Variation in fuel moisture content across pine stands is driven by climate and weather in Catalonia

Supervisor
Dr. Víctor Resco de Dios

Submitted by
Prakash Thapa
Date: 2020 November 24

The University of Lleida

School of Agrifood, Forestry Science and Engineering

Variation in fuel moisture content across pine stands is driven by climate and weather in Catalonia

Supervised by

Víctor Resco de Dios, PhD

Submitted by

Prakash Thapa

Table of Contents

Figure Index

Table Index

Abstract

Fuel moisture is a key fuel trait that often acts as the on/off switch of forest flammability. In this study, I analyzed data of live and dead fuel moisture content across six pine forests in NE Spain collected in the years 2016 and 2017. The objective was to assess fuel moisture variation across a marked climatic gradient in NE Spain. I observed significant variation across sites in live (67-247%) and also in dead (9-18%) fuel moisture. Variation across sites in live fuel moisture was associated with mean annual temperature and precipitation. Seasonal variation in live fuel moisture was apparent for grasses and shrubs, but not for trees. Soil moisture was a significant driver of seasonal variation in grass moisture content. However, no clear trend between dead fuel moisture and mean annual temperature or precipitation was observed, which was driven by diurnal variations in vapor pressure deficit. These results imply that live and dead fuel moisture both can be altered with climate change, enhancing forest flammability.

Keywords:

Forest fire, Fuel moisture variation, Vapor pressure deficit, Soil moisture

1. INTRODUCTION

Forest fire is a complex natural process and one of the most pressing environmental issues in Europe, and other parts of the world, resulting in severe ecological, economic and social consequences. Forest fires play an important role in the dynamics of Mediterranean forests as they can alter ecosystem composition, structure and function through species filtering, nutrient cycling, and by creating a mosaic which further influences fire behavior and ecological processes (Chen, 2006). The magnitude of change occurring during and after a fire depends largely upon fire severity (Neary, Ryan and DeBano, 2005), which may be influenced by the moisture status of vegetation.

The Mediterranean environment is fire-prone because its wet winters allow for enough plant growth that then becomes available to fire during its hot and dry summers (Bodi *et al.*, 2012). In recent decades, the number of fires and burnt area have decreased in the Mediterranean region due to increased efficiency of fire-fighting capacities (Turco *et al.*, 2016). However, land use changes, climate change and reoccurring droughts have led to fires as being perceived as a growing problem (Pausas and Vallejo, 1999; Moriondo *et al.*, 2006). Rural depopulation is leading to land abandonment, which then leads to fuel accumulation and climate change is reducing fuel moisture and, consequently, promoting fire spread.

Fuel moisture is an important on/off switch for forest fire occurrence (Boer *et al.*, 2017). That is, fire activity depends on of four factors, acting as four switches connected in series that, when concomitantly on, lead to large wildfires. These four switches are fuel accumulation, fuel dry down, ignition sources and fire weather (Bradstock, 2010; Boer *et al.*, 2017). After sufficient fuel accumulation, low fuel moisture, along with appropriate fire weather, are necessary for successful fire spread after an ignition. In fact, large wildfires only occur after crossing critical thresholds of fuel dryness (Nolan *et al.*, 2016). Fuel moisture is among the most important fuel characteristics that influence fuel flammability (Argañaraz *et al.*, 2018). High fuel moisture in fuel requires more energy to ignite a fire, because water must be evaporated before any fuel can ignite.

Dead fuel moisture is particularly important for initial propagation. Dead fuel classes are divided based on their size and, for fire spread, the most important ones are those called as 1h (<6mm) or 10h fuels (6-25mm) (Resco De Dios, 2020). Dead fuel classes can also be classified from their location as either surface or suspended. They will usually become more coupled with atmospheric conditions when suspended and surface fuel moisture may be additionally affected by soil moisture (Resco de Dios *et al.*, 2015). Dead fuel moisture content has been shown to be dependent on atmospheric vapor pressure and, in turn, critical thresholds associated with catastrophic fire occur below 14% in Western Europe (Boer *et al.*, 2017).

Live fuel moisture depends in turn on the interplay between soil moisture and plant morpho-physiological traits (root length, transpiration, stomatal resistance etc.) (Chuvieco, Aguado and Dimitrakopoulos, 2004; Qi *et al.*, 2012). In fact, seasonal variation in fuel moisture varies markedly across functional types or life-forms, which can range from being nearly constant in trees to showing nearly 100% of moisture variation within a season in shallow rooted shrubs (Nolan *et al.*, 2018). Consequently, live fuel moisture content varies markedly depending on fuel strata (e.g: canopy vs understory). There is also substantial variation across species, with sclerophyll species often showing lower foliar moisture content because of their high leaf mass per area. That is, because live fuel moisture content is expressed on a dry matter basis, the higher the dry matter, the lower the fuel moisture for a given amount of water (Jolly, Hadlow and Huguet, 2014; Nolan *et al.*, 2020).

Considering all this complexity, some studies document that fuel moisture dynamic transformations associated with major forest fires can occur rapidly for dead fuels (e.g. within days) and within several weeks to months for live fuels (Nolan *et al.*, 2016). In SE Australia (temperate or subtropical forest ecosystems), fire activity increases after live fuel moisture content drops below ca. 100 % and in Mediterranean ecosystem of California, the threshold drops to ca. 70%.

A pending question is how will climate change affect fuel moisture. There is some indication that dead and live fuel moisture will decline in North America under global warming (Flannigan *et al.*, 2016; Liu, 2017), but the patterns and magnitude are far from being resolved, particularly in Mediterranean environments. In order to bridge this knowledge gap, I examined variation in live and dead fuel moisture content during 2 years across an altitudinal gradient encompassing a large gradient in mean annual precipitation (395 mm to 933 mm) and temperature (6.1 °C to 15.1 °C). That is, I used a "simulated" climate change from the climatic variation across the altitudinal gradient. Ideally, one would select the same species across the gradient, but this was not possible given the wide variation in climatic conditions. Instead, I examined variation within Pine species, which, in turn, dominate across much of the burned area in the Western Mediterranean basin.

The key for accurate predictions on changes in fuel moisture lies on developing robust models that balance the trade-off between biological realism and computational intensity. In that sense, a semi-mechanistic model of dead fine fuel moisture, based on vapor pressure deficit, has been developed in recent years (Resco de Dios *et al.*, 2015). However, operational models of live fuel moisture are more difficult given the interplay between soil water availability and plant anatomy and physiology.

The recent observation that predawn water potential, an indicator of water availability in the rhizosphere, is a good predictor of live moisture content in Mediterranean woody plants (Nolan *et al.*, 2018) opens up the possibility of using soil moisture as an indicator of live fuel moisture content. The problem in using soil moisture as a predictor of live fuel moisture content is that soil moisture is often measured in the shallow soil layers, whereas Mediterranean plants can often tap water from deeper in the soil profile or even the groundwater. Furthermore, different functional groups (or fuel classes) use different water sources, further complicating the use of shallow water. However, shallow rooted shrubs, those most critical form the perspective of fire behavior, often rely on shallow water, particularly as the summer advances (Nolan *et al.*, 2018), which indicates the potential relevance of shallow water content for wildfire prediction.

The main objective of this study was to assess fuel moisture variation across different climatic gradient and to assess the potential of simple but semi-mechanistic prediction approaches. Here, I hypothesized that: (1) fuel moisture will decrease with mean annual temperature (MAT) and will increase with mean annual precipitation (MAP) and that the decrease of MAT and increase of MAP will be more marked in live (and particularly understory) fuels than for dead fuels across the fire season; (2) dead fuel moisture can be predicted from vapor pressure deficit; and (3) seasonal variation in live fuel moisture content will be larger for grasses than for shrubs or trees, and that in understory plants may be estimated from shallow soil moisture.

2. METHODS

2.1 Study area

Live and dead fuel moisture samples were collected from six plots located in different areas in NE Spain i.e. Ars, Tuixent, El Ges, Lladurs, Poblet and Maials. The mean annual temperature (MAT) varied from 6.1 ºC to 15.1ºC and mean annual precipitation (MAP) varied from 395 mm to 933 mm (Table 1). There were also differences in tree species and understory composition across sites (Table 1).

Table 1 Site information of study area

Sites	**Mean Annual Temperature (MAT)**	**Mean Annual Precipitation (MAP)**	**Tree species**	**Understory species**
Ars	6.1 ºC	876 mm	*Pinus sylvestris*	*Buxus sempervirens, Juniperus communis, Rhododendron ferrugineum, Rosmarinus officinalis, Tamarix*
Tuixent	7 ºC	933 mm	*Pinus sylvestris*	*Buxus sempervirens, Juniperus communis,*
El Ges	8.6 ºC	840 mm	*Pinus sylvestris*	*Buxus sempervirens, Juniperus communis*

Lladurs	10.4 ºC	708 mm	*Pinus sylvestris, Pinus nigra*	*Buxus sempervirens, Genista, Ilex aquifolium, Juniperus communis*
Poblet	13 ºC	542 mm	*Pinus pinaster*	*Cistus albidus, Erica arborea, Pistacia lentiscus* and *Tamarix*
Maials	15.1ºC	395 mm	*Pinus halepensis*	*Juniperus communis, J. oxycedrus, J. phoenicia, Lavandula officinalis, Pinus halepensis* and *Rosmarinus officinalis*

Additionally, micrometeorological stations measuring relative humidity (RH), temperature of air (Tair) and soil volumetric water content (VWC) were available at four sites: El Ges, Ars, Tuixent and Poblet. This data was used for modeling dead and live fuel moisture, as will be described below.

2.2 Data collection

Fuel moisture measurements were conducted during the fire seasons (May-August) of 2016 and 2017. Live fuel was collected by destructively sampling live foliage and small stems (≤ 3 mm). Live fuel was separately collected for canopy trees, understory shrubs and herbaceous fuels. Similarly, dead fuel particles were collected depending on their size i.e. 1 h (< 6 mm) and 10 h (6–25.4 mm) and position (suspended or on the soil surface). Five tins for each fuel class were collected. After collection, samples were stored immediately in a cooler, sealed with Parafilm and transported to the laboratory. In the laboratory, samples were freshly weighed and then placed in an oven at 105 °C for 48 h. Fuel moisture content (FMC, %) was then calculated as the difference in fresh weight (Fw) minus dry weight (Dw), relative to Dw.

$$\mathrm{FMC} = \frac{(\mathrm{Fw}-\mathrm{Dw})}{\mathrm{Dw}} 100 \qquad \text{(eq. 1)}$$

2.3 Data analysis

Statistical analyses were performed in R 3.4.1. (R Development Core Team, 2017). I examined spatial and temporal changes in tree fuel moisture, shrub fuel moisture, grass fuel moisture, surface 1h and 10h fuel moisture and suspended 1h and 10h fuel moisture across locations and dates with ANOVA analyses. Fuel moisture type was the response variable and date and location were the dependent variables. Then, I examined the effects of climatic drivers on fuel moisture. That is, I correlated mean annual precipitation (MAP) and mean annual temperature (MAT) with annual means of fuel moisture across strata and sites. I then used vapor pressure deficit to estimate dead fine fuel moisture according to the model of Resco de Dios *et al.* (2015) and I tested the relationships between observed and predicted dead fuel moisture using linear regression analyses. The prediction of dead fuel moisture was done using daily mean D (vapor pressure deficit) and it was compared with observed fuel moisture (i.e. suspended 10 h fuel moisture, suspended 1 h fuel moisture, surface 10 h fuel moisture and surface 1 h fuel moisture) separately. *D* was calculated using RH and Tair. In addition, simple correlation analyses were conducted to examine the correlation between soil moisture and live fuel moisture.

3. RESULTS

3.1 Fuel moisture variation in different locations

I observed significant variation in fuel moisture across location, date and their interaction (Tables 2 and 3). Averaged across the season, canopy fuel moisture content ranged from 91-98 % (2016-2017) at the driest site (Maials) to 131-120% at the wettest site (Ars) (Fig. 1a-b). Grass moisture varied between 70-62 % at the driest site (Maials) and 175-247 % at the wettest site (Ars) (Fig. 1c-d). Shrub moisture varied between 74-87% at the driest site (Maials) to 137-124 % at the wettest site (El Ges, Tuixent) (Fig. 1e-f).

Table 2 ANOVA of fuel moisture variation in 2016

Year 2016	Sum Sq	Df	F value	*P*
Tree fuel moisture				
Date	13227.5	22	6.4	5.58e-13 ***
Location	14494.8	4	39.1	< 2.2e-16 ***
Date × Location	4252.3	16	2.8	0.0004202 ***
Grass fuel moisture				
Date	92880	13	10.1	2.968e-13 ***
Location	27363	3	12.9	3.187e-07 ***
Date × Location	60746	13	6.6	5.559e-09 ***
Shrub fuel moisture				
Date	81387	23	7.7	< 2.2e-16 ***
Location	46686	4	25.4	< 2.2e-16 ***
Date × Location	43279	18	5.2	1.19e-10 ***
Surface 10 h fuel moisture				

Date	1550.1	21	14.9	< 2.2e-16 ***
Location	314.3	4	15.9	1.644e-10 ***
Date × Location	279.2	12	4.7	2.773e-06 ***
Surface 1 h fuel moisture				
Date	2616.8	22	19.6	< 2.2e-16 ***
Location	323.7	4	13.4	1.929e-09 ***
Date × Location	469.1	15	5.1	2.489e-08 ***
Suspended 10 h fuel moisture				
Date	451.2	14	17.2	1.985e-15 ***
Location	63.5	1	34	2.839e-07 ***
Date × Location	22.7	1	12.1	0.0009417 ***
Suspended 1 h fuel moisture				
Date	354.6	12	22.5	6.301e-16 ***
Location	34.6	3	8.8	8.837e-05 ***
Date × Location	9.9	2	3.7	0.0294 *

Signif. codes: '*' 0.001 '*' 0.05**

Table 3 ANOVA of fuel moisture variation in 2017

Year 2017	Sum Sq	Df	F value	*P*
Tree fuel moisture				
Date	5855.3	14	11.7	< 2.2e-16 ***
Location	5440.1	4	38.3	< 2.2e-16 ***
Date × Location	8092.9	20	11.4	< 2.2e-16 ***
Grass fuel moisture				
Date	359048	14	21.6	< 2.2e-16 ***
Location	89790	4	18.9	1.717e-12 ***
Date × Location	150990	20	6.3	5.849e-12 ***
Shrub fuel moisture				
Date	40411	14	35.8	< 2.2e-16 ***

Location	9591	4	29.7	< 2.2e-16 ***
Date × Location	11376	19	7.4	9.616e-14 ***
Surface 10 h fuel moisture				
Date	2045.5	13	37.4	< 2.2e-16 ***
Location	654.5	4	38.9	< 2.2e-16 ***
Date × Location	429	18	5.67	1.207e-09 ***
Surface 1 h fuel moisture				
Date	2455.8	13	65.5	< 2.2e-16 ***
Location	982.8	4	85.2	< 2.2e-16 ***
Date × Location	244.5	18	4.7	6.232e-08 ***
Suspended 10 h fuel moisture				
Date	704.2	14	37.4	< 2.2e-16 ***
Location	230.7	4	42.9	< 2.2e-16 ***
Date × Location	269.2	17	11.8	< 2.2e-16 ***
Suspended 1 h fuel moisture				
Date	891.8	14	51.7	< 2.2e-16 ***
Location	139.6	4	28.3	< 2.2e-16 ***
Date × Location	214.8	19	9.1	< 2.2e-16 ***

Signif. codes: '*' 0.001**

Averaged across the season, surface 10 h fuel moisture content ranged around 11 % at the driest site (El Ges, Maials) to 15-18 % at the wettest site (Ars) (2016-2017) (Fig. 2a-b). Similarly, for surface 1 fuel in 2016-2017, average fuel moisture content ranged from 10-11% at the driest site (El Ges, Tuixent) to 14-18 % at the wettest site (Tuixent, Ars) (Fig. 2c-d). Similarly, for suspended 10 h, average fuel moisture content ranged from 9-11% at the driest site (Maials, Lladurs) to around 15 % at the wettest site (Ars) (Fig. 3a-b). Also, for suspended 1 h in 2016-2017, average fuel moisture content ranged from 10-11 % at the driest site (Maials, Lladurs) to around 14 % at the wettest site (Lladurs, Ars) (Fig. 3c-d).

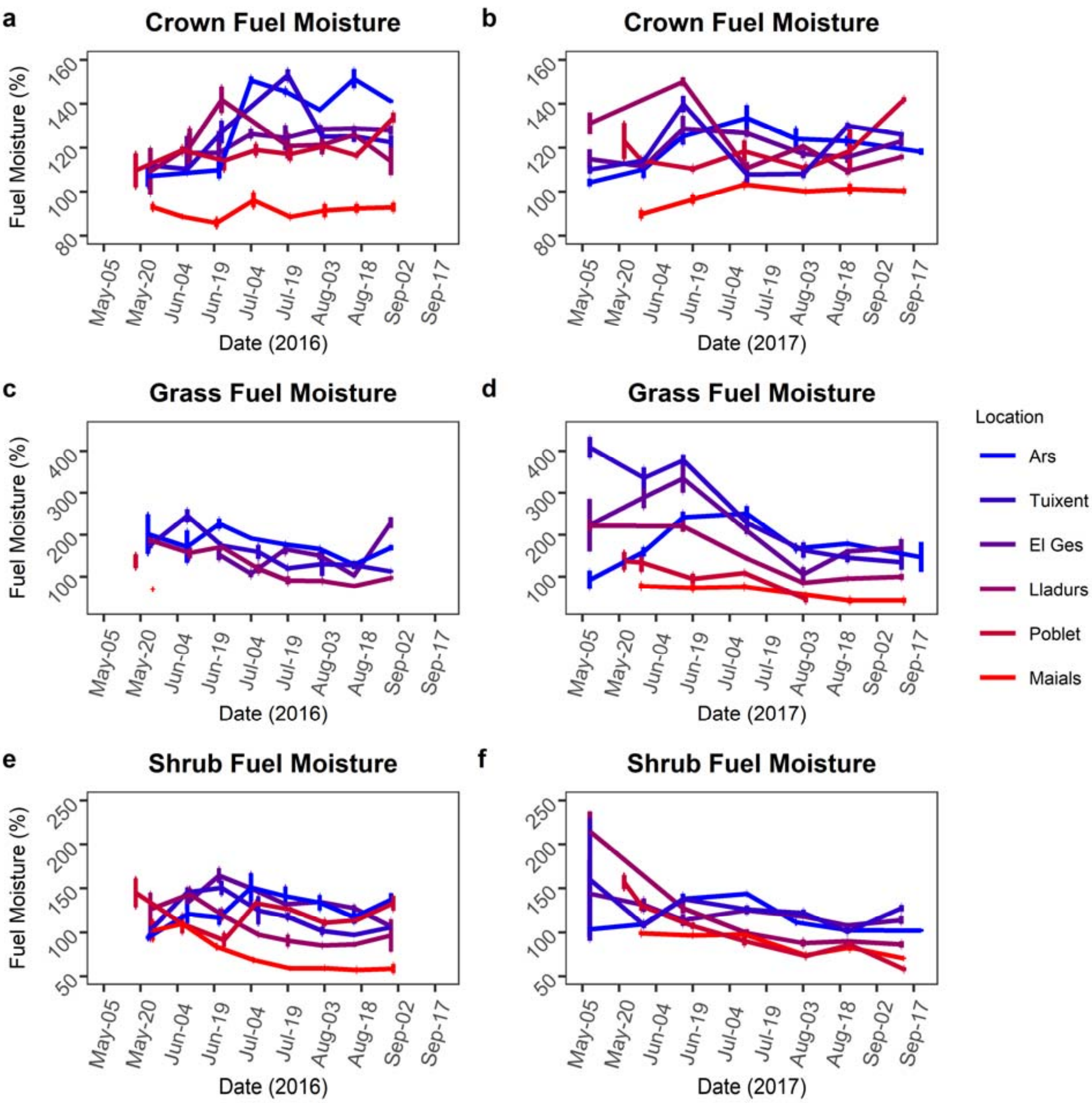

Figure 1 Live fuel moisture content across fuel strata and sites in 2016 and 2017. Note that y-axis scale is different in each strata.

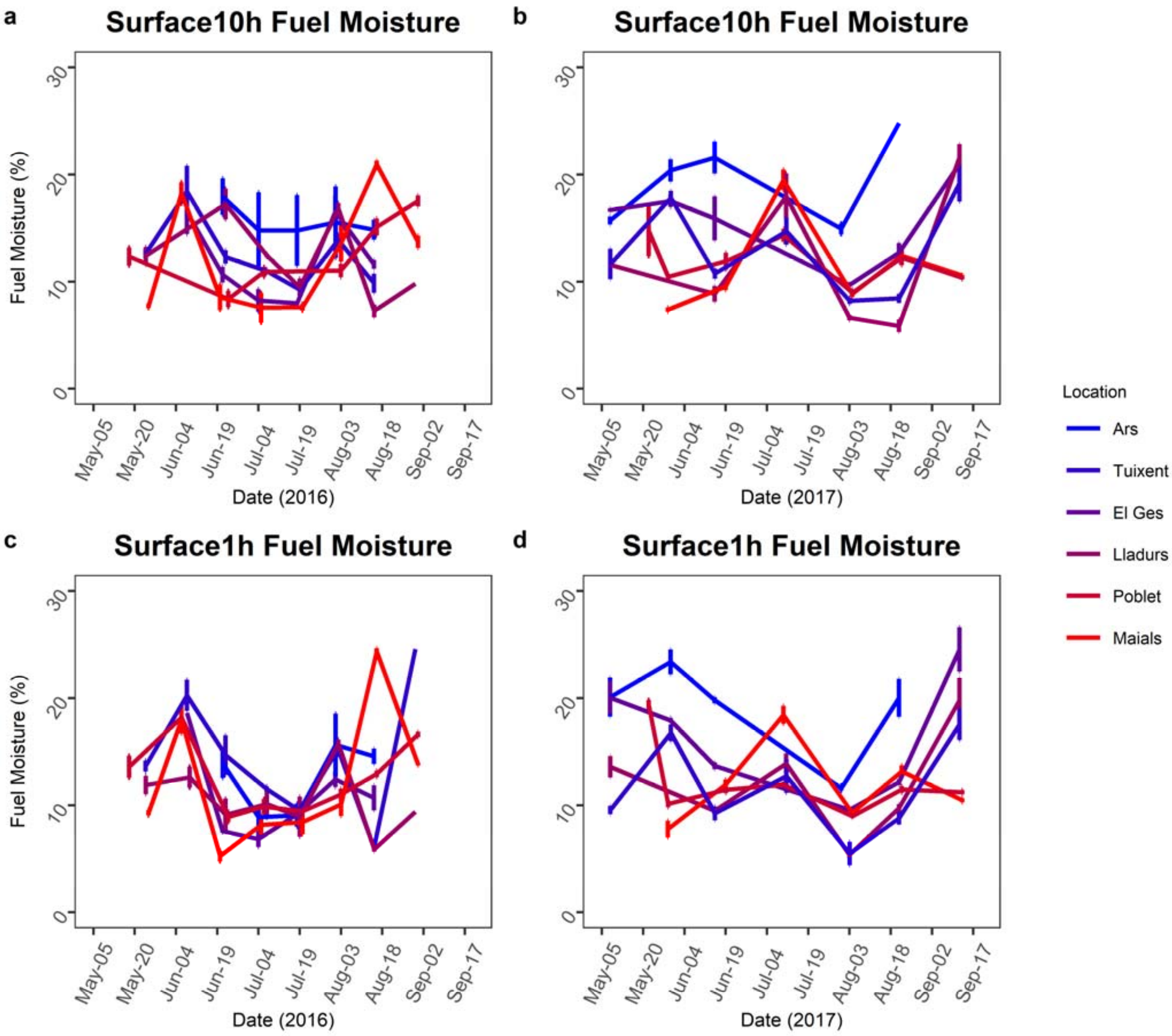

Figure 2 Surface dead fuel moisture content across sites in 2016 and 2017.

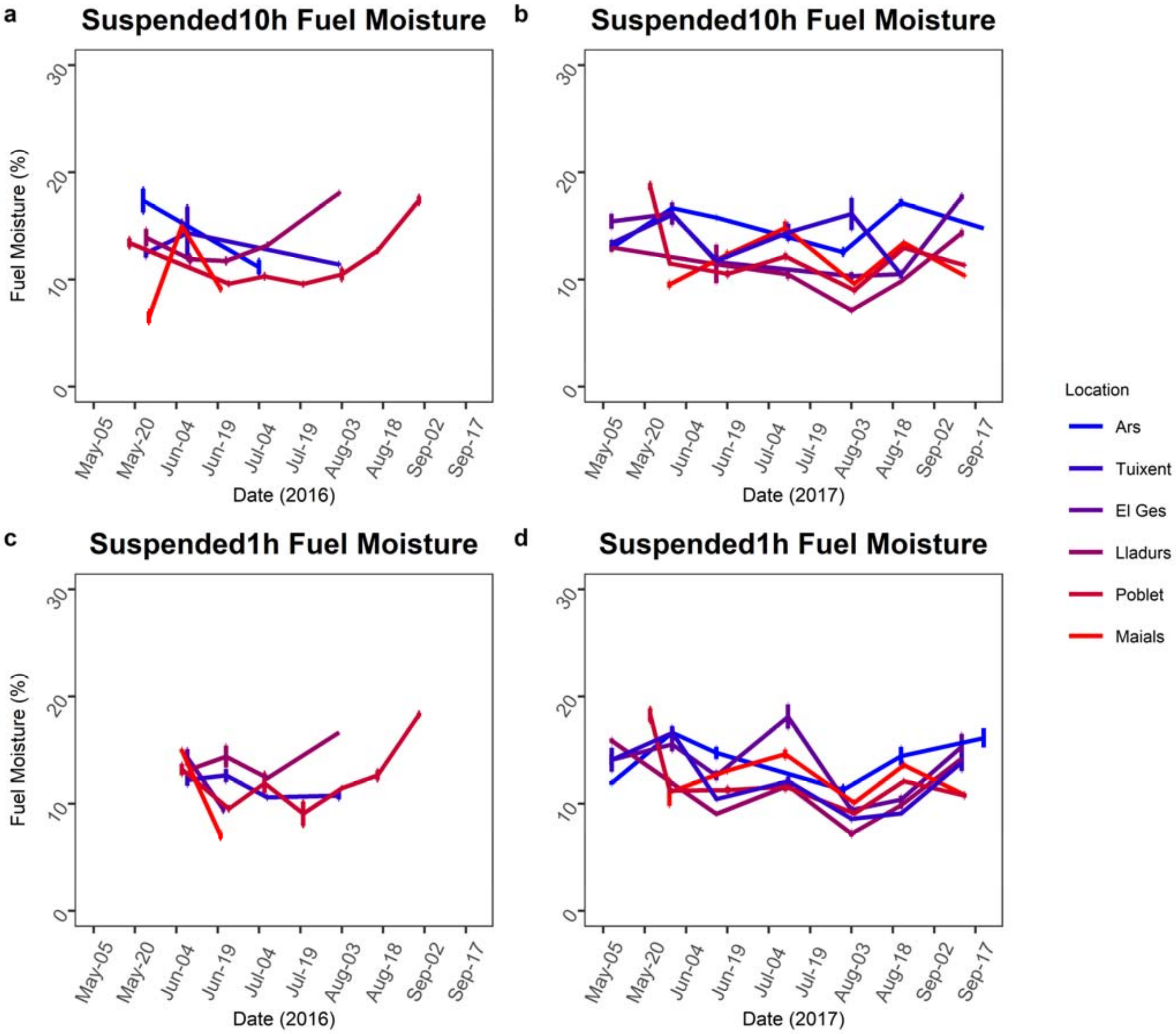

Figure 3 Suspended dead fuel moisture content across sites in 2016 and 2017

I observed that variation in live moisture content increased from trees to grass and to shrubs. That is, the coefficient of variation (CV) in crown fuel, grass fuel and shrub fuel was 13.2%, 42.4% and 25.4%, respectively. Regarding dead fuel moisture variation, CV was 36.0%, 34.9%, 23.0% and 24.0% for surface 1 h, surface 10 h, suspended 1 and suspended 10 h fuel moisture, respectively

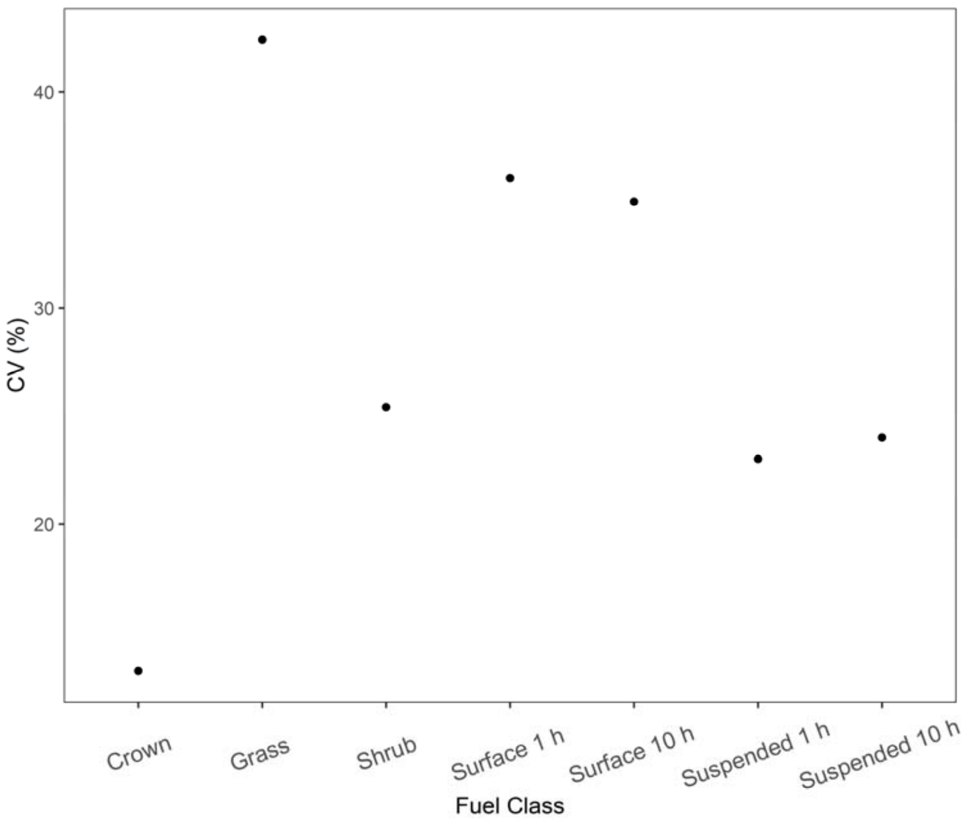

Figure 4 Coefficient of variation (CV) of live and dead fuel moisture

3.2 Effects of climate on fuel moisture content

While comparing average fuel moisture with climatic data (i.e. mean annual temperature and mean annual precipitation) across locations there was a major effect of mean annual temperature (MAT) and mean annual precipitation (MAP) over live fuel moisture (Figures 5 and 6). In live fuels, there was a negative effect of MAT (Fig. 5) over grass fuel moisture (p=0.02, R^2=0.76 (2016); p=0.005, R^2=0.88 (2017)), crown fuel moisture (p=0.02, R^2=0.74 (2016); p=0.07, R^2=0.60 (2017)) and shrub fuel moisture (p=0.05, R^2=0.63 (2016); p=0.004, R^2=0.89 (2017)). Similarly, there was a positive effect of MAP (Fig. 6) over grass fuel moisture (p=0.03, R^2=0.71 (2016); p=0.0006, R^2=0.95 (2017)), crown fuel moisture (p=0.02, R^2=0.74 (2016); p=0.05, R^2=0.64 (2017)) and shrub fuel moisture (p=0.04, R^2=0.67 (2016); p=0.002, R^2=0.92 (2017)). However, there was no clear trend between dead fuel moisture and mean annual temperature or mean annual precipitation (P>0.05, *not shown*).

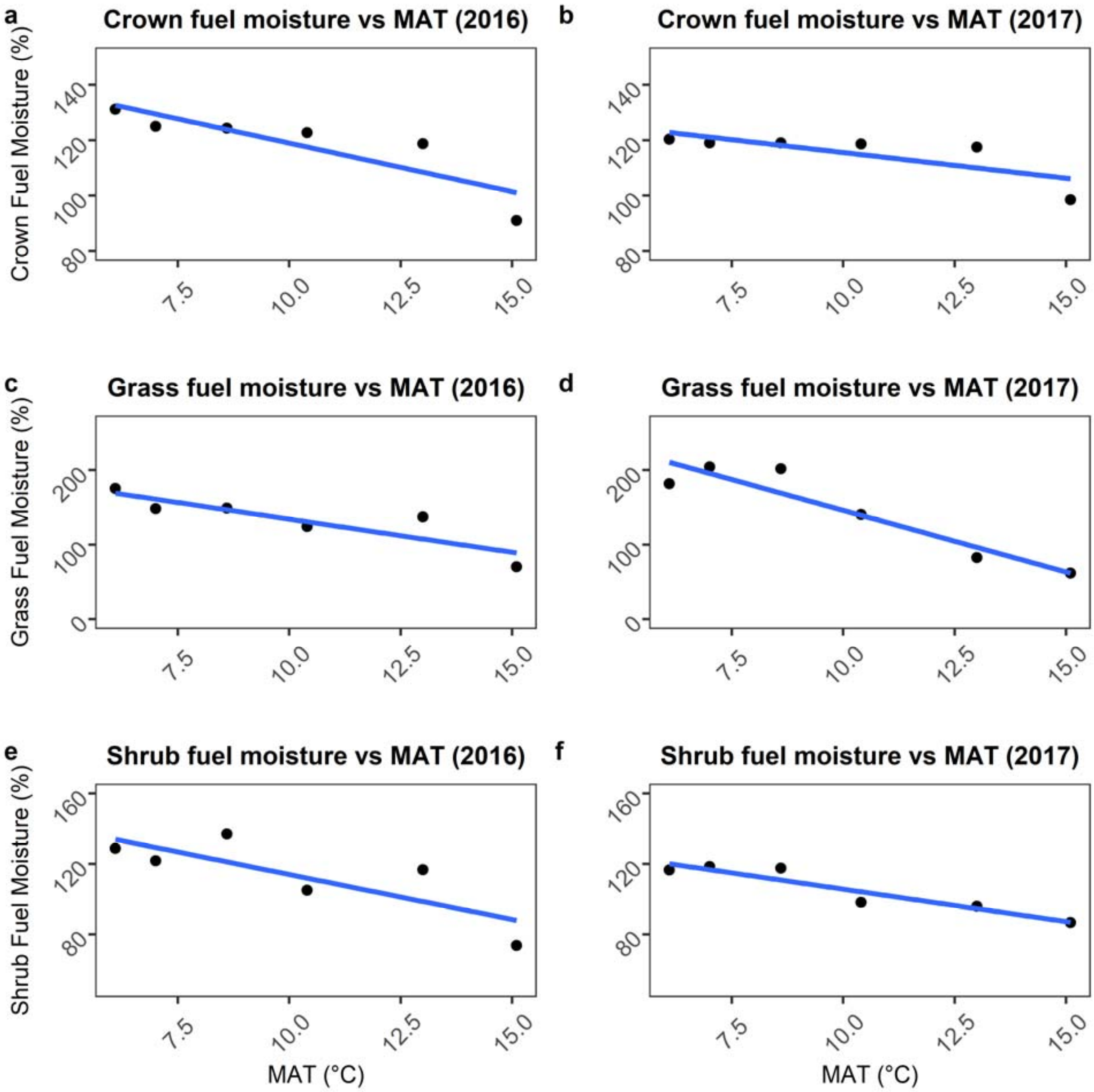

Figure 5 Live fuel moisture content and mean annual temperature (MAT) across sites. Note that y-axis scale is different in each strata.

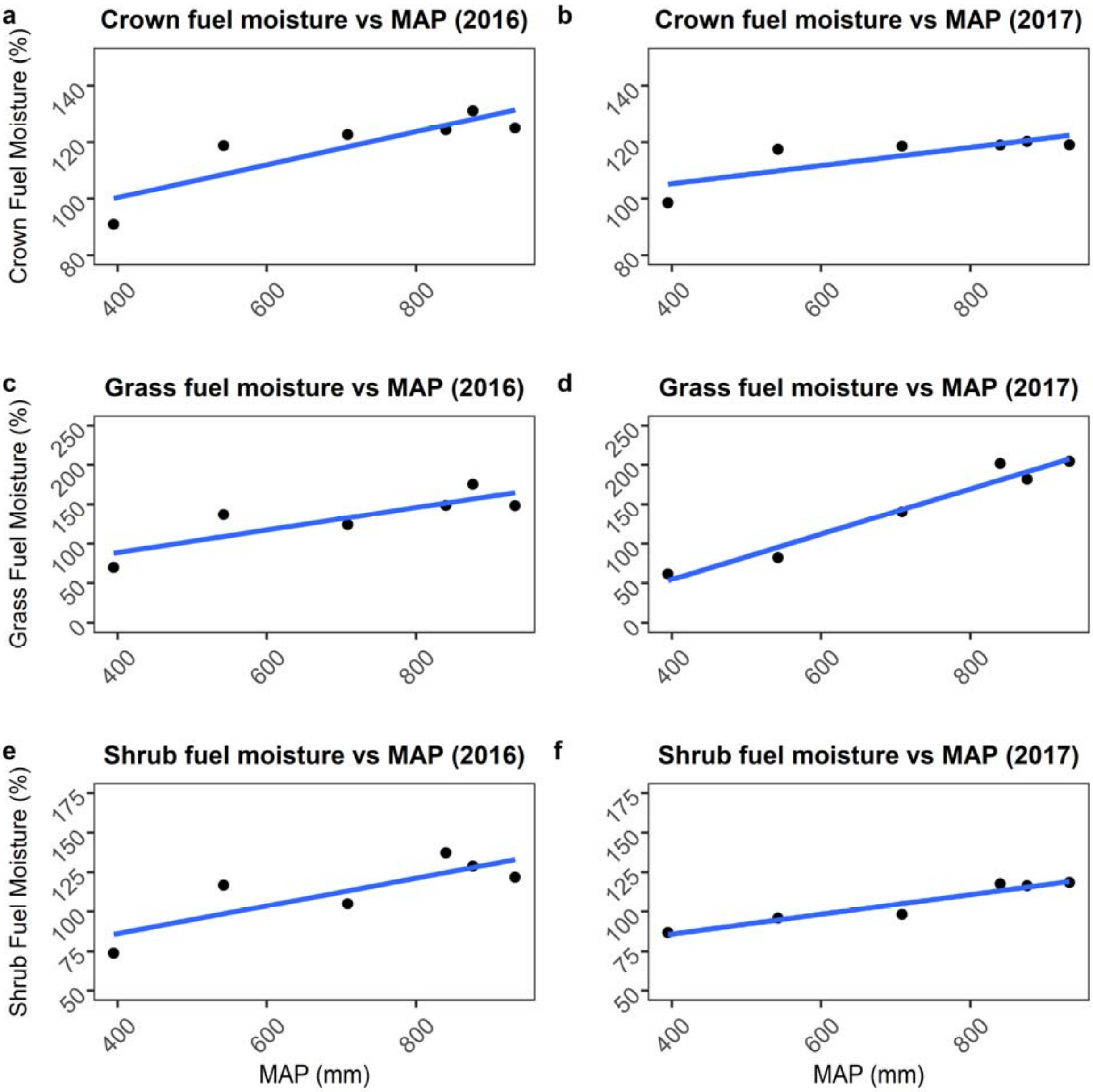

Figure 6 Live fuel moisture content and mean annual precipitation (MAP) across the sites. Note that y-axis scale is different in each strata.

3.3 Comparing observed versus predicted dead fuel moisture

I conducted a regression between observed and predicted dead fuel moisture (FM_D) separately for the data of both years 2016 and 2017 (Fig. 7). The relationship between observed and predicted was always significant for 1h and 10h surface and suspended dead fuels ($p<0.05$, $0.26<R^2<0.78$) but insignificant for surface 10 h for the year 2016 ($p=0.1$). However, I observed that predictions from FM_D consistently over-predicted dead fuel moisture content. That is, the slope of the observed versus predicted varied between 0.26 and 0.60, depending on fuel type, indicating that FM_D predictions were between 74 and 40 % larger than the actual data values (Fig. 7).

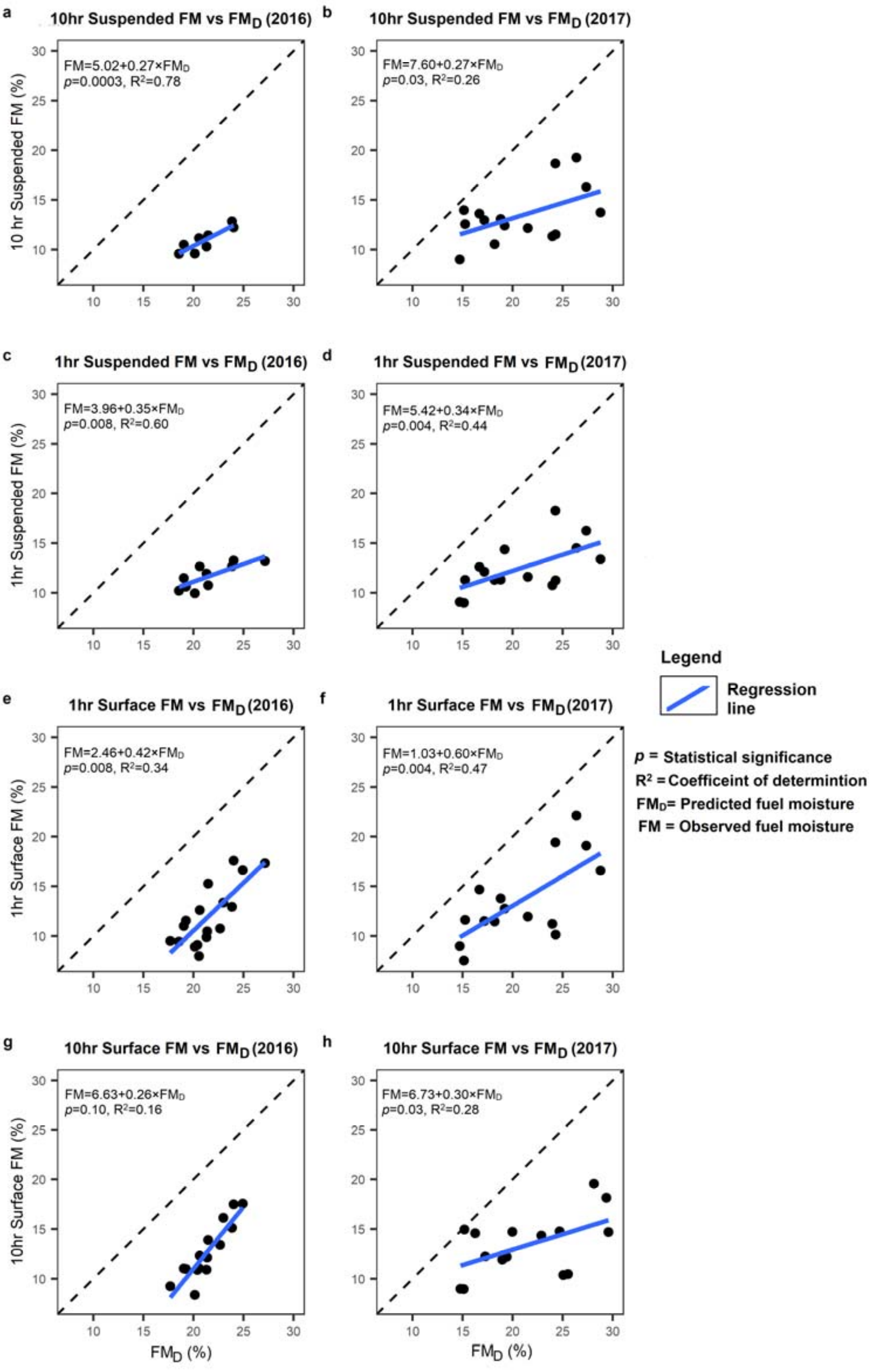

Figure 7 Comparing observed vs predicted dead fuel moisture across dead fuel moisture strata.

3.3 Correlation between soil moisture and live fuel moisture

I conducted a regression between soil volumetric water content (VWC) and live fuel moisture separately for 2016 and 2017 (Fig. 8). For 2016 I observed that grass fuel moisture and crown fuel moisture were positively and negatively correlated with VWC ($p = 0.04$; $R^2 = 0.3$ for grass and $p = 0.01$; $R^2 = 0.3$ for tree), but the relationship was statistically insignificant ($p = 0.86$) with shrub fuel moisture. In the year 2017, shrub fuel moisture and grass fuel moisture were both positively correlated with VWC ($p = 0.01$; $R^2 = 0.37$ for shrub and $p = 0.07$; $R^2 = 0.21$ for grass), but the relationship was statistically insignificant ($p = 0.5$) with crown fuel moisture.

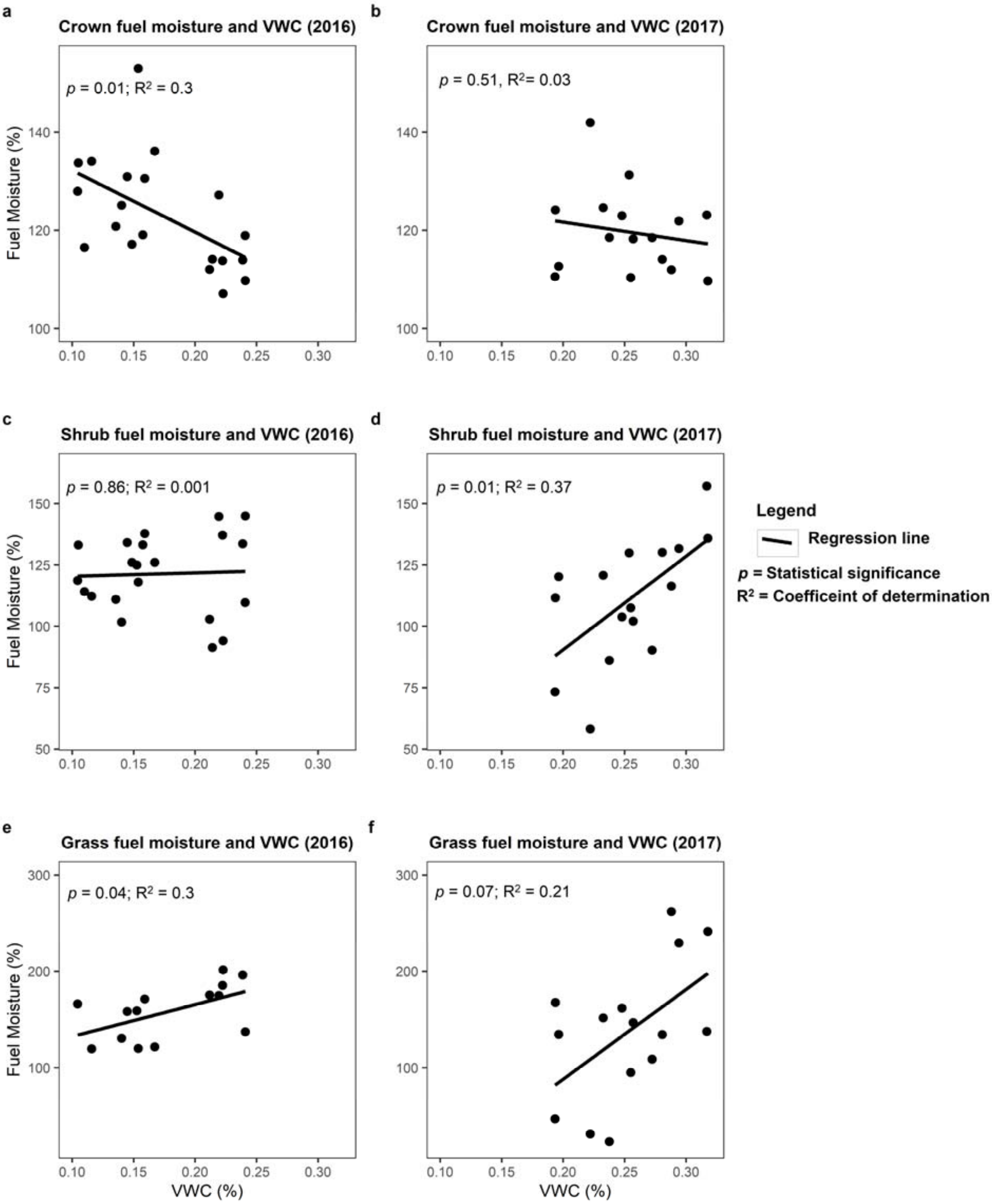

Figure 8 Correlation between soil moisture and live fuel moisture across live fuel moisture strata in 2016 and 2017. Note that y-axis scale is different in each strata.

4. DISCUSSION

I observed substantial variation in fuel moisture across a climatic gradient in the pine forests of Catalonia, although there was a hierarchical degree of controls depending upon the scale and strata of interest. MAT and MAP exerted a primary influence over live fuel moisture such that colder and rainier sites showed higher moisture. Seasonal variation in moisture content was additionally driven by soil moisture, particularly in grasses. Dead fuel moisture content, on the other hand, was mostly driven by short-term weather fluctuations, as indicated by its dependence on vapor pressure deficient.

4.1 Variation in live fuel moisture

Fuel moisture varied significantly across locations. Grass fuels showed the highest average fuel moisture, but also the highest variation and tree moisture was most constant across time. Fuel moisture content varies within species due to phenological and environmental conditions and among species according to both morphological and physiological strategies adopted by plants to regulate water content (Pellizzaro et al., 2017). Here, I observed that variation within the species *Pinus sylvestris* followed a clear climatic trend. This pattern was also apparent when comparing differences across the different pine species (*Pinus sylvestris*, *Pinus pinaster*, *Pinus halepensis*).

My results thus indicate a high climatic sensitivity of live fuel moisture content to changes MAT and MAP. With this dataset, I estimated that an increase in 1 °C MAT led, on average, to a 6.3% decrease in live fuel moisture content. A decrease in 100 mm of MAP led to an average decrease of 7.5% in live fuel moisture increase. This indicates that, under climate change, the rise in temperature and decline in precipitation will lead to a decrease in fuel moisture, consequently enhancing forest flammability. This effect was more marked in grasses, where climatic sensitivity strongly influenced the fuel moisture. A rise in 1 ºC MAT led to an average 11.3% decrease in grass fuel moisture and a decrease in 100 mm of MAP led to an average drop of 15.2 % grass fuel moisture. Similarly, shrub fuels showed an average 4.2 % decrease in fuel moisture with increasing 1 ºC MAT and on a 4.3% decrease in fuel moisture with decreases in 100 mm of MAP. Crown fuels were least sensitive with an average 3.4 % decrease in fuel moisture after a 1 ºC increase in MAT and a 3 % decrease in fuel moisture per every 100 mm decline of MAP.

My results indicate that shallow soil moisture content is a significant driver only of grass moisture content: there was a positive correlation across both years. This was expected from the shallow rooting system of grasses. I observed that the correlation between shrub and shallow VWC was significant in the wettest year, but not in the driest year. This likely results from indicates a shift in water sources used by the shrubs: from shallow water content under high soil moisture to deeper water content in drier periods (Nolan *et al.*, 2018). Consequently, shallow VWC is only a partial indicator of fuel moisture in shrubs. I also observed that shallow VWC is not a reliable indicator of tree moisture: the relationship was not significant in one year and negative in the other year. No known mechanism can explain a negative relationship between tree moisture and VWC, which I interpret as an indicator of a spurious correlation. Such lack of correlation between shallow moisture content and tree moisture likely reflects the deep rooting system of trees.

4.2 Variation in dead fuel moisture

I observed significant differences in dead fuel moisture across sites, dates and their interaction. There was no clear trend between dead fuel moisture and mean annual temperature or precipitation (P>0.05). Dead fuel moisture content was driven by short-term weather fluctuations, as indicated by its dependence on vapor pressure deficient. According to (Boer *et al.*, 2017), fires in Portugal only occur once dead fuel moisture is below 26%, while the majority of burned area in Portugal occurs below 18% and mega-fires occur below 12%. In our study, in the years 2016 and 2017, all the sites showed dead fuel moisture content below these critical thresholds.

The regression between different dead fuel moisture with predicted dead fuel moisture (obtained from mean vapor pressure deficient (*D*)) was statistically significant in most of the cases and the linear relationship varied from low to high. So, dead fuel moisture can be predicted from the vapor pressure deficient using the simple formula derived by Resco de Dios *et al.* (2015). The simplicity of this semi-mechanistic prediction model makes it suitable for a range of fire management applications. However, this model has a trend for over prediction. This model was developed for Australian forests and it may thus require a re-parameterization to correct for this problem.

5. CONCLUSION

Fuel moisture varied across locations. Variation in crown fuels was smaller than in other fuel strata. Average live fuel moisture content decreased with increasing mean annual temperature and with decreasing mean annual precipitation. However, there was no clear trend between dead fuel moisture and mean annual temperature or mean annual precipitation. The regression between different dead fuel moisture with predicted dead fuel moisture showed low to high linear relationship. Soil moisture content was a significant driver only of grass moisture content. This study documents how changing climate and weather impact fuel moisture, with potential carry-over effects on forest fire behavior and forest flammability.

6. REFERENCES

Argañaraz, J. P. *et al.* (2018) 'Determining fuel moisture thresholds to assess wildfire hazard: A contribution to an operational early warning system', *PLoS ONE*, 13(10), pp. 1–19. doi: 10.1371/journal.pone.0204889.

Bodi, M. B. *et al.* (2012) 'A review of fire effects on vegetation and soil in the mediterranean basin', *Boletin de la Asociacion de Geografos Espanoles*, (58), pp. 439–442.

Boer, M. M. *et al.* (2017) 'Changing Weather Extremes Call for Early Warning of Potential for Catastrophic Fire', *Earth's Future*, 5(12), pp. 1196–1202. doi: 10.1002/2017EF000657.

Bradstock, R. A. (2010) 'A biogeographic model of fire regimes in Australia: Current and future implications', *Global Ecology and Biogeography*, 19(2), pp. 145–158. doi: 10.1111/j.1466-8238.2009.00512.x.

Chen, Z. (2006) 'Effects of fire on major forest ecosystem processes: An overview', *Chinese Journal of Applied Ecology*, 17(9), pp. 1726–1732.

Chuvieco, E., Aguado, I. and Dimitrakopoulos, A. P. (2004) 'Conversion of fuel moisture content values to ignition potential for integrated fire danger assessment', *Canadian Journal of Forest Research*, 34(11), pp. 2284–2293. doi: 10.1139/X04-101.

Flannigan, M. D. *et al.* (2016) 'Fuel moisture sensitivity to temperature and precipitation: climate change implications', *Climatic Change*, 134(1–2), pp. 59–71. doi: 10.1007/s10584-015-1521-0.

Jolly, W. M., Hadlow, A. M. and Huguet, K. (2014) 'De-coupling seasonal changes in water content and dry matter to predict live conifer foliar moisture content', *International Journal of Wildland Fire*, 23(4), pp. 480–489. doi: 10.1071/WF13127.

Liu, Y. (2017) 'Responses of dead forest fuel moisture to climate change', *Ecohydrology*, 10(2), pp. 1–10. doi: 10.1002/eco.1760.

Moriondo, M. *et al.* (2006) 'Potential impact of climate change on fire risk in the

Mediterranean area', *Climate Research*, 31(1), pp. 85–95. doi: 10.3354/cr031085.

Neary, D. G., Ryan, K. C. and DeBano, L. F. (eds) (2005) *Wildland Fire in Ecosystems: Effects of Fire on Soil and Water*. United States Department of Agriculture. Available at: https://www.fs.fed.us/rm/pubs/rmrs_gtr042_4.pdf.

Nolan, R. H. *et al.* (2016) 'Large-scale, dynamic transformations in fuel moisture drive wildfire activity across southeastern Australia', *Geophysical Research Letters*, 43(9), pp. 4229–4238. doi: 10.1002/2016GL068614.

Nolan, R. H. *et al.* (2018) 'Physiological drought responses improve predictions of live fuel moisture dynamics in a Mediterranean forest', *Agricultural and Forest Meteorology*. Elsevier, 263(September), pp. 417–427. doi: 10.1016/j.agrformet.2018.09.011.

Nolan, R. H. *et al.* (2020) 'Linking Forest Flammability and Plant Vulnerability to Drought', *Forests*, 11(7), p. 779. doi: 10.3390/f11070779.

Pausas, J. G. and Vallejo, V. R. (1999) 'The role of fire in European Mediterranean ecosystems', in Chuvieco, E. (ed.) *Remote Sensing of Large Wildfires*. 1st edn. Berlin: Springer-Verlag Berlin Heidelberg, pp. 3–16. doi: 10.1007/978-3-642-60164-4_2.

Pellizzaro, G. *et al.* (2017) 'Effects of drought season length on live moisture content dynamic in Mediterranean shrubs: 8 years of data', in *EGU General Assembly*.

Qi, Y. *et al.* (2012) 'Monitoring live fuel moisture using soil moisture and remote sensing proxies', *Fire Ecology*, 8(3), pp. 71–87. doi: 10.4996/fireecology.0803071.

Resco de Dios, V. *et al.* (2015) 'A semi-mechanistic model for predicting the moisture content of fine litter', *Agricultural and Forest Meteorology*. Elsevier B.V., 203, pp. 64–73. doi: 10.1016/j.agrformet.2015.01.002.

Resco De Dios, V. (2020) *Plant-Fire Interactions Applying Ecophysiology to Wildfire Management*. Springer.

Turco, M. *et al.* (2016) 'Decreasing fires in mediterranean Europe', *PLoS ONE*, 11(3). doi: 10.1371/journal.pone.0150663.