Professional Master's Project Report:

Determination of Springtime Foliar Moisture Content in Pitch Pine (*Pinus rigida*)

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Abstract

The flammability of live foliage of conifers is linearly related to foliar moisture content (FMC) which is acknowledged as a key factor in the development of crown fire. Conifer FMC typically reaches a minimum in mid-spring, which corresponds to the time of year when crown fires in closed-canopy pitch pine (*Pinus rigida*) stands in the northeastern United States have been most prevalent. I investigated this period of pitch pine crown fire susceptibility by analyzing six years of FMC data for a Montague, Massachusetts pine barren. After stable dormant-season values, FMC declined following a 2nd-order polynomial function of the heat sum in air (the cumulative sum of mean daily air temperature minus 7 °C), resulting in a minimum FMC value of 109 ± 6 % and 99 ± 4 % at heat sum values of 121 ± 29 °C-days and 108 ± 23 °C-days for 1-year-old and 2-year-old foliage, respectively. After attaining this minimum, FMC rebounded linearly at the rate of 0.2 % per day. When applied to other pitch pine forests, fire managers can track the development of depressed FMC by adding the heat sum in air to their daily weather observations. Based on the Montague data, minimum FMC occurs when the heat sums in soil and air are approximately equal suggesting that FMC decline is a consequence of a lag between above- and below-ground plant phenology due to delayed soil warming.

Introduction

The foliar moisture content (FMC) of live foliage of conifers is known to be a key factor in the development and propagation of crown fire (Van Wagner 1977). Specifically, the time to ignition for live foliage is linearly related to FMC (Dimitrakopoulos and Papaioannou 2001, Xanthopoulos and Wakimoto 1992[1]), so drier foliage is more susceptible to combustion from a given surface fire. Most evergreen conifers in temperate and boreal regions of North America experience a pronounced annual minimum FMC near the start of the growing season (Johnson 1966, Chrosciewicz 1986, Keyes 2006). In the northeastern United States, spring coincides with weather conditions that increase the potential

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[1] At fixed temperature, the exponential relationships reported in equations 1-3 by Xanthopoulos and Wakimoto (1992) are approximately linear given that $C*\exp(k*x) \approx C*(1+k*x)$ for small values of k.

for crown fire development (i.e. low relative humidities and high wind speeds). Not surprisingly, crown fires in closed-canopy pitch pine (*Pinus rigida*) stands have been most prevalent at this time (Duveneck and Patterson 2007). Given this synchrony of low FMC and hazardous fire weather conditions encountered in the Northeast, fire managers would benefit from being able to predict when low FMC occurs.

FMC is not easily obtained. Direct sampling of foliage requires time to collect, process, and analyze samples, and results may only have limited spatial relevance across a given landscape. Alternatives exist, including electronic devices that measure FMC quickly on site and empirical relationships with remote sensing data (e.g. Toomey and Vierling 2005), but the cost, extent and/or complexity of these options may be impractical, especially in the fragmented pine barrens of the Northeast. Establishing a relationship between FMC and a readily-available or easily-calculated environmental parameter would offer fire managers a straightforward and inexpensive means of estimating FMC in pitch pine.

The springtime seasonality of the decline in conifer FMC suggests a connection to the onset of growing season conditions. A first approximation of this phenomenon is to assume that the pattern of FMC decline repeats annually on a calendar-date basis. Some, improving slightly on this assumption, have accounted for variation in the onset of spring as a function of latitude (W.A. Patterson III, personal communication, January 12, 2009). This, however, is inconsistent with the annual variability observed in this study where latitude is a constant. An alternative hypothesis suggests that annual variability reflects year-to-year variation in the onset and development of the growing season (Chrosciewicz 1986). A refinement of this would characterize each growing season on a day-by-day basis accounting for daily fluctuations in temperature and hence the rate of growing season development. This is accomplished by calculating a daily cumulative heat sum in air (cumulative sum of the mean daily air temperature minus a threshold temperature) which is a good predictor for above-ground springtime plant phonological development (Warhol 1999).

Given the above, I investigated, over a six-year period, the relationships between FMC and time since onset of the growing season and the heat sum in air at the Montague Plains Wildlife Management Area, Montague, Massachusetts.

Methods

Site Description

Sampling was conducted in a pitch pine stand in the Montague Plains Wildlife Management Area (the Montague Plains) in Montague, Massachusetts (42° 34'N, 72° 31' W) from February 2003 through October 2008. The Montague Plains are a level glacial outwash delta with acidic, excessively well-drained, sandy and gravelly soils (Hinckley or Windsor soil series) approximately 100 m above sea level (Motzkin et al. 1996). Pitch pine- dominated forests occur on sites previously plowed for agriculture (Motzkin et al. 1996), with pitch pine comprising >85% of the mean basal area (Clark and Patterson 2003). Stand characteristics in 2003 included a basal area of 33.1 m^2/ha, a stem density of 1,782 trees/ha, average canopy cover of 92%, and a stand origin date in the mid-1960's (Duveneck 2005). Mean annual precipitation ranges from 107 to 112 cm. Mean annual daily temperature is 7.8°C (Clark and Patterson 2003). Extreme temperatures have been observed throughout the growing season, including below-freezing nighttime temperatures and daytime temperatures typically 2-3°C higher than the regional average.

Foliage Sampling and FMC Determination

Sampling intervals ranged from 7-14 days just before and during the start of the growing season (March-May), to 2-4 weeks during the rest of the growing season, and 6-8 weeks during the winter. Needles were collected after 12:00 PM on days without precipitation, allowing for evaporation of overnight fog or dew and any previous day's precipitation suspended in the foliage. Needles were not collected when snow and/or ice were suspended in the canopy. Two branches were pruned from each of six different codominant pines occurring within closed-canopy stands. Trees with two generations of needles were selected over those with only one generation during the winter and spring, with the exception of the year 2003 when only the most recent year's needles were harvested. The pruning equipment had a vertical limitation of ~7.5m., so only trees with sufficient live foliage at or below this height were sampled. Branches from the base of the canopy are appropriate for this study because they comprise the ladder fuels necessary for torching and crown fire development.

For each branch, needles were separated from the stem according to the year they were formed (i.e. the needle generation) and placed into labeled, zip-lock bags. Fresh samples (typically 10-100 g) were weighed to the nearest 0.1 g on the day of collection and dried to a constant weight at 70°C. Percent FMC (dry weight basis) was calculated, with individual FMC values averaged across branch pairs and then across all six trees to obtain the mean moisture content for each generation of foliage sampled. Outliers greater than three standard deviations from the mean were disregarded.

Heat Sum Calculation

Air and soil temperatures were monitored on-site using an automated weather station (Vantage Pro2 with Temperature Probe, Davis Instruments Corp., Hayward, CA) beginning 8 April 2008. Mean daily temperatures were calculated as the average of hourly temperatures. Soil temperature was measured 10 cm below the soil surface.

Off-site, daily air temperature data were acquired from the National Climatic Data Center (NCDC) website (http://www.ncdc.noaa.gov/oa/ncdc.html, last accessed 23 December 2008) for the nearest National Weather Service (NWS) recording station at Orange Municipal Airport in Orange, MA (approximately 20 km east of the MPWMA and ~60 m higher in elevation), and daily 10-cm soil temperature data were obtained from the Harvard Forest online data archive for the Fisher Meteorological Station (http://harvardforest.fas.harvard.edu/data/p00/hf001/HF001-data.html, last accessed 29 December 2008) in Petersham, MA (approximately 30 km ESE of the MPWMA and ~240 m higher in elevation). Data were downloaded for the months of March-June for the years 2003-2008 (i.e. the study period), with missing values replaced with interpolated values using available data on adjacent days.

Off-site air and soil temperatures were correlated with on-site data for the period of 8 April 2008 through 21 June 2008. The resulting correlation functions were used to estimate on-site air and soil temperatures for the full study period. For consistency across years, measured on-site temperatures for 2008 were replaced with the estimated temperatures.

The heat sums in air and soil (AIRSUM and SOILSUM) were computed using a temperature threshold of +7°C, which corresponds approximately to growing season conditions favorable for plant growth (Warhol 1999). Beginning with the first day in March or April with a mean daily air or soil temperature greater than +7.0°C, daily heat sum increments were calculated and summed (e.g., a day with a mean daily temperature, air or soil, of +9.5°C would yield a heat sum increment of 2.5°C-days which would be added to the previous day's cumulative sum). A power function relationship was derived to relate SOILSUM to AIRSUM.

For each year in the study period, the first day of the growing season was identified as the first day with a non-zero AIRSUM. This first day was designated as time zero, with each successive calendar day increasing by one day. The time since the onset of the growing season as an analysis variable is referred to as TIME. A 2nd-order polynomial relationship was derived to relate TIME to AIRSUM.

Analysis

One-year-old (1-YR) and 2-year-old (2-YR) foliage generations were analyzed separately, with the analysis for each generation divided as: 1) the period of decline and minimum FMC, which was analyzed as a function of the AIRSUM; and 2) the period of FMC rebound, which was analyzed as a function of TIME.

For the decline and minimum period, the condition of AIRSUM $\leq$ 200 ºC-days was subjectively imposed, encompassing all data during the decline and in the vicinity of the minimum (Figure 1). The data were pooled across sample years for each generation and fitted with 2nd-order polynomials using SAS statistical analysis software (SAS 9.1.3, the SAS Institute Inc., Cary, NC). The coordinates of the minima and propagation of standard error were hand-calculated using the fit parameters and statistics generated by SAS.

For the rebound period, a lower cutoff of TIME > 48 days was calculated using results from the above analysis, and an upper cutoff of TIME < 150 days (approx. 5 months after the onset of the growing season, typically including FMC measurements through mid-August) was subjectively imposed (Figure 2). The data were pooled across sample years for each generation and fitted with a linear function using SAS.

Results

All fits were significant (P<.0001, Figures 3 and 4), explaining 74% and 69% of the variation in FMC for the decline period and 60% and 65% of the variation for the rebound period for the 1-YR and 2-YR generations, respectively. The polynomial fits for the decline and minimum period (Figure 3) yielded minimum FMC values of 109 ± 6% and 99 ± 4% occurring at AIRSUM values of 121 ± 29°C-days and 108 ± 23°C-days (± SEM) for 1-YR and 2-YR foliage, respectively. Linear fits for the rebound period (Figure 4) show that FMC rebounds at the rate of approximately 0.2% per day following the occurrence of the minimum. Fitting functions are in good agreement at the minimum with 1-YR FMC values of 109% from both periods, and 2-YR FMC values of 99% and 100% for the decline and rebound periods, respectively.

Using the power function relationship between AIRSUM and SOILSUM (Figure 5), the corresponding mean SOILSUM values at the minima were computed as 133°C-days and 114°C-days. Similarly, using the 2nd-order polynomial relationships between TIME and AIRSUM (Figure 6), equivalent values of TIME were calculated and averaged for the two minima, which yielded the analytic cutoff of 48 days mentioned above.

To provide a reference by which to measure the significance of the FMC decline, I determined the mean FMC for each needle generation during the dormant season (defined as October 30 through the first day of the growing season as determined by the heat sum calculations). Dormant season values were 138 ± 1% for 1-YR foliage and 122 ± 1% for 2-YR foliage.

Discussion

Previously unreported in the literature, minimum springtime FMC values for pitch pine provide estimates of the worst-case canopy-fuel conditions. These may serve as inputs to crown fire modeling programs whose outputs may help guide silvicultural treatments to meet canopy fuel management objectives to reduce the hazard of crown fires (Duveneck and Patterson 2007). Relative proportions of 1-YR and 2-YR foliage vary by location and even from tree to tree

Although 2-YR FMC routinely drops below 100% in the spring, the relative abundance of needle generations varies by location and from tree to tree. For example, in the Montague Plains only a small subset of pitch pine trees within the sample stand held both 1-YR and 2-YR needles during the study period, and when present, 2-YR needles were markedly more sparse than 1-YR needles. So, in the Montague Plains, 1-YR needles constitute the majority of live foliage mass, and the corresponding 1-YR FMC is most relevant for crown fire propagation. This is consistent with the definition of canopy bulk density (CBD), a stand-level attribute that quantifies live crown fuels to predict crown fire rates of spread (Van Wagner 1977). CBD is dominated by the weight live foliage (Duveneck and Patterson 2007), so the most pertinent FMC value is that which corresponds to the majority of the live canopy fuels. When both needle generations occur in comparable proportions throughout a stand, then using a weighted average, or more conservatively, the lower of the two values may be justified.

The occurrence of trees with 2-YR foliage is nonetheless critical because drier, older needles render these trees more susceptible to torching which in turn increases the susceptibility of the stand as a whole to crown fire development.

At the FMC minimum, the SOILSUM was greater than the AIRSUM for both 1-YR and 2-YR foliage. Although little is known about the phenology of fine roots in response to soil temperature, I assume that stimulation of root meristems and subsequent root extension are analogous to aboveground bud-break and shoot extension; i.e. that they are facilitated by warming of the medium in which they occur. If this is, as expected, a normal plant physiological response and quantified as heat sum, then comparable heat sum values in air and soil would stimulate shoot and root growth, respectively. SOILSUM values exceeding AIRSUM values at the FMC minimum observed here suggest that root growth had attained a similar level of activity as shoot growth. This supports my hypothesis that the mechanism for FMC decline is primarily driven by a lag between aboveground and belowground plant phenology, with FMC rebounding only after the belowground plant root system attains some minimum level of activity to support the aboveground plant. This mechanism would be general to any locale that experiences markedly cold winters (i.e. temperate and boreal North America), so the pattern of springtime FMC decline, minimum, and rebound observed consistently among evergreen conifers is probably generally related to this phenomenon.

To test this idea for pitch pine, I applied the FMC equations developed above to FMC data acquired for two another pitch pine stand at Acadia National Park, Isle au Haut, Maine, for 1994 (Maguire 1995). This location corresponds roughly to the northern limit of pitch pine along the Atlantic coastal plain. Springtime temperature data were estimated for Bar Harbor in 1994 using a correlation between 2008 data for Bar Harbor and Bangor, Maine downloaded from the NCDC. The lowest FMC value at Bar Harbor was determined when the AIRSUM value was 130 °C-days, which is within one standard error of the minima reported above for Montague.

Worst-case scenarios are helpful to quantify canopy fuels parameters and state objectives, but as any reduction in FMC represents an increase in the probability of crown fire, it is also useful to identify a period where the FMC deficit is critical. Focusing on the 1-YR needles that constitute the majority of the canopy fuels at the MPWMA, I speculate that a reduction in FMC by 20% (i.e. dormant season

FMC minus 20%) represents a significant increase in fire danger for canopy fuels. Time to ignition (TTI) as a function of FMC reported for other pine species (Table 1) suggests that a 20% reduction in FMC can reduce TTI by 7-13%, depending on pre-ignition fuel temperature. A greater effect was observed for lower-temperature ignitions, which is significant for fuels with high concentrations of volatile compounds (W.A. Patterson and M.A. Gill, unpublished data). A reduction by 20% for 1-YR foliage puts the critical FMC threshold at 118%, which is first attained when the AIRSUM = 44°C-days (from equation in Figure 3a). The end of this period technically corresponds to TIME = 89 days (from equation in Figure 4a), but this may be overly conservative because by this time the new generation of foliage (0-YR) has become a significant component of the crown foliage (personal observation). Thus, the end of the critical period of depressed FMC corresponds to the extension of succulent new shoots and foliage that effectively buffer adjacent crowns from crown fire propagation by forming an outer crown sheath of new needles with very high moisture content (200-300%). Phenology of new shoots and foliage was not measured as part of this study, but 0-YR foliage was collected each year soon after the needles were fully-formed and visibly differentiated from the stem (Table 2), showing that FMC was consistently >200% at TIME = 100 days.

To demonstrate the relevance of this critically low FMC period to historic fire occurrence in Massachusetts, I determined the AIRSUM value for the dates of **XX** historical fires, including **XX** on the Montague Plains from 1907 to 2006, 3 of which were known crown fires, and 1 major crown fire in Plymouth, Massachusetts (Figure 7).

Adding the AIRSUM to daily fire weather observations can thus significantly aid fire managers in assessing crown fire hazard in pitch pine forests, in the context of both prescribed fire and wildfire. To help managers incorporate the AIRSUM into their daily fire weather observations, I have created a spreadsheet calculator that is available for download on the Northeastern Barrens and Fuels website (http://www.umass.edu/nebarrensfuels/). The spreadsheet allows the user to enter mean daily temperature, or alternatively maximum and minimum daily temperature, which automatically updates estimated FMC values.

Coarse temporal data from Acadia National Park, Maine for pitch, white, and red pine suggest that FMC decline is more or less simultaneous among these species but that there are significant differences in the rate and extent of FMC decline (Maguire 1995). White pine in particular exhibited a more marked FMC deficit with a significantly lower minimum FMC. White pine co-occurs with pitch pine at the MPWMA, sometimes constituting the majority of stand basal are or forming a dense understory. Its live crown depth is greater, reaching closer to the ground, and it typically retains more than two generations of foliage through the winter, making it a potentially significant ladder fuel.

More work is needed to quantify the distribution and abundance of trees with both 1-YR and 2-YR foliage. As mentioned above, these trees are the most likely to torch and initiate a crown fire within a stand, and the likelihood of this occurring within a given hectare is proportional to the abundance of these trees in stems/ha. If patterns of distribution can be established, or if unique attributes of such trees can be identified, then preventative management actions may be effected to remove or alter (e.g. pruning) these trees to reduce the threat of crown fire.

Catastrophic crown fires in pitch pine have also been known to occur during late summer droughts (Patterson et al. 1983) that incur similar foliar water deficits. Relating FMC to a measure of soil dryness, such as the Keetch-Byram drought index (KBDI) or other measure of soil moisture stress, may provide a means of identifying and quantifying FMC deficits under growing season drought conditions (see e.g. Dimitrakopoulos and Bemmerzouk 2003).

Table 1 **Summary of linear relationships between foliar moisture content (FMC) and time to ignition (TTI) for four pine species (TTI = a + b*FMC), and the relative significance of a reduction in FMC by a value of 20%.**

Species	a	b	ΔTTI* (s)	ΔTTI/TTI† (%)
Pinus ponderosa‡	15.206	0.111	2.217	7
P. contorta‡	17.203	0.119	2.377	7
P. brutia§	5.018	0.322	6.440	13
P. halapensis§	5.246	0.311	6.220	13

* The reduction in TTI given a reduction in FMC by a value of 20%.

† The percent reduction in TTI given the TTI for FMC = 138%.

‡ Equations for these species derived from equations 1 and 2 reported in Xanthopoulos and Wakimoto (1992) using the approximate mathematical equality of e^k*x ? 1+k*x for small values of k and assuming a fixed pre-ignition fuel temperature of 445 °C.

§ From Dimitrakopoulos and Papaioannou (2001) with a pre-ignition fuel temperature of 200 °C.

Table 2 **Initial foliar moisture content (FMC) values for newly-formed foliage, collected after visible differentiation between shoot and needles, and corresponding values of time since onset of the growing season, exhibiting the high FMC that effectively buffers adjacent crowns from crown fire propagation.**

Year	FMC (%)	TIME (days)
2003	160.7	164
2004	201.6	123
2005	215.8	113
2006	208.3	120
2007	189	124
2008	229.2	100

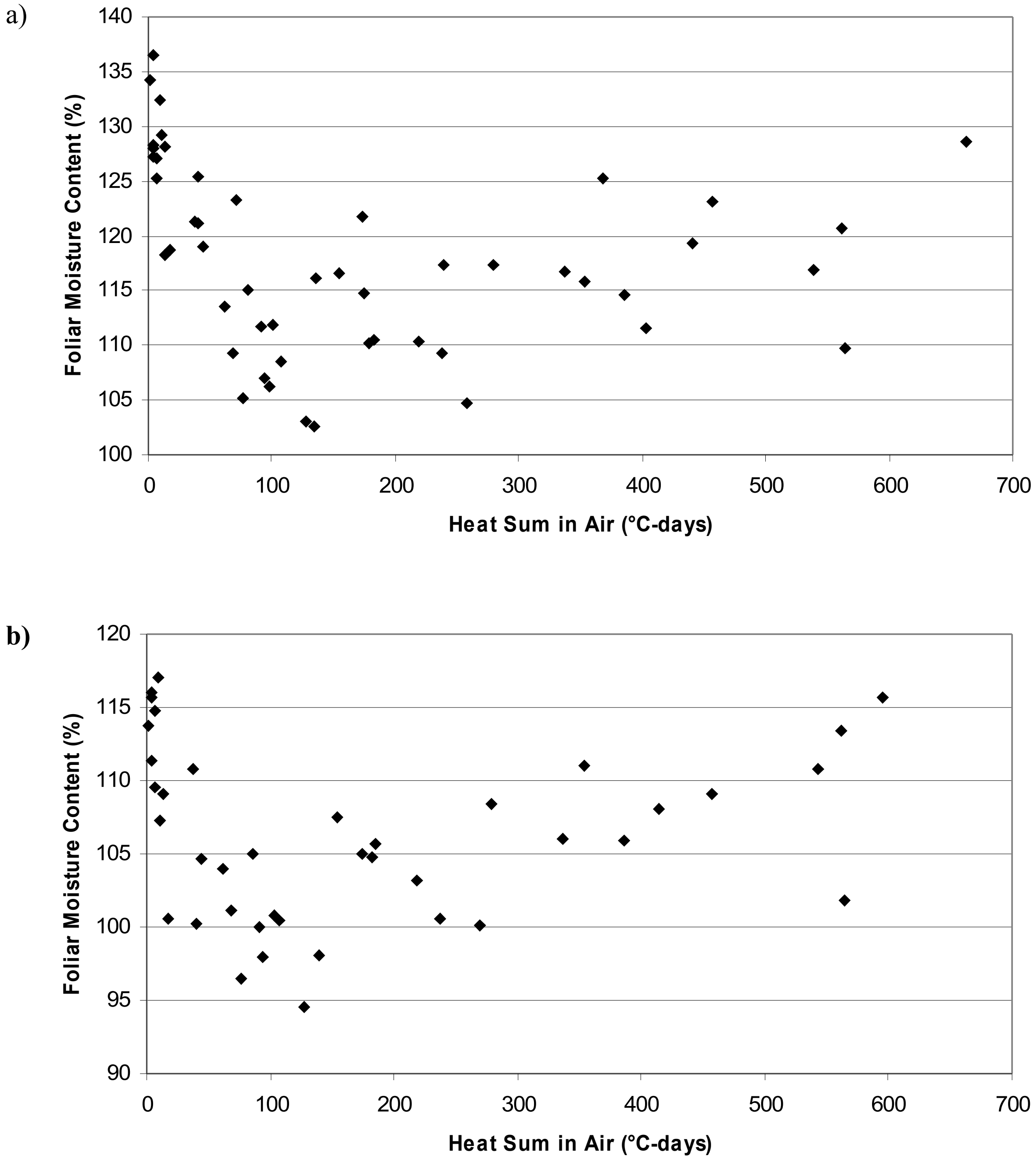

Figure 1 Plots of foliar moisture content (FMC) vs. the heat sum in air (AIRSUM) for a) 1-year-old (1-YR) and b) 2-year old (2-YR) foliage.

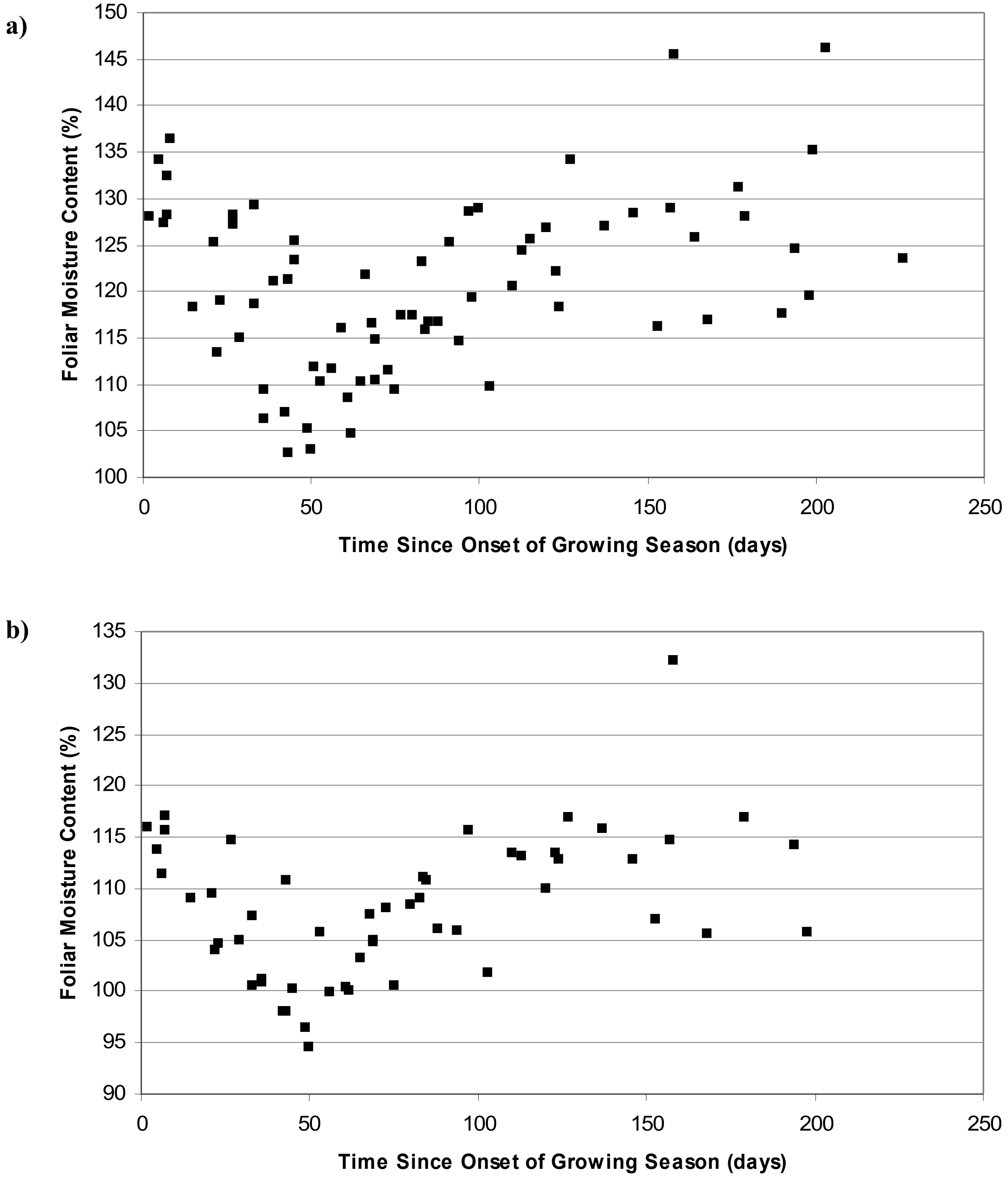

Figure 2 **Plots of foliar moisture content (FMC) vs. time since the onset of the growing season (TIME), as determined by the first day with a non-zero heat sum in air, for a) 1-year-old (1-YR) and b) 2-year old (2-YR) foliage.**

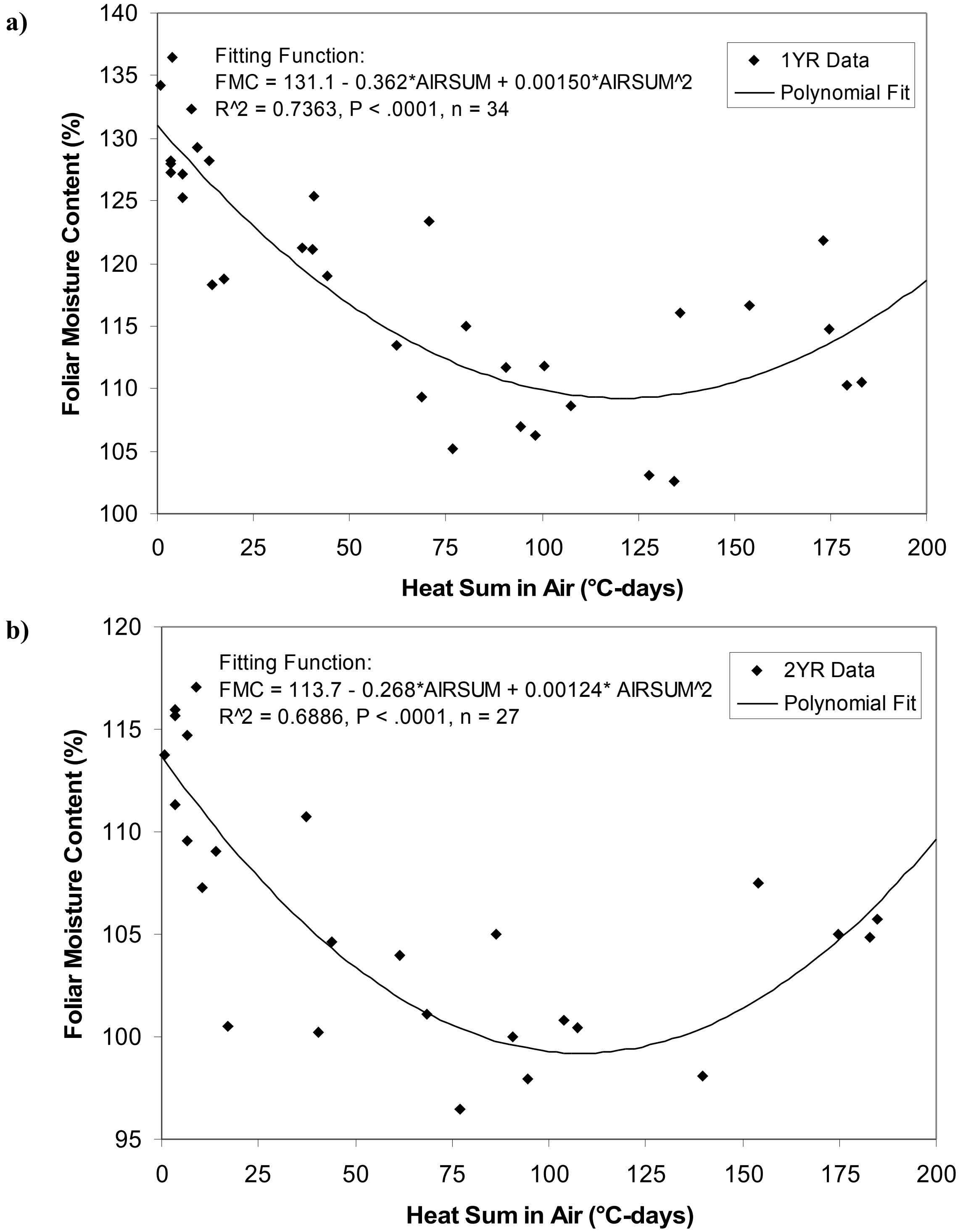

Figure 3 Plots of foliar moisture content (FMC) vs. the heat sum in air (AIRSUM) with the 2nd-order polynomial fitting functions for a) 1-year-old (1-YR) and b) 2-year old (2-YR) foliage.

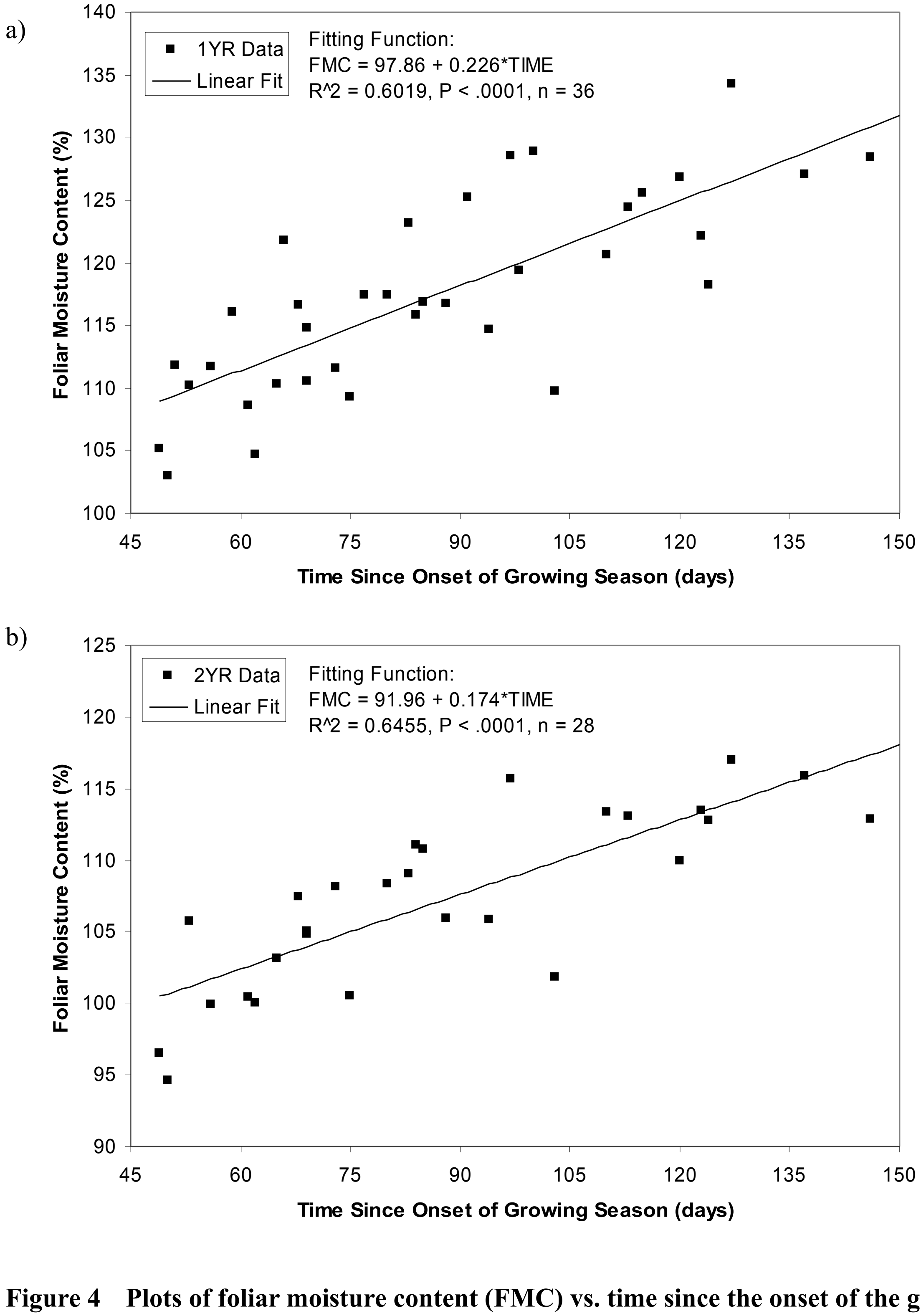

Figure 4 **Plots of foliar moisture content (FMC) vs. time since the onset of the growing season (TIME), as determined by the first day with a non-zero heat sum in air, with a linear fitting function for a) 1-year-old (1-YR) and b) 2-year old (2-YR) foliage.**

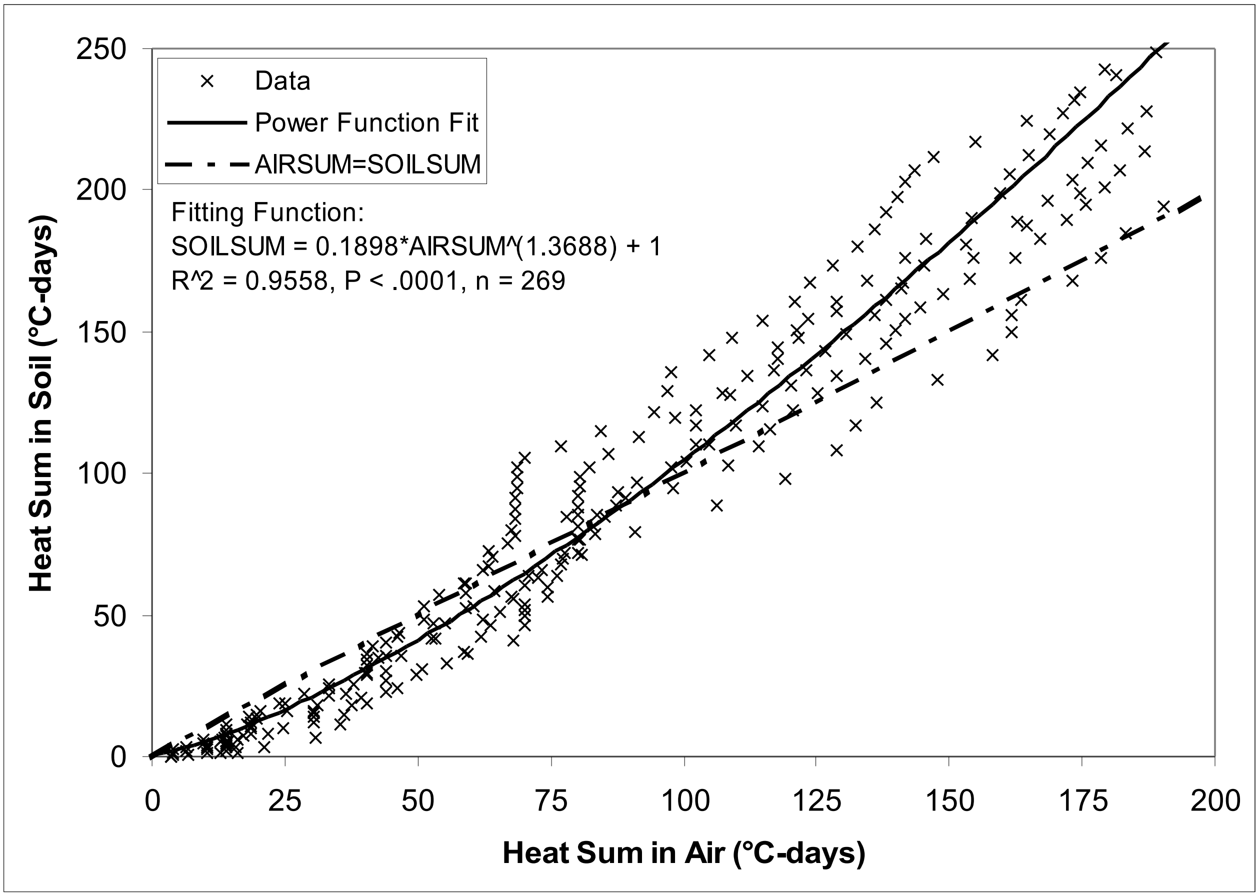

Figure 5 The heat sum in soil (SOILSUM) vs. the heat sum in air (AIRSUM) with fitting function and fit statistics.

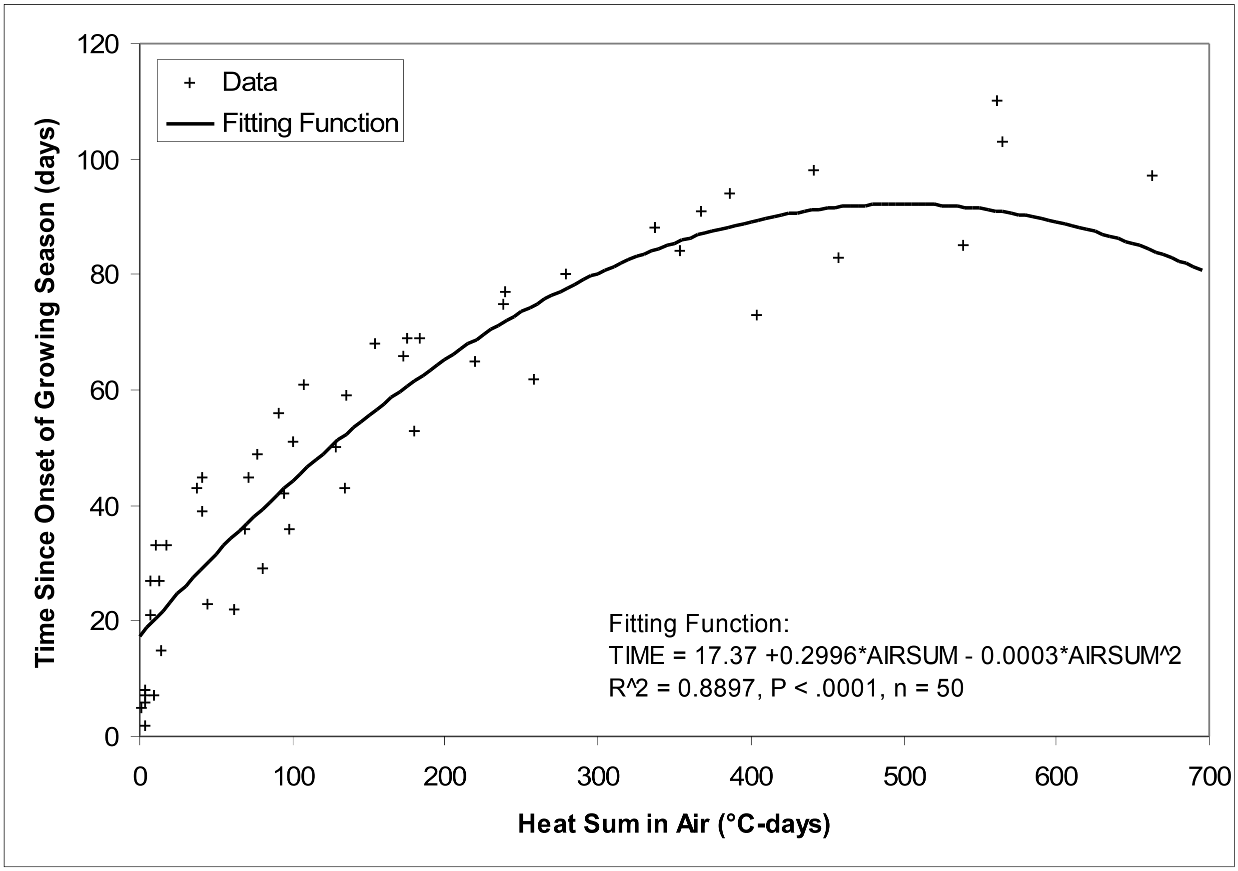

Figure 6 Time since onset of growing season (TIME) vs. the heat sum in air (AIRSUM) with fitting function and fit statistics.

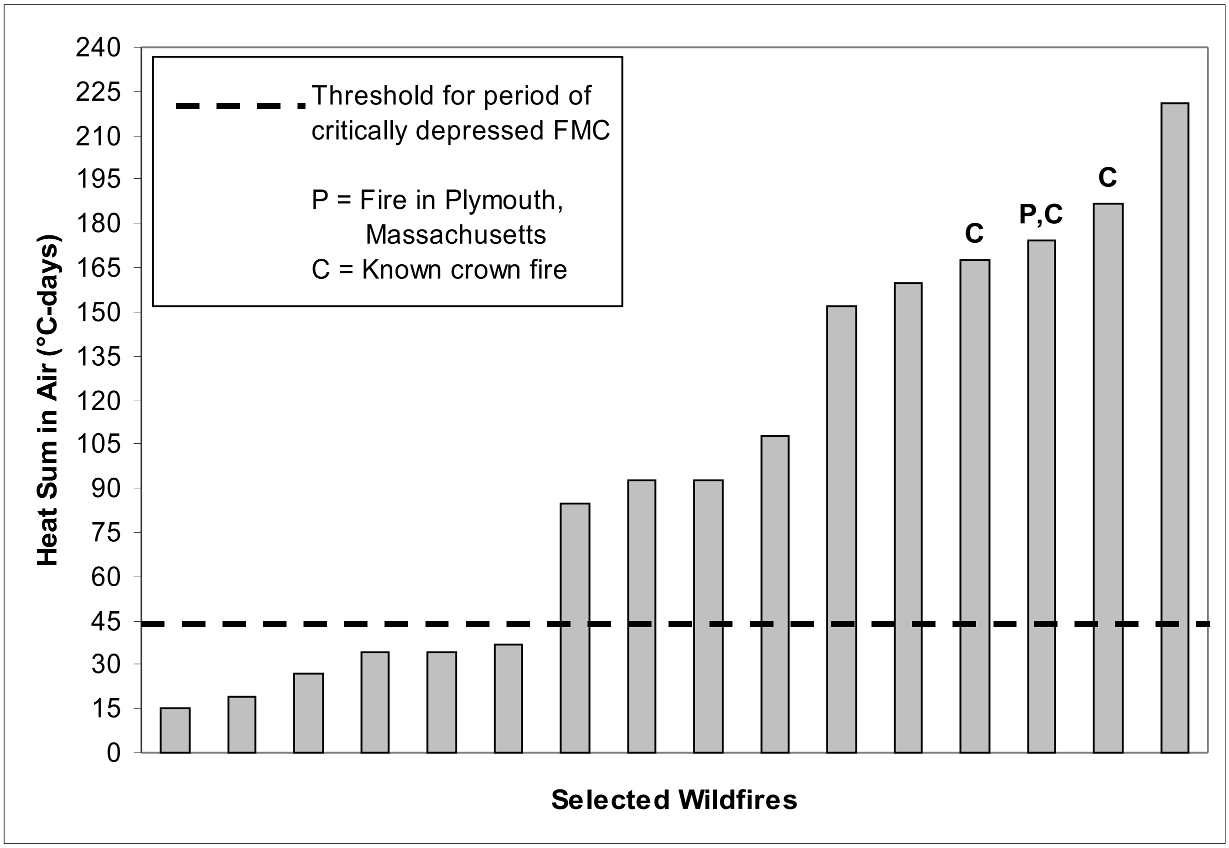

Figure 7 **Estimated values of the heat sum in air on the date of occurrence for selected historical wildfires at the Montague Plains, Montague, Massachusetts and Plymouth, Massachusetts with the corresponding threshold for significantly depressed foliar moisture content (FMC) determined from this study. Weather data were obtained from the National Climatic Data Center (NCDC, http://www.ncdc.noaa.gov/oa/ncdc.html) for the nearest available recording stations, and dates of Montague fires were acquired from Motzkin et al. (1996) and anectodally.**

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