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Fine fuel moisture for site- and species-specific fire danger assessment in comparison to fire danger indices

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ABSTRACT

Fire danger index performance as well as site- and species-specific fire danger is generally derived from fire occurrence records. However, in areas with a moderate overall fire danger, these analyses may be hampered by a small number of fires by unit area or generally missing fire data. However, as fire danger is expected to be linked to micrometeorology and dead fine fuel moisture, the use of litter and 10-h fuel moisture measurements for the aforementioned analyses was successfully tested in eight forest stands in southern Germany, using Spearman's rank correlation and various plotting techniques. The results show a reasonable ranking of fire danger indices. Furthermore, significant differences of litter moisture/fire danger between coniferous and deciduous forest stands exist at low to medium fire danger that fade away as fire danger increases. A comparison to standardized 10-h fuel moisture measurement revealed that differences between Scots pine and European beech litter moisture are not based on micrometeorological conditions in the forest stands, but rather on differences of the litter layer itself or the underlying soil.

1. Introduction

Assessing the performance of fire danger indices and identifying areas and stand types with different risk levels are key questions in forest fire research and management. As fire danger is closely linked to within-stand fuel moisture (dryer fuels tending to ignite more easily and to burn more intensively (Pyne et al., 1996)) and thus to meteorological conditions within forest stands, these questions can be attributed to the field of forest meteorology.

A wide range of fire danger indices is available worldwide, e.g. the Canadian Fire Weather Index System (CFWIS) and its components (van Wagner, 1987), the US National Fire Danger Rating System (NFDRS) and its components (Bradshaw et al., 1983; Burgan, 1988; Cohen and Deeming, 1985) and many single indices such as the Russian Nesterov Index (Nesterov, 1949). A review of fire danger, as well as fire behaviour modelling systems and their development in Australia, Europe and North America can be found in Fujioka et al. (2008). They all use standard (open air) meteorological data from open field stations in order to assess the fire potential on a given day (Andrews et al., 2003; Pyne et al., 1996). This information may be used for prevention and management purposes, such as the scheduling of patrols and aerial observations, public warnings and fire-fighting resource allocation.

The selection or verification of a fire danger index for use in a particular area should be based on statistical criteria. A wide range of methods is available from the literature when a comparison to daily fire occurrence records can be made. In this case, each day of the dataset is usually classified into a 'fire-day' or 'no-fire-day' (in some cases additionally into 'multiple-fire-day' and 'large-fire-day') and the fire danger index values in those groups are tested against each other (Andrews et al., 2003). Models and tests used include weighted binomial regression (Haines et al., 1983), logistic regression (Garcia et al., 1995; Martell et al., 1987; Reineking et al., 2010), the Mahalanobis distance used with normalized index values (Viegas et al., 1999) and the c-index (Verbesselt et al., 2006). Andrews et al. (2003) suggest using a combination of logistic regression, percentile comparisons between fire- and no-fire days, the Mahalanobis distance as well as subjective considerations. Eastaugh et al. (2012) stress that potentially different index frequency distributions have to be accounted for and propose a two-part non-parametric comparator (slope and intercept of ranked fire-day percentiles) that was later used by Arpaci et al. (2013) to select best-performing fire danger indices for Austrian ecoregions. A spatially and temporally explicit non-parametric

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logistic regression was employed by Preisler et al. (2004) to estimate wildfire risk and to assess the utility of fire danger indices in Oregon state, while accounting for temporal and spatial dependence (e.g. topography and fuel conditions), as well as non-linear relationships.

In addition to selecting a suitable fire danger index, assessment of susceptibility of different forest types, areas, topographical locations, etc. is also of interest, e.g. for advanced fire danger assessments, preparedness planning or fuel treatment measures. This assessment is normally also based on fire occurrence data where the fire locations are linked to explanatory variables such as stand type, elevation, distance to roads and population density. Examples include Kwak et al. (2012) using a generalized linear mixed model and identifying influences of slope, elevation, aspect, population density and distance from roads, but no influences of forest cover on forest fire occurrence and Arpaci et al. (2014), who applied machine learning techniques (MaxEnt and RandomForests). While they could also identify distance to buildings and population density as important drivers of fire occurrence, their models disagreed on the role of forest type and topography.

Unfortunately, the techniques presented so far may not be universally applicable, since fire occurrence data may be missing or there might just be too few fires to support meaningful analyses. Such is the case in our study area, the state of Bavaria in southern Germany, where fire occurrence is relatively low (on average 96 fires per year with an average burnt area of about 60 ha in the last 60 years (cf. Wastl et al. (2012)); total forest area: 7,055,019 ha (BMEL, 2014)) and records with precise information are only available for a very limited time period (date of fire since 2005 and fire location since 2015). This low fire occurrence can be explained with a strong Atlantic influence due to the prevailing westerlies, which lead to frequent precipitation and only occasional periods of drought and elevated fire danger. Furthermore, there are few agricultural and forestry practices which pose a fire risk and these can easily be carried out in times of low fire danger. High population and fire service density usually lead to a rapid discovery and attack on any occurring fires and thus to low area burned. Only very few fires are of a natural origin; human causes range from negligence, use of machinery in transportation, forestry, and agriculture to arson. It is also hypothesized that with a limited number of days with high fire danger, public warnings are working well and thus there may be fewer fires on a meteorologically highly fire-prone day than under moderate conditions. Wastl et al. (2012) showed the substantial influence in variable human-caused ignition, based on the fact that low annual fire occurrence is not always connected to low meteorological fire danger indices, but also to human restraint in times of elevated fire danger. Additionally, they could prove that annual numbers of fire and area burnt decreased significantly from 1951 to 2010, while overall meteorological fire danger (based on a combination of many stations and indices) increased; yet another influence of anthropogenic behaviour and ignition sources. Thus, the standard fire-occurrence based methods described so far cannot be carried out or have to be expected to produce misleading results.

In a similar situation on the small-scale Hawaiian islands subjected only to a moderate fire danger, Dolling et al. (2005) investigated the relationship between the Keetch-Byram Drought Index (KBDI) and monthly total area burned. A comparison of models for the probability of monthly fire occurrence and conditional large fire occurrence in the western US, including historic (month-in-year and location) versus single and multiple (monthly mean) fire danger indices as explanatory variables was used by Preisler et al. (2008). They identified the model (and thus set of indices) best suited to describe their data with the Mutual Information statistic (MI). In addition to this accumulation of fire occurrence data, few examples can be found in the literature where other parameters have been used to assess the performance of fire danger indices and the relative susceptibility of different sites and forest types. Haines et al. (1983) related fire danger indices to observed fire behaviour and Abbott et al. (2007) assessed how well different fuel moisture codes of the Canadian Fire Weather Index System correspond to forest floor moisture of burnt and unburned jack pine stands. Dead fine fuel moisture was also used to determine the influence of forest type, season and stand density on the relationship of Fine Fuel Moisture Code (FFMC) of the Canadian Fire Weather Index System to litter moisture (Wotton and Beverly, 2007) and to select fire danger indices for fine fuel moisture modelling (Aguado et al., 2007; Pereira et al., 2012). Furthermore, Wotton (2009) gives some examples of litter moisture to Fine Fuel Moisture Code relations, Nyman et al. (2015) quantified the effects of topographic aspect on fine fuel moisture and Lopes et al. (2006) analysed the relation of fuel moisture content and fire occurrence. Along a similar line, many more authors tried to model or validate fine fuel moisture in relation to meteorological parameters (Lopes et al., 2010; Matthews, 2006; Matthews et al., 2007, 2010; Resco de Dios et al., 2015; Rothermel et al., 1986; Ruiz González et al., 2009; Slijepcevic et al., 2015; Snyder et al., 2006; Weise et al., 2005; Wittich, 2005). Detailed reviews can be found in Viney (1991) and Matthews (2014), however their main focus lies on technical modelling aspects. Nevertheless, Matthews (2014) states that progress has been concerning the influences of fuel structure, topography and micrometeorology as well as a characterization of fine fuel moisture content in the landscape. Overall, studies linking dead fine fuel moisture to fire danger indices in general, and in particular concerning temperate European forests and climate, are missing or very limited.

This paper tests robust techniques for assessing fire danger index performance and fire susceptibility of different sites and forest types based on ample dead fine fuel and automated 10-h fuel moisture measurements and to analyse such measurements made in southern Germany in 2010 and 2013.

2. Material and methods

2.1. Litter moisture sampling and 10-h fuel moisture measurements

The study was conducted in the state of Bavaria, Germany, where litter moisture was measured at 8 different forest stands distributed across 4 geographic locations and in two years (2010 and 2013, cf. Fig. 1 and Table 1). The 2010 sampling sites comprised the four major tree species Norway spruce (*Picea abies* L.), Scots pine (*Pinus sylvestris* L.), European beech (*Fagus sylvatica* L.) and pedunculate oak (*Quercus robur* L.) and were distributed across the state. Detailed information about the sampling sites can be found in Table 1. In 2013, only European beech and Scots pine were sampled, however, measurements additionally included automated 10-h fuel moisture sticks, which were evaluated in comparison to the manual litter moisture measurements (Schunk et al., 2014). The sampling sites were mainly research forests of the forest climate stations Würzburg, Altdorf, Freising and Altötting run by the Bavarian Forest Institute (Bayerische Landesanstalt für Wald und Forstwirtschaft – LWF). However, at several sites (Leerstetten, Hohenbercha and Altötting) state and private forests in the vicinity of these forest climate stations were selected, as these permitted sampling of additional species or facilitated the sampling process.

Well within each of the stands, a 30 m long transect was established along which the sampling took place. Samples of the litter (O_L) layer consisting predominantly of dead leaves and needles, as well as small branches (diameter < 4 mm), dead parts of flowers and fruits, were gathered by hand at three randomly selected points