content varied from 11.0% ± 1.2% to 38.9% ± 1.2% for matches and from 9.6 ± 1.2% to 27.4 ± 1.5%. *Betula costata* fuels ignited and

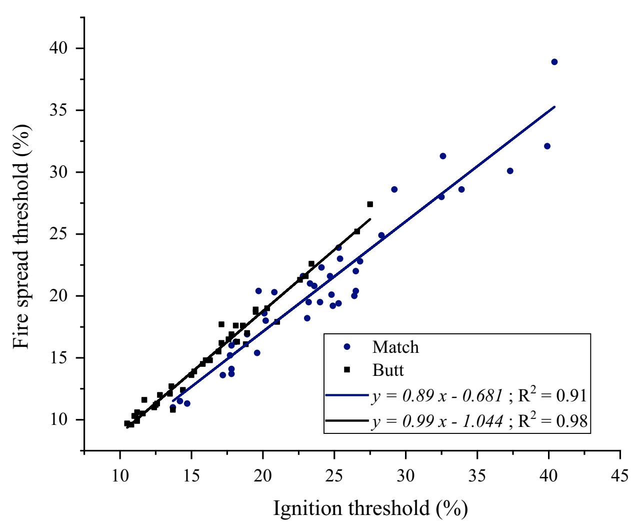


**Fig. 2** Ignition and fire spread moisture threshold relationship

**Table 1** Moisture content thresholds for ignition and fire spread

| Fuel species | Ignition moisture match (%) | Ignition moisture butt (%) | Spread moisture match (%) | Spread moisture butt (%) | Ignition versus spread moisture for Match | Ignition versus spread moisture for butt |
|---|---|---|---|---|---|---|
| *Betula costata* Trautv | 40.4 ± 2.5 | 26.6 ± 4.0 | 38.9 ± 1.2 | 25.2 ± 3.7 | 1.5 | 1.4 |
| *Picea koraiensis* Nakai | 39.9 ± 4.5 | 27.5 ± 1.7 | 32.1 ± 1.8 | 27.4 ± 1.5 | 7.8 | 0.1 |
| *Acer tegmentosum* Maxim | 37.3 ± 3.0 | 23.4 ± 1.4 | 30.1 ± 1.2 | 22.6 ± 1.7 | 7.2 | 0.8 |
| *Pinus sylvestris* L. | 33.9 ± 6.6 | 22.6 ± 3.5 | 28.6 ± 2.5 | 21.3 ± 2.8 | 5.3 | 1.3 |
| *Juglans mandshurica* Maxim | 32.6 ± 4.2 | 17.1 ± 1.3 | 31.3 ± 3.9 | 16.2 ± 1.9 | 1.3 | 0.9 |
| *Pinus koraiensis* Siebold & Zucc. | 32.5 ± 3.8 | 23.0 ± 4.4 | 28.0 ± 2.8 | 21.6 ± 4.1 | 4.5 | 1.4 |
| *Fraxinus mandshurica* Rupr. | 29.2 ± 2.0 | 18.6 ± 1.9 | 28.6 ± 2.1 | 17.6 ± 2.4 | 0.6 | 1.0 |
| *Larix gmelinii* Rupr. | 28.3 ± 3.0 | 19.5 ± 1.2 | 24.9 ± 3.0 | 18.9 ± 1.0 | 3.4 | 0.6 |
| *Betula platyphylla* Sukaczev and *Quercus mongolica* Fisch. | 26.8 ± 1.9 | 18.8 ± 1.4 | 22.8 ± 3.8 | 16.1 ± 2.6 | 4.0 | 2.7 |
| *Acer mono* H.Ohashi | 26.5 ± 6.3 | 11.7 ± 0.7 | 20.4 ± 2.5 | 11.6 ± 1.4 | 6.1 | 0.1 |
| *Quercus mongolica* Fisch. | 26.5 ± 2.5 | 17.8 ± 2.7 | 22.0 ± 2.4 | 16.9 ± 2.0 | 4.5 | 0.9 |
| *Ulmus pumila* L. | 26.4 ± 3.1 | 18.1 ± 3.4 | 20.0 ± 2.2 | 17.7 ± 1.7 | 6.4 | 0.4 |
| *Pinus tabuliformis* Carr. | 25.4 ± 0.4 | 20.3 ± 2.2 | 23.0 ± 2.0 | 19.0 ± 2.7 | 2.4 | 1.3 |
| *Tilia amurensis* Rupr. | 25.3 ± 2.7 | 13.6 ± 3.5 | 23.9 ± 2.0 | 12.7 ± 3.7 | 5.9 | 1.3 |
| *Populus davidiana* Dode and *Quercus mongolica* Fisch. | 25.3 ± 1.8 | 15.2 ± 1.6 | 19.4 ± 2.0 | 13.9 ± 2.1 | 1.4 | 0.9 |
| *Ulmus laciniata* Mayr | 24.9 ± 2.3 | 18.9 ± 1.5 | 19.2 ± 0.9 | 17.0 ± 1.4 | 4.7 | 1.2 |
| *Abies nephrolepis* Maxim. | 24.8 ± 2.3 | 16.0 ± 1.4 | 20.1 ± 1.3 | 14.8 ± 2.2 | 3.1 | 1.4 |
| *Ledum palustre* L. and *Larix gmelinii* Rupr. | 24.7 ± 1.4 | 15.0 ± 1.4 | 21.6 ± 1.0 | 13.6 ± 2.0 | 1.8 | 3.1 |
| *Rhododendron and Larix gmelinii* Rupr. | 24.1 ± 1.7 | 21.0 ± 3.0 | 22.3 ± 2.5 | 17.9 ± 2.4 | 4.5 | 0.8 |
| *Betula platyphylla* Sukaczev | 24.0 ± 2.0 | 19.5 ± 2.2 | 19.5 ± 1.8 | 18.7 ± 3.6 | 5.7 | 1.9 |
| *Deyeuxia langsdorffii* Kunth | 23.6 ± 2.1 | 13.7 ± 1.1 | 20.8 ± 3.0 | 10.8 ± 1.8 | 2.8 | 2.9 |
| *Ulmus sp* | 23.3 ± 2.6 | 18.2 ± 1.8 | 21.0 ± 1.2 | 16.3 ± 2.4 | 2.3 | 1.9 |
| *Pinus koraiensis* L. *and Betula platyphylla* Sukaczev | 23.2 ± 1.2 | 16.9 ± 2.6 | 19.5 ± 0.9 | 15.5 ± 2.0 | 3.7 | 1.4 |
| *Pinus sylvestris* L. and *Betula platyphylla* Sukaczev | 23.1 ± 2.4 | 15.8 ± 1.8 | 18.2 ± 3.8 | 14.5 ± 2.4 | 4.9 | 1.3 |
| *Grass and Larix gmelinii* Rupr. | 22.8 ± 1.3 | 18.1 ± 1.0 | 21.6 ± 2.0 | 17.6 ± 1.1 | 1.2 | 0.5 |
| *Tilia mandshurica* L. | 20.8 ± 6.0 | 11.6 ± 2.0 | 20.3 ± 6.0 | 10.5 ± 2.0 | 0.5 | 1.1 |
| *Larix gmelinii* Rupr. and *Betula platyphylla* Sukaczev | 20.2 ± 0.9 | 17.6 ± 1.1 | 18.0 ± 1.3 | 16.5 ± 1.9 | 2.2 | 1.1 |
| *Alnus hirsuta* Moench | 20.1 ± 2.1 | 10.8 ± 1.0 | 18.6 ± 2.4 | 09.6 ± 1.2 | 1.5 | 1.2 |
| *Chosenia arbutifolia A.K.Skvortsov* | 19.7 ± 2.8 | 12.5 ± 1.8 | 20.4 ± 5.3 | 11.2 ± 1.2 | 1.3 | 1.3 |
| *Viburnum dilatatum* Thunb. | 19.6 ± 2.7 | 13.5 ± 0.7 | 15.4 ± 5.5 | 12.1 ± 0.8 | 4.2 | 1.4 |
| Ulmus davidiana Planch. var. Japónica (Rehd.) Nakai | 18.9 ± 1.4 | 16.3 ± 0.6 | 16.9 ± 1.1 | 14.8 ± 0.7 | 2 | 1.5 |
| *Rhamnus davurica* Pall. | 18.1 ± 3.2 | 11.1 ± 1.5 | 16.3 ± 2.5 | 10.3 ± 1.3 | 1.8 | 0.8 |
| *Rhamnus sp* | 17.8 ± 3.4 | 12.8 ± 1.5 | 14.1 ± 1.4 | 12.0 ± 1.0 | 1.8 | 1.3 |
| *Sorbus alnifolia* K.Koch | 17.8 ± 3.4 | 14.4 ± 2.4 | 13.7 ± 4.4 | 12.4 ± 2.2 | 3.7 | 0.8 |
| *Populus simonii* Carrière | 17.8 ± 1.8 | 11.2 ± 2.0 | 16.0 ± 1.7 | 09.9 ± 1.7 | 4.1 | 2.0 |
| *Lonicera japonica* Thunb. | 17.7 ± 6.6 | 12.6 ± 3.4 | 15.2 ± 4.8 | 11.3 ± 3.6 | 2.5 | 1.3 |
| *Populus davidiana* Dode | 17.2 ± 0.2 | 12.4 ± 1.9 | 13.6 ± 2.0 | 11.0 ± 1.9 | 3.6 | 1.4 |
| *Corylus mandshurica* Maxim. | 14.7 ± 1.3 | 11.2 ± 3.0 | 11.3 ± 1.6 | 10.6 ± 2.7 | 3.4 | 0.6 |
| *Acer ginnala* Maxim. | 14.2 ± 2.0 | 11.0 ± 1.4 | 11.5 ± 1.1 | 10.3 ± 1.3 | 2.7 | 0.7 |
| *Syringa reticulana* P.S.Green & M.C.Chang | 13.7 ± 2.2 | 10.5 ± 1.1 | 11.0 ± 1.2 | 09.7 ± 0.7 | 2.7 | 0.8 |

spread under slightly higher thresholds of moisture content than other fuel species. Its leaves and twigs burned at a maximum moisture content of 40.4 ± 2.5%, and its ignition resulted in a fire spread of 38.9% of moisture content using matches. On the other hand, *Syringa reticulana* fuels ignited when the moisture content was 13.7%, and resulted in a fire spread at 11.0% moisture. When moisture contents were higher than 35%, the fuel did not ignite. Ignitability and combustibility analysis showed three fuel groupings: the first group is composed with broadleaf deciduous species (*Betula costata, Acer tegmentosum, Juglans mandshurica*), evergreen coniferous species (*Picea koraiensis, Pinus sylvestris, Pinus koraiensis*), and deciduous coniferous species (*Larix gmelinii*), had moisture content thresholds above 25% for both ignition and spread of fire; the second group (with a moisture content threshold between 20 and 25%) was composed of mixed fuels of the first and third groups and; the third group was composed with species for which ignition and fire spread threshold were below 20%. The ignition or fire spread threshold of the most flammable species was reduced when these were associated with the lower ignition threshold species. Hence, mixed plantations are less likely to burn as readily when they are composed of a mixture of less and more flammable species.

A highly significant discrepancy was observed between the ignition moisture content, and the fire spread moisture content ($t = 4.04$; $p < 0.001$). The two-way ANOVA results ($p < 0.001$; Tables 2 and 3) showed that wind speed and source of ignition had a significant effect on ignition and fire spread thresholds. However, there was no relationship between wind speed and source of ignition ($p = 0.760$, Table 2; $p = 0.164$, Table 3) and may be considered independently from one another. A significant difference in wind speed on ignition and fire spread threshold was observed when the wind speed was 10 km/h (2.77 m $s^{-1}$) compared to 14 km/h (3.89 m $s^{-1}$). On the other hand, the effect of wind speed on ignition and fire spread did not vary significantly when increased from 10 to 12 km/h or from 12 to 14 km/h (test of Tukey in Table S1 and Table S2).

Table 4 shows that the correlation between ignition and fire spread moisture contents was high ($r = 0.94$). However, there was a moderate, negative correlation between ignition source and moisture content at ignition or rate of fire spread, and only significant between ignition source and rate of fire spread. There was a low but significant association between wind speed and moisture content at ignition or rate of fire spread.

For each ignition source, the ignition and the fire spread moisture content threshold relationship was established (Fig. 1). The relationship was strong for both sources of ignition: butts (98%) and matches (91%).

**Table 2** Analysis of variance of ignition moisture threshold

| | Df | Sum of squares | Mean of squares | F value | *P*-value |
|---|---|---|---|---|---|
| Ignition source | 1 | 9.64 | 9.64 | 134.80 | < 0.001 |
| Wind speed | 2 | 2.39 | 2.39 | 33.44 | < 0.001 |
| Source of ignition * Wind speed | 2 | 0.01 | 0.01 | 0.09 | 0.760 |
| Residuals | 266 | 19.03 | 0.07 | | |

**Table 3** Analysis of variance of spread moisture threshold

| | df | Sum of squares | Mean of squares | F value | *P*-value |
|---|---|---|---|---|---|
| Ignition source | 1 | 6.119 | 6.119 | 70.486 | < 0.001 |
| Wind speed | 2 | 1.952 | 1.952 | 22.478 | < 0.001 |
| Source of ignition * Wind speed | 2 | 0.169 | 0.169 | 1.945 | 0.164 |
| Residuals | 266 | 23.093 | 0.087 | | |

**Table 4** Spearman correlation-coefficient matrix of ignition moisture content threshold, spread moisture content threshold, source of energy, and wind speed

| | Ignition moisture | Spread moisture | Ignition source | Wind speed |
|---|---|---|---|---|
| Ignition moisture | 1 | | | |
| Spread moisture | 0.94 | 1 | | |
| Source of ignition | –0.56 | –0.45*** | 1 | |
| Wind speed | 0.27*** | 0.25*** | 0 | 1 |

## Discussion

The purpose of this study was to determine the critical moisture extinction point of various fuel types to ignite and to spread fire when fuels are lit by matches or by cigarette butts. The results support observations in the laboratory analysis of fuel moisture content thresholds at time of ignition and rate of spread of fire. A significant difference was observed between the ignition threshold and the fire spread threshold (Student's test). The results also indicate that both ignition and fire spread thresholds depend on fuel type (see ANOVA results). The results show that the occurrence of fire does not necessarily lead to the spread of fire due to several key factors such as fuel moisture content thresholds, wind speed, and slope.

The ignition and fire spread threshold values of fuel species in this study are in agreement with the 10%–40% range established by Rothermel (1972)and validate more recent research (Chuvieco et al. 2004; Santana and Marrs 2014). A variability of ignition and fire spread thresholds was observed, ignition thresholds between 10.5–40.4% and fire spread thresholds between 9.7–38.9%. Fuel species from the genera *Betula, Picea, Pinus, Acer, Juglans, Larix,* and *Ulmus* promote ignition and sustain fire spread under higher or slightly higher levels of fuel moisture levels than other fuel species (26.4–40.4% for ignition, and 16.1–38.9% for fire spread). For the remaining fuel types, (e.g., *Syringa reticulana, Acer ginnala, Betula platyphylla-Quercus mongolica*, *Populus davidiana*) ignition and fire spread thresholds were in the range of 11.0–25.4% and 9.7–16.9%, respectively. Our results confirm the variability of ignition and fire spread thresholds of different fuel types in previous studies: 8% for *Eucalyptus pachyloma* and *E. tetragona* (McCaw 1995); 20–25% (in the absence of wind) and 25–30% (with wind) for *Pinus radiata* (Woodman and Rawson 1982); 30% for *Pinus radiata* (Plucinski and Anderson 2008); 35% for *P. pinaster* (Fernandes et al. 2008); and 36% for *Ulex europaeus* (Anderson and Anderson 2010). Bradstock s et al. (2012) reported that eucalypt litter fuels did not ignite when moisture content was higher than 28%. In addition, when the moisture content was between 22 and 28%, ignition and fire spread were difficult. However, when moisture content was between 16–22%, pine fuels ignited and burned readily. Other studies related to the inflammation threshold are described in Plucinski (2003) for species of the genera *Pinus, Eucalyptus,* and *Picea*.

In this study, the fire spread moisture threshold is defined as the moisture of extinction, as determined by Rothermel (1972), as the fuel moisture content above which fire cannot spread or be sustained. Ignition and fire spread moisture thresholds differ for all fuel species. Therefore, species with low ignition and spread moisture thresholds should be interplanted with those with high thresholds to reduce the risk of fire ignition and spread. As reported by Valette (1990), the abundance of species with low ignitability will have the effect of reducing the combustibility of the plantation; in contrast, the richness of highly inflammable species renders the mixture plantations greater combustibility. These results are in agreement with previous findings (Weise et al. 2005; Plucinski and Anderson 2008; Ganteaume et al. 2011), which underlined the variations among fuel types to ignite or to spread fire. They also confirm the results of Cawson and Duff (2019) and Ganteaume et al. (2009) that flammability of dead fuels is related to the chemical composition of species and/or to meteorological conditions. Mixed and broadleaf stands were characterized by slightly lower ignition point and spread thresholds than pure coniferous stands; this is consistent with the findings of Liu et al. (2012).

Laboratory experiments under controlled conditions have the advantage of producing more accurate results than field experiments (Davies and Legg 2011), but their results do not accurately reflect real-world situations. Although laboratory experiments are not surrogates for field fires (Fernandes and Cruz 2012), the findings of this study are a contribution to improved forest fire management. Thus, further laboratory and field experiments on dead and live fuels are needed to establish the relationships among ignition and fire spread moisture content thresholds with slope, wind speed, time of ignition, fire spread, and fuel chemical composition variables. The findings of this study suggest the benefits of mixed species plantations to reduce fuel hazard and fire risk, as some fuel types at 12% moisture content ignite but do not result in fire spread, while others up to 25% do. As a result, mono-specific plantations are predisposed to burn more readily than natural forests. The results also suggest that forest fire managers should pay particular attention to the respective thresholds of each fuel type when carrying out a prescribed burn. Information from this laboratory experiment should provide fire managers in northeast China greater understanding of the requirements of prescribed burning and the level of good-practice guidelines, allowing them to adjust management to meet the criteria (Charles and Garten 2006; Wang et al. 2013). This will contribute to the preservation of both biodiversity and the provision of ecosystem services (Allen et al. 2016). The present work did not consider other variables that may influence fire development, such as the density of fuels, fuel proportions (in the case of mixed fuels), fuel age; thus, experimentation including these factors is needed in future research.

## Conclusion

Using matches and cigarette butts, variability of ignition and fire spread thresholds were observed, with an ignition moisture content threshold 10.5–40.4% and a fire spread moisture content threshold 9.7–38.9%. Fuels at different moisture contents ignited according to the species, wind speed, and ignition source (matches or cigarette butts). Some fuel species at 15% moisture content did not ignite, whereas other species ignited at 40% moisture content and fire spread at 38% moisture using matches, or ignited at 27% moisture levels and the fire spread at 25% moisture content using cigarette butts. Wind speed and ignition source had a significant effect on ignition and fire spread and may be analyzed independently from one another. Matches were more effective at igniting and spreading fire with fuels with high moisture levels than cigarette butts. Although ignition and fire spread thresholds were measured using laboratory experiments, the estimated threshold for each fuel type remains a useful indicator for defining when fire hazards may occur in a forest. The best way to mitigate fire risk in forest plantations is through mixing species with low ignition threshold with those with a high threshold.

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**Compliance with ethical standards**

**Conflict of interest** The authors declare no conflict of interest.



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