Models for predicting fire ignition probability in graminoids from boreo-temperate moorland ecosystems

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Running title: Fire ignition in boreo-temperate graminoids

Summary: There is an increase in dead fuel of graminoids after winter in boreo-temperate ecosystems. This dead fuel and its low moisture content play an important role in determining initial fire ignition. Here, we assess the probability of ignition as function of the dead fuel moisture content, which assists in improving fire predictions.

Abstract

It is predicted an increase in both the frequency and severity of wildfires in boreo-temperate ecosystems. Therefore, in order to develop efficient fire rating systems, relationships between the fuel moisture content (FMC) of vegetation and ignition thresholds need to be determined. We developed fire ignition probability models for three graminoid species collected in central England, but common in boreo-temperate ecosystems (*Eriophorum angustifolium, E. vaginatum* and *Molinia caerulea*). Specifically, we assessed through laboratory experiments: (1) seasonal differences between early-spring and late-summer in fuel traits such as height, fuel load, fuel bulk density and dead fuel load proportion, and (2) the role of these fuel traits, environmental conditions and dead FMC in determining the probability of ignition. There were seasonal differences in fuel traits between species, with an increase in dead fuel load proportion after winter. The dead FMC was the only variable determining initial sustained ignitions. However, the seasonal differences in dead fuel were not sufficient to affect the FMC threshold at which graminoids start to ignite. Graminoids start to ignite at high levels of dead FMC, and there are differences between species (from 36.1% to 48.1%). This work assists in improving fire ignition predictions in graminoid-dominated ecosystems by providing warnings based on critical moisture thresholds.

Keywords: dead fuel, flammability, fuel moisture content, seasonal variation, wild fire

Introduction

Current predictions of climate change suggest that summers will be drier and hotter in boreo-temperate ecosystems leading, to an increase in both the frequency and severity of wildfires (Albertson *et al.* 2009; Krawchuk *et al.* 2009). Policy-makers and land managers should, therefore, adopt strategies to minimize possible ecosystem damage. An important goal is to establish relationships between fuel moisture content (FMC) and ignition thresholds (Plucinski *et al.* 2010; Santana and Marrs 2014), as well as to incorporate them into efficient fire rating systems (van Wagner 1987; Aguado *et al.* 2007; Matthews 2014).

A factor affecting ignition probability is vegetation type. On British moors, we have already derived ignition response curves for a range of contrasting shrub species (*Calluna vulgaris* (L.) Hull, *Empetrum nigrum* L., *Ulex europaeus* L. and *Vaccinium myrtillus* L.), mosses (*Sphagnum* spp. L.) and peat (Santana and Marrs 2014). However, large parts of these ecosystems have a graminoid component, inter-mixed mainly in *C. vulgaris* heathlands and *Sphagnum*-dominated bogs, as well as covering large areas where they are the dominant species (Phillips 1954; Wein 1973; Taylor *et al.* 2001; Marrs *et al.* 2004). Here, we use the term graminoid to describe three dominant species; i.e., two species in the Cyperaceae (*Eriophorum angustifolium* Honck. and *E. vaginatum* L.) and one grass in the Poaceae (*Molinia caerulea* (L.) Moench). Despite the wet conditions where these species dominate, wildfires are frequent in early-spring and late-summer because the seasonal variation of dead fuels (Davies and Legg 2008; Albertson *et al.* 2009; McMorrow 2011). In spring, leaves are dessicated as consequence of the frost damage caused in winter (Robertson and Woolhouse 1984); therefore, when the weather begins to warm up the probability of fire ignition increases. Nonetheless, as the season progresses through summer, the graminoid leaf material starts to "green-up" lowering the likelihood of fire. Only at the end of summer, and where there has been several weeks of severe drought, does the probability of ignition increase again (Albertson *et al.* 2009).

Relatively little is known about the response to fire of graminoids in boreo-temperate ecosystems, but research in other fire-prone areas have pointed out their high flammability (Gantaume *et al.* 2010; Santana *et al.* 2011). Graminoids ignite easily, and once the fire starts, they can exhibit high rates of both fire spread and fire intensity (Cheney and Sullivan 1997). Moreover, grasses/graminoids usually contain large proportions of dead fuel load, which may respond very quickly to changing, dry environmental conditions (de Groot *et al.* 2005). Therefore, in order to predict the probability of ignition in graminoids from boreo-temperate ecosystems, it is essential to measure the possible effects of these different fuel structural traits, as well as their interactions with the growing season.

In this paper we develop fire ignition probability models for the three graminoids common in boreo-temperate ecosystems: i.e. *E. angustifolium, E. vaginatum* and *M. caerulea*, Specifically, we carried out a series of laboratory experiments and assessed: (1) seasonal differences between early-spring and late-summer in fuel structural traits such as height, fuel load, fuel bulk density and dead fuel proportion, and (2) the role of these fuel traits, environmental conditions and dead fuel moisture in determining the probability of ignition. We hypothesized that the proportion of dead fuel would be greater in early-spring compared to late-autumn, thus leading to fire ignition at higher FMC values. This work, therefore, can assist in improving the predictions of fire danger rating-systems, by providing better warnings based on critical moisture thresholds in graminoid-dominated ecosystems.

Methods

Site description and field sampling

Plant material was collected from the Peak District Natural Park (53°18'N, 1°43'W) in Central England in both early-spring (20th March 2014) and late-summer (26th August-16th September 2013). Samples of *E. angustifolium, E. vaginatum* and *M. caerulea* were collected by complete excavation of 15 tussocks for each species with underlying soil intact in each season. The sampling area where tussocks were extracted was approximately of one hectare, and a minimum distance of five meters was left between selected tussocks. The sampled material was then transported to the laboratory for processing where they were maintained. Tussocks were kept alive in the laboratory because were extracted with their roots within an underlying peat/soil core.

Laboratory preparation of the fuel-beds

In order to standardize the ignition experiments, a *ca.* 20 × 20 cm square was cut from each tussock and burned in our ignition tests (Figure S1 in supplementary material). This size has been considered sufficient to provide initial sustained ignitions in laboratory experiments (de Groot *et al.* 2005; Plucinski *et al.* 2010; Santana and Marrs 2014). In addition, a 5 × 20 cm strip was cut in a standard way next to each sampled square to assess: (i) the total amount of fuel and the proportion of dead fuel, and (ii) the FMC of both dead and live fuel. The green and dead fuel within this strip was cut manually, separated, and weighed before and after oven-drying at 80ºC for two days. FMC was then determined separately as the percentage of dry mass. The fuel bulk density of each square was then calculated by dividing the estimated amount of dry fuel (kg m^{-2}) by the average height of the fuel within the rectangle.

A range of dead fuel moisture contents were created for each species; this was achieved by saturating the vegetation by immersion, and then allowing it to dry for several days under laboratory conditions to produce test fuel beds with a range of FMC. Ignition tests started two days after the immersions and approximately 10 days were needed to obtain the complete range of dead FMC tested. Green fuels did not experience high moisture variations because they were kept alive until the ignition test was performed (i.e., the tussock was rooted to the underlying peat/soil).

Experimental conditions, ignition source and ignition tests

All ignition experiments were performed within a glasshouse with a temperature of 21.9 ± 5.1°C (Mean ± SD, n=90) and a relative humidity of 40.2 ± 9.3%. A domestic fan was used to provide a constant air flow of 0.3 $m \cdot s^{-1}$ (measured with an anemometer-Viking ART 02041, Sweden) in the central point of the square. The incidence of wind in these types of experiments has an increasing effect in igniting fuel beds (Marino *et al.* 2010); therefore, wind speed was minimal to provide conservative estimates of ignition probability. Air-flow was supplied at angle of 45º (Santana and Marrs 2014).

A flaming source was used for ignition tests using commercial kerosene pills designed for barbecues (Zip, Standard Brands, UK). The pills were rectangular (19 × 17 × 12 mm; L × W × W). The flaming ignition source, when lit, remained on fire for 383 ± 32 s (mean ± SD, n=6) and the flames reached a maximum height of 101 ± 7 mm (see Santana and Marrs 2014). Our method aimed to simulate small human ignitions.

To perform the ignition tests, the pill was lit and placed at the front side of the grass square. Sustained ignition was considered successful if fire reached the opposite side of the square (20 cm, Figure S1). The distance from the ignition point to the bottom edge allowed enough fire development to demonstrate sustainable ignition (de Groot *et al.*

2005; Plucinski *et al.* 2010; Santana and Marrs 2014). Fifteen tests were performed for each species and season. The proportion of fuel consumed in each test was estimated visually.

Statistical analysis

Seasonal differences in fuel structural traits were analyzed by using the student's *t*-test. The probability of sustained ignition for each species was modelled using Generalized Linear Models (GLM) with a binomial error distribution and a logit-link function (Crawley 2012). Initially, we considered dead FMC, green FMC, air temperature, relative humidity, season, height, fuel bulk density, green fuel load, dead fuel load and proportion of dead fuel as predictor variables. Starting from the full interaction model, the minimal adequate GLM was obtained by sequential removal of non-significant model terms (Analysis of deviance, F tests, $P>0.05$; Crawley 2012). Goodness of fit was measured using Nagerkelke's pseudo R^2 statistic, and the discriminative ability of the models over a range of cut-off points was assessed using the area under the Receiver Operating Characteristic (ROC) (Hosmer and Lemeshow 2000). However, because only the dead fraction FMC was selected as a significant variable for all three species, the FMC at which 50% of ignitions were successful (M_{50}) was estimated for each species and used as the fire ignition threshold (Plucinski *et al.* 2010; Santana and Marrs 2014). The maximum FMC at which successful ignition occurred (M_{max}) was also estimated. All statistical analyses were performed in the R statistical environment (version 2.14.2., Development Core Team 2012, Vienna).

Results

There were seasonal differences in the fuel structure of the three species (Figure 1). *M. caerulea* had a lower height in early-spring whereas *E. vaginatum* was lower in late-summer. No difference in height was found for *E. angustifolium* between seasons (Figure 1a). Dead fuel load increased in *E. vaginatum* and *M. caerulea* in spring, whereas green fuel load in *M. caerulea* decreased (Table 2). Total fuel load increased in *E. vaginatum* in spring, and Green FMC was higher in spring for *M. caerulea* (Table 2). The fuel bulk density remained constant between seasons for the three species (Figure 1b), but the proportion of the vegetation load present as dead fuel increased in spring for all three species (Figure 1c).

The probability of sustained ignition was related to the dead FMC for all the three species as it was the only variable selected as significant within the GLM models (Table 1, Figure 2). There were no significant effects of seasonal variation in fuel structure. Air temperature and relative humidity were also not selected because they were relatively constant during the ignition tests, as well as height, fuel load, bulk density and dead fuel proportion (Table 2). M_{50} values were similar for *M. caerulea* and *E. angustifolium* (ca.48%) but *E. vaginatum* was lower (36%) (Table 1, Figure 2). M_{max} values were similar for all three species ranging between 52 and 56% (Table 1).

Fuel consumption varied among species when successful ignition occurred. Proportionally to the total fuel load, *E. vaginatum* experienced the highest consumption (mean±SE: 58.6±4.7 %, n=12), followed by *E. angustifolium* (50.2±3.1%, n=12) and *M. caerulea* (45.1±2.1%, n=15).

Discussion

There were seasonal differences in fuel structure of the three graminoid species (*E. angustifolium, E. vaginatum* and *M. caerulea*). Two species showed differences in height and dead fuel load, and all showed an increased proportion of dead fuel in early-spring. The spring increase is probably a result of low winter temperatures; i.e., air temperatures in this region fall well below 0ºC in winter and can promote tissue damage and leaf death (Davies and Legg 2008). This damage can be accentuated when the soil freezes as this restricts water uptake from the root system when evaporative demand is high (Robertson and Woolhouse 1984). Life-history traits also accentuate differences between species; *M. caerulea* accumulates greater amounts of dead fuel because all its green tissues die in winter (Taylor *et al.* 2001). In contrast, shoots in *E. vaginatum* and *E. angustifolium* are able to survive winter frosts, although tissue damage can occur (Phillips 1954; Wein 1973). Therefore, the key role of dead FMC in initial sustained ignitions found in this work suggests that the increase in dead fuel in early-spring might influence wildfire incidence. In fact, it has been recorded that outbreaks of "grassland fires" in British ecosystems occurs mainly in April-May (Albertson *et al.* 2009; McMorrow 2011).

Our results from these three graminoid species showed that the dead FMC was the most important variable in determining ignition probability, confirming results for grasses from other ecosystems (de Groot *et al.* 2005; Dimitrakopoulos *et al.* 2010; Gantaume *et al.* 2010). The FMC of dead fuels is determined mostly by meteorological conditions, and can fall quicker than green fuels below ignition thresholds (de Groot *et al.* 2005; Matthews 2014). However, our initial hypothesis, that there would be seasonal differences in M_{50} was not supported. Whilst there were differences in dead fuel proportion within the vegetation, it appears that the absolute amounts were not sufficiently different to affect ignition. Similar results were found by Santana and Marrs (2014) in laboratory simulations for the shrub *C. vulgaris*. It was suggested that when the flame plume is long enough to contact vertically and horizontally with sufficient dead fuel, it can start sustained ignitions independently of the dead fuel proportion (Santana and Marrs 2014). In contrast, in the same study, ignition through smouldering sources simulating cigarettes ends or embers were indeed influenced by the dead fuel proportion. With smouldering sources, contact with fuel is restricted to the surface area of the source and higher densities and proportions of dead fuel may be needed to produce the initial flame at higher FMC (Santana and Marrs 2014). Therefore, although no differences were found between seasons for flaming ignition sources, further studies are needed to test whether this probability is variable with respect to the nature of the ignition source.

The dead FMC at which 50% of the ignition were successful in the studied species was high (M_{50} *ca.* 36-48%) in comparison to other vegetation types typical from British ecosystems. These values are larger than other components of moorland systems, e.g. the litter of the main shrub species *C. vulgaris*, *Sphagnum* mosses and peat (M_{50} *ca.* 19-35%; Table S1) (Santana and Marrs 2014). Similarly, the probability of ignition was also greater than in *Calluna* vegetation with dead fuel proportions up to 60% (M_{50} *ca.* 30%, Table S1) (Santana and Marrs 2014). This fact, therefore, highlights the graminoid component as one of the most fire-prone vegetation types in boreo-temperate ecosystems.

It is worth noting that M_{50} values observed in this work for *E. vaginatum* (36.1%) were similar to those observed in grasses from other studies elsewhere in the world which varied between 35-38% (Table S1) (Burrows *et al.* 1991; de Groot *et al.* 2005; Dimitrakopoulos *et al.* 2010). However, the M_{50} values for *M. caerulea* and *E.*

angustifolium observed here were much greater (48.1% and 47.8% respectively). This may be a consequence of the heterogeneous distribution of the dead FMC throughout their vertical structures. In this experiment, complete tussocks of grasses containing wet peat soil were used; accordingly, the lower part of vegetation was in contact with the peat and was maintained at higher moisture contents than the upper parts which were isolated from the peat in contact with drier air. It is likely that the upper parts in the drier conditions were at the point where sustained ignitions could occur, leaving the rest unaffected. This fact may explain the low fuel consumptions observed in this experiment (45-59%).

The M_{50} values for *M. caerulea* are of particular concern as they are greater than all other moorland components tested. Given the large areas dominated by this species in the United Kingdom (Bardgett et al. 1995), it is clearly a high-risk species for initiating wildfire. One strategy to mitigate this risk would be to increase the conversion of *M. caerulea*-dominated land to a more-mixed species moorland with a greater shrub component (Marrs et al, 2004; Milligan et al. 2004).

When interpreting the results of this study it is essential to note that it is an initial laboratory study, and these results need to be complemented, on the one hand, with more laboratory work testing different environmental conditions and, on the other hand, with studies under realistic field conditions. For example, it would be interesting to determine the importance of relative humidity and air temperature, since in this work experiments were performed within a relatively low range for both variables. Furthermore, here, we assess the probability of initial sustained ignition at a small scale, which later can develop in a larger-scale fire. Future experimental fires under field conditions are needed to corroborate the fuel moisture levels and environmental conditions needed to produce fires at larger scales. We showed that graminoids started to ignite at high levels of dead FMC (36-48%), producing superficial fires with low consumption levels; but it is possible that lower values of moisture are needed to obtain sustained and more intense wildfires at large scales.

Conclusions

Three important results were reported in this work. First, there were seasonal differences in height among species, with a marked increase in the dead fuel proportion in early spring. Second, the dead fuel moisture content of these graminoids played the most important role in determining initial sustained ignition. However, the seasonal differences in dead fuel load proportion observed here were not sufficient to affect the dead FMC threshold at which graminoids start to ignite. Third, these graminoids can start to ignite at high levels of dead FMC, but they produce superficial fires with low consumption levels. The M_{50} values differed between species, since *E. vaginatum* (36.1%) had lower values than *M. caerulea* and *E. angustifolium* (48.1% and 47.8% respectively). This work, therefore, helps in improving the future forecasting of fire ignition in boreo-temperate grasslands, where the incidence of fire is expected to increase in the next few decades as a consequence of global climate change.

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TABLES

Table 1. GLM models relating the probability of sustained ignition in relation to dead fuel moisture content (FMC) in three different species of graminoids from British upland moorland ecosystems.

Species	Tests (n)	Sustained ignitions	M_{50}	M_{max}	Model parameters						Pseudo R^2	ROC area
					Predictor	Estimate	SE	z-value	Odds ratio	*P*		
E. angustifolium	30	12	47.8	52.7	Intercept	6.69	2.59	2.58		0.009	0.4	0.92
					FMC	-0.14	0.05	-2.72	0.86	0.006		
E. vaginatum	30	12	36.1	56.3	Intercept	3.25	1.51	2.15		0.031	0.21	0.74
					FMC	-0.09	0.04	-2.42	0.91	0.015		
M. caerulea	30	15	48.1	53.7	Intercept	9.15	3.43	2.67		0.008	0.42	0.91
					FMC	-0.19	0.07	-2.76	0.83	0.006		

Table 2. Seasonal differences in fuel moisture content (FMC) and fuel load of dead and green fuels during the ignition experiments (student's *t*-test). Mean and standard deviation are shown (n =15).

Species	Season	Total fuel load (kg m^{-2})	Dead fuel load (kg m^{-2})	Green fuel load (kg m^{-2})	Dead FMC (%)	Green FMC (%)
E. angustifolium	Summer	0.7 ± 0.4	0.2 ± 0.1	0.4 ± 0.3	55 ± 17	64 ± 6
	Spring	0.6 ± 0.2	0.3 ± 0.2	0.3 ± 0.1	50 ± 16	66 ± 7
	t	0.621	1.81	-1.134	0.781	-0.801
	p-value	0.541	0.085	0.266	0.441	0.429
E. vaginatum	Summer	2.0 ± 1.1	1.0 ± 0.7	1.0 ± 0.5	38 ± 17	59 ± 4
	Spring	3.2 ± 1.3	2.4 ± 1.2	0.8 ± 0.3	46 ± 11	60 ± 4
	t	**-2.679**	**-3.973**	1.379	-1.635	-0.345
	p-value	**0.012**	<**0.001**	0.181	0.114	0.732
M. caerulea	Summer	2.9 ± 1.9	1.2 ± 0.7	1.7 ± 1.4	43 ± 15	50 ± 7
	Spring	2.1 ± 0.9	2.0 ± 0.9	0.1 ± 0.1	51 ± 12	80 ± 11
	t	1.348	**4.3**	**-2.825**	-1.662	**-8.793**
	p-value	0.191	<**0.001**	**0.008**	0.108	<**0.001**

FIGURES

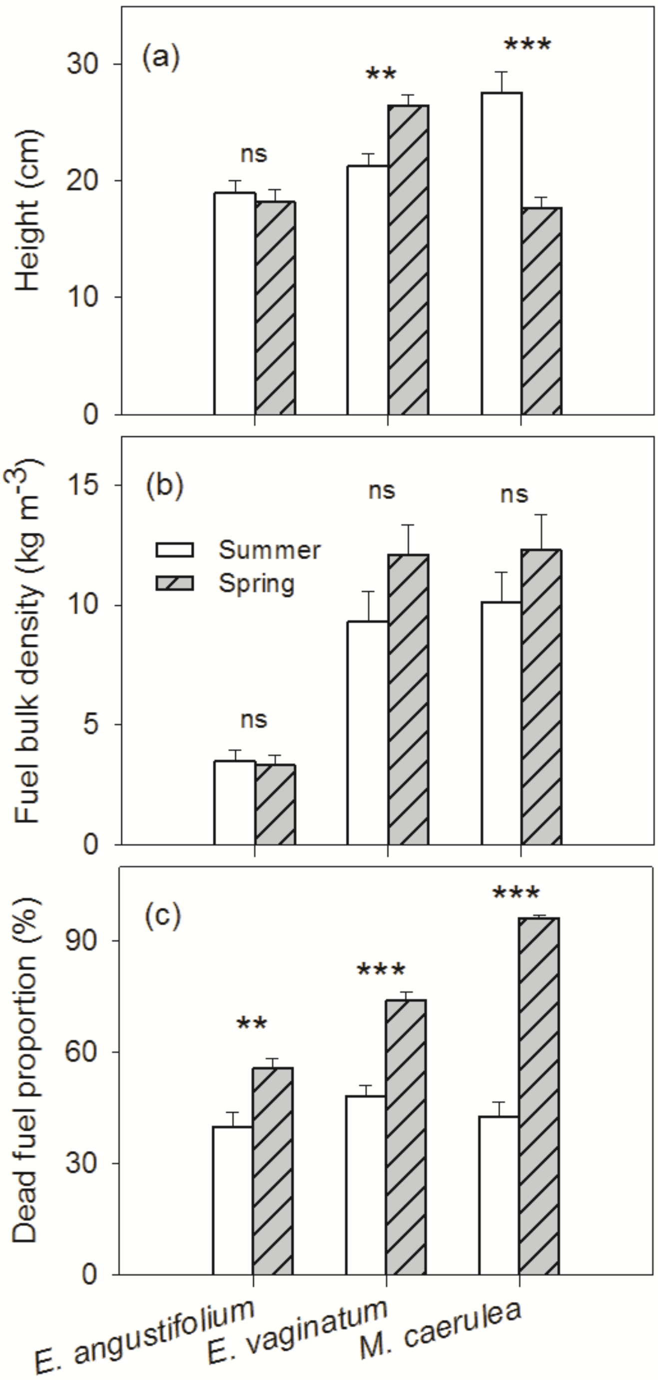

Figure 1. Fuel structural traits for three graminoid species typical of boreo-temperate ecosystems in two different seasons (early-spring and late-summer). Three different traits are shown: (a) total height, (b) fuel bulk density, and (c) dead fuel proportion load. Error bars denotes standard error (n=15). Significance: ns= non-significant, ** <0.01, *** <0.001.

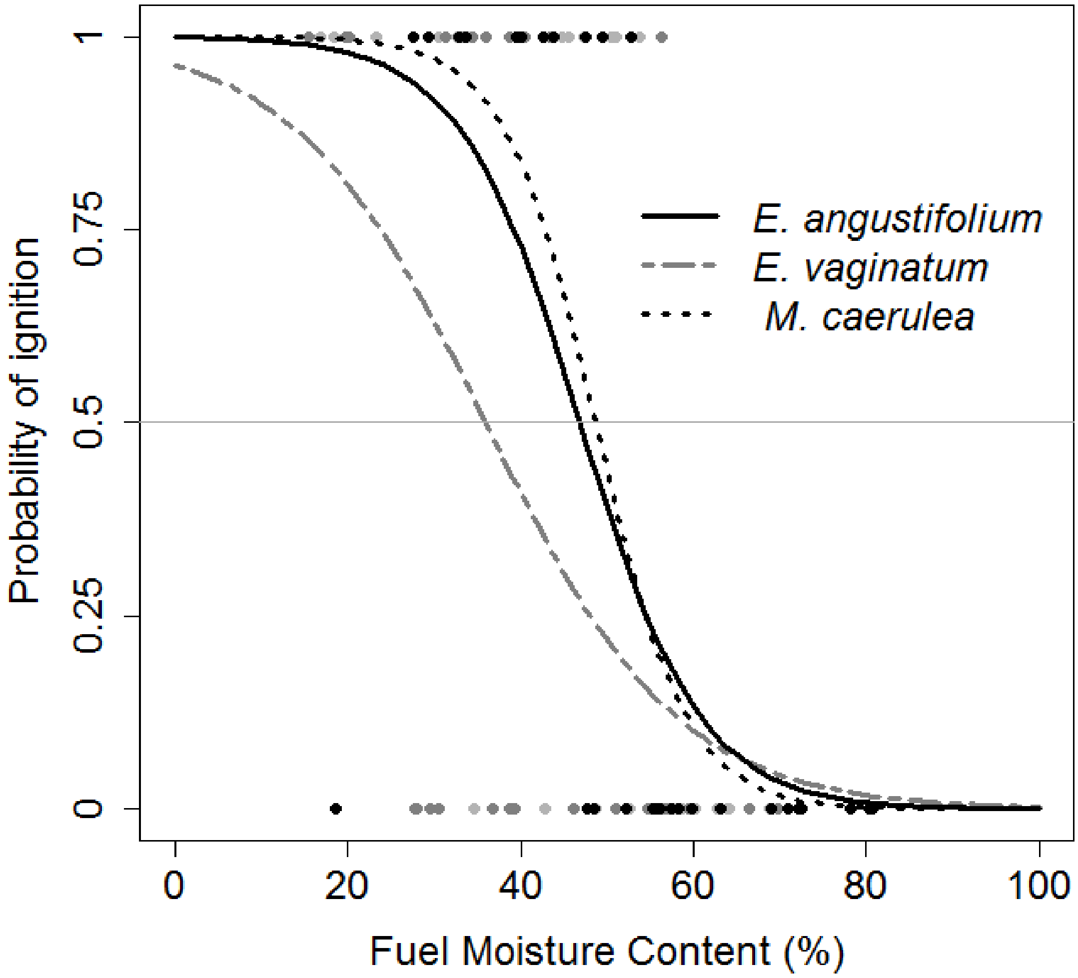

Figure 2. Generalized Linear models (GLM) showing the probability of ignition in three graminoids typical of boreo-temperate ecosystems as a function of dead fuel moisture content.