Fakultät Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt

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Contributions to the assessment of past, present and future forest fire danger in Bavaria and the Alpine region

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In loving memory of my grandmother Lina
and my father Gerhard, who did not live
to see the completion of this thesis.

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Summary

Background and aims

Forest fire is a major disturbance in the earth system, with multiple feedback mechanisms regarding vegetation and climate. Although its current influence in Central Europe is relatively limited, rating of fire danger is an important measure for prevention (e.g. public warnings) and preparedness planning. Furthermore, climate change with the associated increase in temperature and extreme events can be expected to alter current patterns of fire danger and occurrence.

Since fire ignition is greatly hindered by presence of moisture in forest fuels (e.g. litter), fuel moisture dynamics play a major role in the temporal and species/site-specific fire susceptibility and are thus also the basis of most fire danger rating systems.

The present thesis aims to contribute to a better understanding of recent and future changes of fire danger, as well as its rating, in the state of Bavaria, Germany, and the adjacent Alpine area.

To achieve this, studies relating to the absorption, measurement and dynamics of litter moisture, as well as to the behaviour of fire danger indices in complex topography and in long time series (both recent and in a projected future scenario) have been conducted in six specific publications that are part of this thesis.

Material and methods

In the laboratory, equilibrium moisture content of litter from four major German tree species was measured using conditioning in a climate chamber and over saturated salt solutions, as well as gravimetric moisture determination.

Several different potential (permittivity and electrical resistance-based) techniques for automated measurement of litter moisture in the field were tested and compared to a large set of manually (sampling by hand and oven-drying) determined moisture values.

Manual measurements from eight sites distributed across the state of Bavaria and conducted in two years (2010 and 2013) were used to assess the performance of fire danger indices and to identify differences between sites made up of different species.

A further study investigated the effect of complex topography-induced meteorological conditions and station location on fire danger and its rating, using comparisons of meteorological data, fire danger indices and a major fire occurrence in autumn 2011.

The presence, extent and patterns of long-term trends and changes in extreme values of fire danger in the Alpine area were analysed using seven fire danger indices computed for 25 meteorological stations with long time series. In addition, comparisons to fire occurrence data were made in three pilot areas in the Western, Northern and Southern Alps.
Potential future changes were projected with the Canadian Fine Fuel Moisture Code calculated from a single regional climate model (COSMO-CLM) and a multi-model of seven other regional climate models, for SRES scenario A1B and periods 1991-2010 vs. 2031-2050. The results derived from those models were compared and the models themselves evaluated.

Results and discussion

Significant differences in the hygroscopicity of leaf and needle litter across a wide range of relative humidity were identified, which are also present in the literature for other species and regions. Higher moisture absorption by dead leaves may be caused by their different physical and chemical properties and could partially explain the lower fire occurrence observed for deciduous forests in Bavaria. However, equilibrium moisture content is never actually reached in the field. Sample conditioning in the climate chamber proved reliable and easy to use, although there are limitations regarding stability over time and the minimum of relative humidity achievable. Although saturated salt solutions are not affected by this, condensation can be a problem when they are used at high relative humidities, they may be toxic and/or corrosive and sample size and number are usually much more limited.
Regarding methods for automatic litter moisture content determination, highly significant correlations of sensor outputs and litter moisture were found for all techniques, with frequency domain performing better than electrical resistance-based measurements. However, standard deviations for several sensors of a type tended to become irregular at high moisture contents, potentially indicating an exceedance of the working ranges, and a large drift over time was noted. The latter necessitates frequent in-situ calibration based on gravimetric moisture measurements and therefore greatly impairs the usefulness of the tested techniques for routine monitoring applications. However, they may be interesting for scientific studies where gravimetric moisture determination is carried out in any case.
When such manual gravimetric measurements were related to fire danger indices, the latter could be evaluated without having to rely on the few local fire occurrences that are furthermore subject to human influences and ignition causes. Spearman's rank correlation proved a simple, robust and non-parametric statistic for those comparisons. In the low to

medium range of fire danger, significant differences between species and sites could also be found, with deciduous forests again exhibiting higher moisture contents due to the depth and structure of their litter layers.

Complex topography was found to influence meteorological conditions defining fire danger in many different ways. Temperature inversion created steady warm and dry conditions at intermediate elevations in the case study, while high diurnal variations with a regular wetting of fuels by dew or rime occurred in the valley. This situation can only be resolved by fire danger indices calculated in sub-daily (e.g. hourly) intervals and input data from relevant elevations.

Recent climate change proved to have a significant influence on meteorological fire danger for many stations, regions and fire danger indices. While the highest share of increasing and significant trends could be found in the Southern Alps, stations in other areas were characterized by fewer significant and even some decreasing trends (e.g. Inner and Northern Alps). Changes for exceptionally high fire danger (95^{th} percentile) were more pronounced than those of median (50^{th} percentile) conditions, confirming stronger increases in extremes rather than in mean value. Regional patterns were similar in the extreme value analysis. Comparison to fire occurrence data revealed complex interactions of fire danger and human influences/ignition sources, e.g. a decreasing number of fires and burnt area in Bavaria and Ticino, although meteorological fire danger actually increased at the same time.

Projected future changes using the multi-model approach indicate a coarse continuation of recent trends with the area south of the Alps most affected. However, large differences to the COSMO-CLM exist, up to opposing trends for relatively large areas. These are mostly due to high uncertainties in the projection of future precipitation, which are additionally increased by the complex terrain in the study area. As the multi-model approach better accounts for the uncertainty and associated variability of precipitation projections in the seven regional climate models, it is preferred and highly recommended for general use.

Conclusions

In the present thesis, a range of new facts and techniques for fire danger rating in temperate Europe could be established and/or tested. In particular, input data for fuel moisture models (equilibrium moisture content) could be provided and a novel technique for independent fire danger index assessment was presented. The studies also revealed the causes of known patterns of fire occurrence, such as moisture behaviour in leaf litter leading to fewer fires in such stands and a greatly increased fire danger at mid-elevation forest in the Alpine area during temperature inversion. The data and methods presented should now be adopted by the local meteorological service and forest management agencies to improve operational fire danger rating.

Zusammenfassung

Hintergrund und Zielsetzung

Waldbrände sind bedeutende Störungen im Erdsystem, die mit einer Vielzahl von Rückkopplungen in Bezug auf die Vegetation und das Klima verbunden sind. Obwohl ihr derzeitiger Einfluss in Mitteleuropa relativ begrenzt ist, stellt die Abschätzung der Waldbrandgefahr eine wichtige Maßnahme zur Vorbeugung (z.B. Herausgabe von Warnmeldungen) und Bereitschaftsplanung dar. Weiterhin kann davon ausgegangen werden, dass der Klimawandel und die damit verbundene Zunahme von Temperatur und Extremereignissen die gegenwärtigen Muster der Waldbrandgefahr und des Auftretens von Bränden ändern werden.

Nachdem die Brandentzündung durch Feuchtigkeit in möglichen Brennmaterialien (z.B. Waldstreu) deutlich erschwert wird, spielt das Feuchteverhalten eine grundlegende Rolle in der zeit- und baumart-/standortspezifischen Waldbrandgefahr und ist deshalb auch die Grundlage der meisten Waldbrandgefahrenindices.

Ziel der vorliegenden Arbeit ist es, zu einem besseren Verständnis der bisherigen und zukünftigen Veränderungen in der Waldbrandgefahr, sowie zu ihrer Abschätzung im Freistaat Bayern, Deutschland, und im angrenzenden Alpenraum beizutragen.

Um dies zu erreichen wurden die Aufnahme, Messung und die Dynamik der Feuchtigkeit von Waldstreu, sowie das Verhalten von Waldbrandindices in komplexem Gelände und langen (historischen und für die Zukunft projizierten) Zeitreihen untersucht und in sechs eigenständigen Veröffentlichungen publiziert, die Bestandteil dieser Arbeit sind.

Material und Methoden

Die Gleichgewichtsfeuchte von Streu der vier deutschen Hauptbaumarten wurde im Labor gemessen, wobei die Proben in der Klimakammer sowie über gesättigten Salzlösungen konditioniert wurden und die Feuchtebestimmung gravimetrisch erfolgte.

Mehrere mögliche Messverfahren zur automatisierten Bestimmung der Streufeuchte im Wald (basierend auf der dielektrischen Leitfähigkeit und dem elektrischen Widerstand) wurden getestet und mit einer Vielzahl an manuell (händische Probenahme und Ofentrocknung) ermittelten Feuchtegehalten verglichen.

Die manuell bestimmte Feuchtigkeit aus acht über Bayern verteilten Waldbeständen und zwei Messjahren (2010 und 2013) wurde verwendet um das Leistungsvermögen von Waldbrandindices zu bewerten und um Unterschiede zwischen Beständen unterschiedlicher Baumarten aufzudecken.

Eine weitere Studie erforschte die Auswirkungen von bergmeteorologischen Effekten und dem Standort von Messstationen auf die Waldbrandgefahr und deren Abschätzung. Dafür wurden meteorologische Daten, daraus berechnete Waldbrandindizes sowie ein bedeutender Waldbrand aus dem Herbst 2011 herangezogen.

Das Vorliegen, der Umfang und regionale Muster von langfristigen Trends und Änderungen in den Extremwerten der Waldbrandgefahr im Alpenraum wurden anhand von sieben Waldbrandindices sowie 25 meteorologischen Stationen mit langen Zeitreihen analysiert. Zusätzlich wurden Vergleiche zu Waldbranddaten aus Pilotgebieten in den West-, Nord- und Südalpen angestellt.

Mögliche zukünftige Veränderungen wurden mit Hilfe eines einzelnen regionalen Klimamodells (COSMO-CLM) sowie eines Multimodells aus sieben anderen regionalen Klimamodellen und des kanadischen Fine Fuel Moisture Code für das SRES-Szenario A1B und die Zeiträume 1991-2010 im Vergleich zu 2031-2050 projiziert. Die Ergebnisse der beiden Modelle wurden gegenübergestellt und die Modelle selbst bewertet.

Ergebnisse und Diskussion

Über einen weiten Bereich relativer Luftfeuchtigkeit konnten signifikante Unterschiede in der Hygroskopizität von Blatt- und Nadelstreu nachweisen werden, die in ähnlicher Form auch für andere Regionen und Baumarten in der Literatur zu finden sind. Die höhere Feuchtigkeit von abgestorbenen Laubblättern dürfte von ihren unterschiedlichen physikalischen und chemischen Eigenschaften ausgehen und könnte bereits zur Erklärung der beobachteten Brandhäufigkeit in Laub- und Nadelwäldern herangezogen werden. Allerdings wird die Gleichgewichtsfeuchte unter Freilandbedingungen niemals erreicht. Die Probenkonditionierung in der Klimakammer erwies sich als zuverlässig und leicht in der Handhabung, wobei es Beschränkungen hinsichtlich der Stabilität und der minimal erreichbaren Luftfeuchtigkeit gibt. Während die gesättigten Salzlösungen hiervon nicht betroffen sind kann Kondensation hier zu Problemen bei sehr hohen Luftfeuchtigkeiten führen, die Lösungen selbst können giftig und/oder korrosiv sein und die Größe und Anzahl der Proben ist bei diesem Verfahren deutlich eingeschränkt.

In Bezug auf die automatische Bestimmung der Streufeuchte konnten hochsignifikante Korrelationen zwischen den Werten der einzelnen Sensortypen und der gravimetrisch bestimmten Streufeuchte festgestellt werden, wobei die dielektrischen Messverfahren besser abschnitten als die widerstandsbasierten. Die Standardabweichungen von mehreren Sensoren eines Typs verhielten sich jedoch ab einer gewissen Streufeuchte sehr unregelmäßig, was möglicherweise ein Überschreiten der Messbereiche anzeigt. Außerdem wurde eine große Drift festgestellt, die eine regelmäßige Kalibrierung anhand vor Ort manuell bestimmter Streufeuchte erfordert, was die Brauchbarkeit der Verfahren für das Routinemonitoring sehr stark einschränkt. Für wissenschaftliche Studien, bei denen die Streufeuchte ohnehin regelmäßig gravimetrisch bestimmt wird, können diese jedoch trotzdem interessant sein.

Wenn manuell ermittelte Streufeuchtewerte mit Waldbrandindizes verknüpft werden, können letztere bewertet werden ohne dafür auf die wenigen stattfindenden Waldbrände angewiesen zu sein, die zusätzlich stark von menschlichen Einwirkungen und Zündquellen geprägt sind. Spearman's Rangkorrelation erwies sich als einfacher, robuster und nichtparametrischer Test für diese Vergleiche. Im Bereich niedriger und mittlerer Gefahr zeigten sich weiterhin signifikante Unterschiede zwischen den Baumarten bzw. Beständen, wobei die Laubbestände aufgrund der Mächtigkeit und Struktur ihrer Streuschichten höhere Feuchtegehalte aufwiesen.

Komplexes Gelände beeinflusste die Meteorologie und damit auch die Waldbrandgefahr auf vielfältige Art und Weise. Inversionswetterlagen führten in der Fallstudie zu beständig warm-trockenen Verhältnissen in mittleren Lagen, während große tageszeitliche Schwankungen und eine regelmäßige Befeuchtung der Brennstoffe durch Tau oder Reif in im Tal auftraten. Diese Gegebenheiten können nur von Waldbrandindices mit hoher zeitlicher Auflösung (z.B. stündlich) abgebildet werden, wenn zeitgleich meteorologische Ausgangsdaten aus den relevanten Höhenlagen zur Verfügung stehen.

Es konnte gezeigt werden, dass der rezente Klimawandel bei vielen Kombinationen von Klimastationen, Waldbrandindices und Regionen einen signifikanten Einfluss auf die Waldbrandgefahr hat. Während der größte Anteil an signifikanten und ansteigenden Trends in den Südalpen lag, waren die Stationen in den anderen Gebieten (z.B. Nordalpen und inneralpiner Raum) durch eine geringere Anzahl an signifikanten und sogar durch einige rückläufige Trends gekennzeichnet. Die Veränderungen der außergewöhnlich hohen Gefahr (95. Perzentil) waren ausgeprägter als die mittlerer Bedingungen (50. Perzentil, Median) und bestätigen den stärkeren Einfluss des Klimawandels auf Extreme als auf Mittelwerte. Die Extremwertanalyse ergab ähnliche regionale Muster. Vergleiche zu Waldbranddaten zeigten die komplexen Wechselwirkungen von (meteorologischer) Waldbrandgefahr und menschlichen Einwirkungen/Zündquellen. So kam es in Bayern und im Tessin zu einem Rückgang der Brandanzahl und -fläche, obwohl sich die meteorologische Gefahr im gleichen Zeitraum erhöht hat.

Die anhand des Multimodell-Ansatzes projizierten zukünftigen Veränderungen setzen die rezenten Trends grob fort, wobei die Region südlich der Alpen weiterhin am stärksten betroffen ist. Allerdings ergaben sich große Unterschiede zu den Ergebnissen des COSMO-CLM, bis hin zu großflächig entgegengesetzten Veränderungen der Waldbrandgefahr. Diese sind im Wesentlichen durch die großen Unsicherheiten bei der Projektion des zukünftigen Niederschlags bedingt, die durch das komplexe Gelände im Untersuchungsgebiet noch weiter erhöht werden. Nachdem der Multimodell-Ansatz die Unsicherheit und damit verbundene Variabilität der sieben regionalen Klimamodelle besser berücksichtigt, wird dieser bevorzugt und für die allgemeine Verwendung empfohlen.

Schlussfolgerungen

In der vorliegenden Arbeit wurden eine Reihe neuer Fakten und Techniken für die Beurteilung der Waldbrandgefahr im gemäßigten Teil Europas ermittelt und getestet. So konnten Eingangsdaten (Gleichgewichtsfeuchte) für Streufeuchtemodelle und eine neue Methode für die unabhängige Bewertung von Waldbrandindices zur Verfügung gestellt werden. Die Untersuchungen zeigten auch Gründe für die bekannten Muster des Auftretens von Waldbränden auf, wie das Feuchteverhalten der Laubstreu, dass zu weniger Bränden in solchen Beständen führt, sowie eine massiv erhöhte Brandgefahr in den mittleren Lagen des Alpenraums während Inversionswetterlagen. Die enthaltenen Daten und Methoden sollten nun vom lokalen Wetterdienst und den Forstbehörden eingesetzt werden, um die operationelle Waldbrandprognose zu verbessern.

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1 Introduction

The earth is the only planet known to have life and therefore also the only planet to have fire (Pyne *et al.* 1996; Scott 2014). Charcoal records reveal that fires occurred as early as the late Silurian (420-400 ma before present, Scott 2014) to early Devonian (Glasspool *et al.* 2006). With the further development of plants (i.e. potential fuel) and the associated rise of atmospheric oxygen content, fires became more frequent and widespread (Scott & Glasspool 2006). The management of fire was one of the defining actions of human beings (Pyne *et al.* 1996). Today, forest and other wildland fires are linked to most ecosystems worldwide (Omi 2005). In a very general, conceptual sense, vegetation fire occurrence can be linked to aridity and productivity (cf. Figure 1, Murphy *et al.* 2011, Krawchuk & Moritz 2011, Scott 2014): while intense aridity in dessert areas provides the meteorological conditions for excessive fires, it does not support the growth of vegetation (i.e. fuel) that could burn. On the other hand, lush vegetation in humid areas hardly burns as wet fuels do not allow a fire to start and propagate (Murphy *et al.* 2011, cf. chapters 1.2.2 and 1.2.3). Thus, best conditions for fires can be found at intermediate levels of aridity and primary productivity, and they are often linked to seasonal dry/wet climate (Scott 2014).

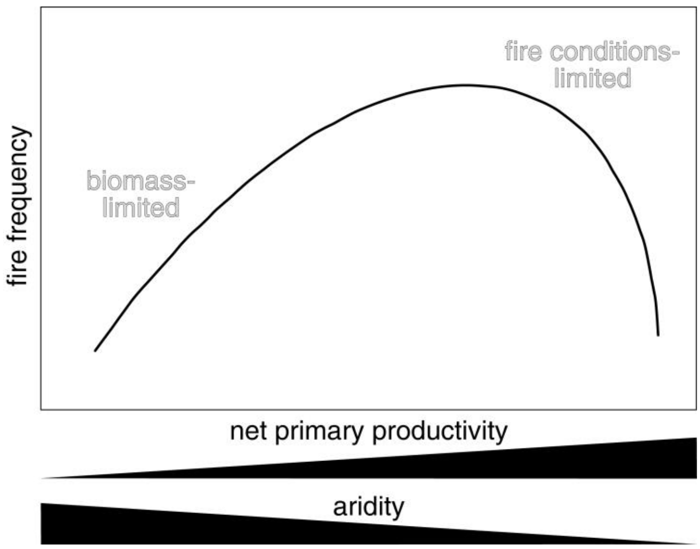

Figure 1: Fire frequency as conceptually limited by aridity and productivity, according to Murphy *et al.* (2011).

While these conditions are ideally met by tropical savannas (Bowman *et al.* 2009), fires are also an important disturbance in the temperate zone, where air masses mix and there are more or less intensive fire seasons according to prevailing wet and dry periods (Pyne *et al.* 1996). Interestingly, fire practices in its main constituents, North America and Europe, are substantially different. While intensive agriculture and forestry have largely reduced fire occurrence in the latter (through fuel utilization and thus reduction), the continuation of fire regimes is regarded essential for managing wildlands and areas under commercial agricultural and forestry use in North America (Pyne *et al.* 1996).

In addition to aridity and productivity, many more factors and interactions have to be considered when combustion, fire behaviour, fire regimes and fire risk are considered in general. The interactions of oxygen, heat and fuel availability during combustion have been simplified in the so-called ‘fire triangle’ (cf. Countryman 1972, Pyne *et al.* 1996). However, this is only applicable to very small scales, e.g. the flame level (Keane 2015). Moritz *et al.* (2005) developed a more comprehensive representation, including scaling effects at both the temporal and spatial levels, which is shown in Figure 2.

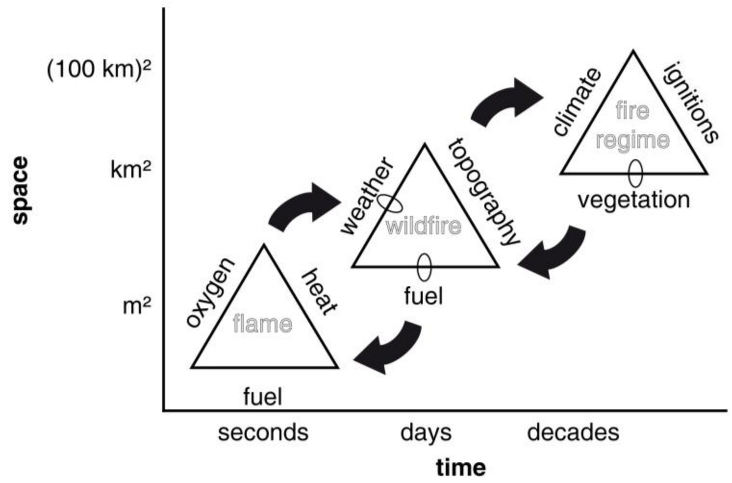

Figure 2: Interactions and controls of fire at different scales, according to Moritz *et al.* (2005). Ellipses: feedback mechanisms.

The lowest triangle therein represents the original ‘fire triangle’, indicating that the combustion process requires oxygen, heat (supplied by an ignition source or the burning fire itself) and fuel to start and proceed (Countryman 1972; Pyne *et al.* 1996). The term ‘fuel’ not only contains the presence, amount and distribution of fuels, but also its moisture content and subsequent ability to burn (available fuel, Keane (2015), cf. chapters 1.2.2 and 1.2.3). It can thus be understood to have another sub-level of factors influencing fuel moisture, that itself stretches across several scales and interacts with the other parameters (e.g. fuel arrangement, topography, vegetation/land cover, diurnal, synoptic and seasonal weather conditions as well as climate change).

Wildfire and its behaviour are governed by weather conditions, fuel and topography, with strong feedback mechanisms between the fire and its control parameters (weather and fuel, small ellipses in Figure 2), as well as interactions with the small- and short-scale flame level (Keane 2015; Moritz *et al.* 2005).

In the long run and at the landscape level, long-term climate (drought, climate zone, climatic changes), ignition patterns (human, lightning) and vegetation type create a fire regime with characteristic patterns and recurrence intervals (Moritz *et al.* 2005). Once more, internal feedbacks between vegetation and fire regime, as well as to the lower-order triangles (in Figure 2) are essential for the working and understanding of the system (Moritz *et al.* 2005; Keane 2015).

1.1 Climatic changes

The complex interrelations of pre-industrial climatic changes, vegetation and wildfires can be read from charcoal records (Power *et al.* 2008). More recent climate change can be attributed to emissions of climate forcing gases (e.g. carbon dioxide, methane and nitrous oxide) unprecedented in the last 800.000 years and has led to a global surface temperature increase of 0.85°C (1880-2012, IPCC 2013). There is high confidence (95%) that these emissions and the associated warming since the mid-20th century are due to human activities, e.g. from fossil fuel burning and cement production (IPCC 2013). In addition to the general warming, a likely overall increase of northern hemisphere mid-latitude land precipitation (medium confidence before 1951 and high confidence after 1951) and changes in extremes (e.g. very likely global increase of warm days in 1951-2010, high confidence for greater magnitude and duration of droughts, likely increase of drought frequency and intensity in Mediterranean Europe and West Africa since 1950) could be detected (IPCC 2013, 2014).

Westerling *et al.* (2006) found a sudden increase in large, western US wildfires due to earlier snowmelt and higher spring and summer temperatures and Clarke *et al.* (2013) detected significant increases of McArthur’s forest fire danger index (both in magnitude and fire season length) from 1979 to 2010 for many stations in Australia. Worldwide fire season length was investigated by Jolly *et al.* (2015) using three different daily global climate data sets and fire danger indices, respectively, and proved to have increased by 18.7% from 1970 to 2013.

Projections of future climate can be made using complex, atmosphere-ocean general circulation models (AOGCM) and various downscaling techniques for resolution enhancement (IPCC 2013). These models are driven by estimates of socioeconomic development and associated forcing gas concentrations (IPCC Special Report on Emission Scenarios, SRES, Nakićenović 2000) or the more recent representative concentration pathways (RCP, IPCC 2013).

Carvalho *et al.* (2006, 2011) used regional climate models (RCMs) to project future changes in fire danger (as expressed by the Canadian fire weather index and its components) for Portugal and Badeck *et al.* (2004) performed a similar analysis with temperature-increase scenarios for Brandenburg, Germany. Potential effects on fire occurrence and burnt area can be derived by linking climate models and the relation of fire danger indices to past fire occurrence. Flannigan *et al.* (2005) found significant increases for future area burnt in Canada, using two global climate models and a 3×CO_2 scenario. However, there were also large variations in fire activity. Substantial increases of the latter could be derived from downscaled global climate models for the Greater Yellowstone Ecosystem by Westerling *et al.* (2011). Similarly, dramatic increases in area burnt and fire occurrence (478 and 279%, respectively) were projected for Portugal using a regional climate model (Carvalho *et al.* 2010). However, these approaches do not take vegetation changes and feedbacks of increased wildfire on fuel availability and the climate system into account. Parks *et al.* (2016) and Westerling & Bryant (2008) for example found decreases of fire risk for parts of the United States as biomass productivity decreases in formerly critical areas. Dynamic global vegetation models (DGVM) can take account of climate change, vegetation, human ignitions, wildfire and their complex interactions (Scott 2014). Examples of their use include Sheehan *et al.* (2015), Thonicke & Cramer (2006), Sitch *et al.* (2003), Venevsky *et al.* (2002) and Thonicke *et al.* (2001).

1.2 Fuels and basic processes

In order to fully comprehend forest fire danger, ignition and spread, it is necessary to take a step back from these global interactions and consider the underlying processes at a small-scale level.

1.2.1 Fuels

Fuels, in a very general sense, are combustible materials (Omi 2005). With regard to forest fires, the aboveground phytobiomass (i.e. all plant material above the mineral soil) constitute fuel (Pyne *et al.* 1996) and can be further classified.

Live fuels are living plants that can take up water from the soil, control their moisture content by ecophysiological processes (e.g. transpiration, stomatal closure) and thus maintain a high water content even in dry periods; whereas dead fuels no longer possess these abilities and depend solely on the surrounding conditions (Keane 2015; Pyne *et al.* 1996; Johnson & Miyanishi 2001).

Fuel layers are commonly divided into canopy/aerial (2 m and higher above the ground), ground (all organic matter below the ground line) and surface (in-between the ground line and canopy) fuels (Keane 2015). Common definitions (Pyne *et al.* 1996; Keane 2015; Johnson & Miyanishi 2001) put the ground line on top of the fermentation and humus (duff, O_h) layers, while the undecomposed litter (O_l) layer is already included in the surface fuels. This is based on the significantly different moisture and fire behaviour of those layers, which will be discussed further in the following chapters.

The variety of fuel components present in the forest can in total be described as a fuel complex (Pyne *et al.* 1996) or, more generally, as a fuel bed (Keane 2015). Several systems and techniques are available for the classification of fuel beds in fuel models, simplified numeric descriptions that can e.g. be used in fire behaviour models (Pyne *et al.* 1996; Anderson 1982; Rothermel 1972; Scott & Burgan 2005).

1.2.2 Fire ignition and burning

In order for a fuel to burn, however, it first needs to be ignited. In very general terms, this requires the presence of an ignition source transferring energy (by conduction, convection, radiation, or a mixture of those) to the fuel (Pyne *et al.* 1996; Scott 2014). This initiates the phase of pre-ignition/preheating linked to endothermic reactions and the raising of fuel temperature, as well as the evaporation of free water and release of volatile substances (dehydration, Pyne *et al.* 1996, Keane 2015). Continuing influence of the ignition source leads to a depletion of adsorbed moisture within the fuel, followed by pyrolysis (i.e. thermal degradation) and flammable gas release (Pyne *et al.* 1996; Johnson & Miyanishi 2001). The actual ignition is the transition between this preheating phase and self-sustaining combustion, which may occur given a sufficient rate of flammable gas generation, high temperatures and/or the presence of an open flame (so-called piloted ignition, Pyne *et al.* 1996).

It should be noted that fuel moisture is a major determinant of ignitability and the energy required for ignition, as it impedes fuel heating (Pyne *et al.* 1996; Scott 2014), leads to a cooling effect (Britton *et al.* 1973) and a dilution of combustible gases (Chandler *et al.*

1983). Higher particle thermal conductivity and volumetric heat capacity may additionally hinder fire ignition and spread in wet fuels (Omi 2005). Thus, fire danger is related to the dryness of fuels (as already observed in Figure 1), and this is also used in the 'moisture of extinction' concept (Keane 2015; Rothermel 1972; Trabaud 1976); the fuel moisture content above which combustion no longer occurs. In an experimental study, this threshold was found between 40 and 45% of fuel moisture in dead fuels (Trabaud 1976).

Combustion may occur as a flaming, smoldering or glowing process, depending on the fuel arrangement, heat and oxygen supply (Pyne *et al.* 1996; Johnson & Miyanishi 2001). A simplified representation of the combustion process can be found in Eq. 1, showing the oxidation of the glucose molecule, a basic chemical unit of many forest fuels (Omi 2005). This is essentially a rapid, exothermic reverse of photosynthesis (Pyne *et al.* 1996).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + heat$$ **(Eq. 1)**

Spreading of a burning fire involves the same processes (heat transfer to neighbouring fuels, surface dehydration, heating and pyrolysis) as ignition (Pyne *et al.* 1996; Scott 2014). Depending on the fuel layer, three basic types of fire behaviour can be distinguished: surface fires showing flaming combustion of litter, grass and shrubs, crown fires burning in the canopy layer and often depending on surface fires underneath, and ground fires in organic fuels underneath the surface (Pyne *et al.* 1996; Scott 2014; USDA Forest Service 1956). The latter are characterized by smoldering combustion and are usually also started by surface fires. Thus, most fires burn or at least start in the surface/litter layer.

1.2.3 Dead fuel moisture

As indicated above, fuel moisture is an important parameter influencing the fire ignition and burning processes and therefore a critical parameter in fire behaviour (Keane 2015) and fire danger rating (Davis *et al.* 1959) applications.

The moisture content of materials and fuels (u_G, in percent) is generally expressed on a dry-weight basis using Eq. 2 (Pyne *et al.* 1996; Johnson & Miyanishi 2001).

$$u_G = \frac{m_w - m_d}{m_d} \times 100$$ **(Eq. 2)**

Where m_w and m_d are the wet and oven-dry mass of a sample, respectively. Thus, moisture content is the weight of water per weight of oven-dry material, a value that can range from few to several 100% in dead fuels (Pyne *et al.* 1996).

Water in a dead fuel can either be present as 'free water' (e.g. in vessels or cavities) at high moisture contents above fiber saturation or as bound water (Keane 2015). The latter is known as 'hygroscopicity' of dead fuels and caused by the chemical structure of the cellulose and lignin in its cell walls, which are attracting and binding water molecules (Keane 2015; Johnson & Miyanishi 2001). While there is always an exchange of moisture between the fuel and the surrounding atmosphere, storing the fuel under the same conditions (temperature and relative humidity) will eventually lead to a steady state without any net moisture exchange called 'equilibrium moisture content' (EMC). It is not identical when reached from a higher (desorption) or a lower (adsorption) fuel moisture (hysteresis, Keane 2015, Pyne *et al.* 1996, Johnson & Miyanishi 2001) and depending on temperature and relative humidity. Sorption isotherms can be used to present EMC as a function of relative humidity for a given temperature (cf. Figure 3).

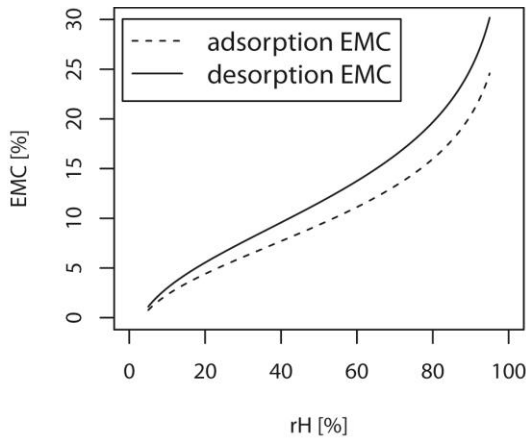

Figure 3: Sorption isotherms for recent Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) litter at 22°C, data from Anderson (1990). EMC: equilibrium moisture content, rH: relative humidity.

In addition to the steady-state EMC, the time a fuel needs to adapt to a sudden change in atmospheric conditions can also be used for characterization. The fuel moisture response follows a negative exponential curve and the response time ('time lag') has been defined as the time taken to reach 1 - 1/e (≙63%) of the difference between the initial and the final (equilibrium) moisture content (Pyne *et al.* 1996; Anderson 1989; Anderson *et al.* 1978). Time lags increase logarithmically with the diameter of woody fuels (Keane 2015) and can vary extremely in dead surface fuels (Pyne *et al.* 1996; Schroeder & Buck 1970). For duff and litter layers, a dependence on the degree of decomposition and bulk density could be found, with slightly decomposed, low-density layers showing faster drying than more compact and decomposed layers (Plamondon *et al.* 1972).

In a real-world forest, however, fuel moisture is not only determined by atmospheric conditions, the EMC and time lag mentioned before; position of the fuel (both topographic and within a site), stand climate, precipitation (direct or as throughfall), dew, water uptake from the ground and many more parameters also play an important role (Pyne *et al.* 1996).

1.3 Fire danger rating

In the ideal case, fire danger rating is “a definite, integrated, meaningful, and consistent tool immediately useful in the practice of fire control” (Davis *et al.* 1959) and can thus be employed for various fire management actions (e.g. fire prevention, public warnings, resource allocation and scheduling of prescribed fires, Pyne *et al.* 1996). In Bavaria, fire danger index outputs are used for public warnings and as a help to schedule observation flights for fire detection. While fire danger rating systems can integrate factors other than meteorology (e.g. stand type/species/fuels, phenology, topography), most of them only consider prevailing weather and keep any remaining factors constant (Pyne *et al.* 1996). This allows for a uniform rating of fire danger over large areas and comparisons among areas, seasons and years; however, species, topographic and other small scale differences have to be accounted for during the interpretation of index values.

It should also be noted that the term ‘fire danger’ is not consistently used in the fire community (cf. Bachmann & Allgöwer 2001) and that the outputs of fire danger indices available may reflect different properties, such as the probability of a fire igniting, fuel consumption or potential fire behaviour. The wide variety of fire danger indices available (e.g. Table 1) is based on fire occurrence statistics, experimental data or process-based models. In the following chapters, three exemplary indices/systems are presented.

1.3.1 Baumgartner index

The Baumgartner fire danger index was constructed by Baumgartner *et al.* (1967) on the basis of fire occurrence data (1,706 forest fires that occurred in Bavaria between 1950 and 1959) related to meteorological observations. The mean weather conditions before and after the day of the fire are shown in Figure 4.

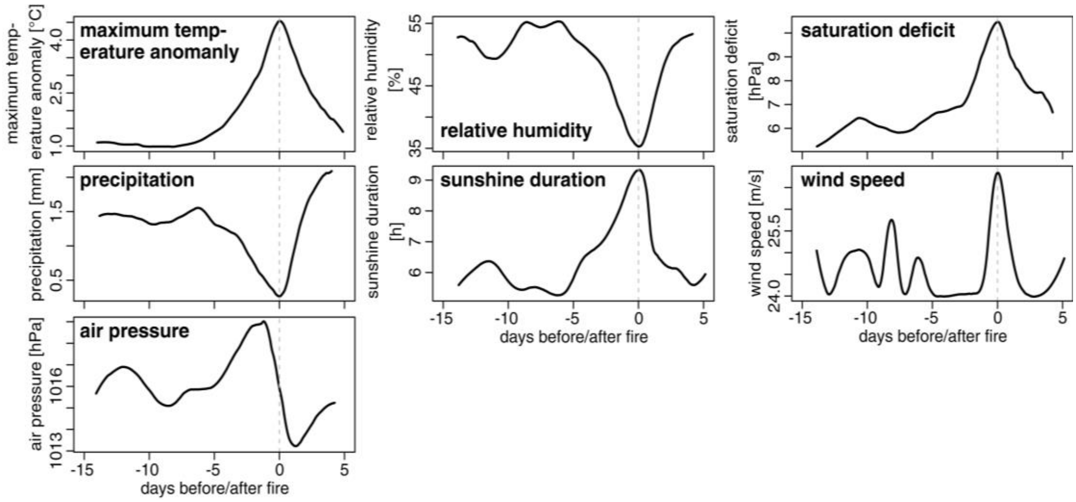

Figure 4: Average meteorological conditions before and after forest fire occurrence in Bavaria 1950-1959, after Baumgartner *et al.* (1967). The dashed vertical line represents the day of the fire start.

Baumgartner *et al.* (1967) revealed that fires on average occur in a period of falling air pressure after a prevailing high-pressure system, associated with an absence of precipitation and an increasing (maximum) temperature anomaly, sunshine duration and saturation deficit. Wind speed also increased shortly before the fire occurred. Interestingly, forest fires can thus be expected not to occur within, but rather at the end of a fine-weather period (Baumgartner *et al.* 1967). Similar findings were also made by Geiger (1948) and in Canada (Flannigan 2014).

Baumgartner *et al.* (1967) further reasoned that drying-dependent fire danger can be described by energy balances and evaporation measures, while it is diminished by precipitation. Thus the difference of evaporation and precipitation was calculated and a five-day accumulation was found to be sufficient for assessing the fire danger of the following day. Danger classes could be defined from 20%-steps of cumulative fire frequency (cf. Figure 5, Baumgartner *et al.* 1967). However, this assessment was only possible for months with a sufficient number of fires (March through September) and the classification differed from month to month, with higher evaporation necessary to reach the same fire danger level/cumulative fire frequency in summer than in spring and autumn. In addition to this meteorological assessment, Baumgartner *et al.* (1967) also suggested to adapt the regional fire danger levels according to fire occurrence statistics.

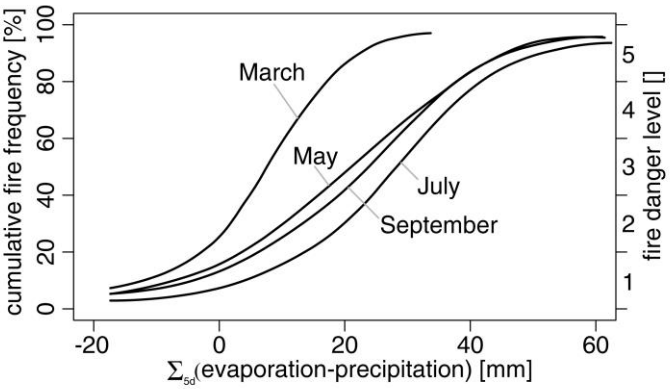

Figure 5: Fire frequency per 5-day accumulated difference of evaporation and precipitation and fire danger levels derived. Only the months March, May, July and September are shown for clarity. After Baumgartner *et al.* (1967).

1.3.2 Canadian Fire Weather Index System

In contrast, the Canadian Fire Weather Index System (CFWIS) and its predecessors are empirical indices developed from basic physical models calibrated with field data, including meteorological and fuel moisture measurements, as well as small-scale test fires (van Wagner 1987; Wotton 2009). Mature Jack pine (*Pinus banksiana* Lamb.) and Lodgepole pine (*Pinus contorta* Dougl.) were chosen as the standard forest type. The system consists of six components related to the moisture of three different fuel classes (fine fuel moisture code - FFMC, duff moisture code - DMC, drought code - DC), rate of spread (initial spread index - ISI), fuel consumption/availability (buildup index - BUI) and fire intensity (fire weather index - FWI); cf. Figure 6,van Wagner (1987).

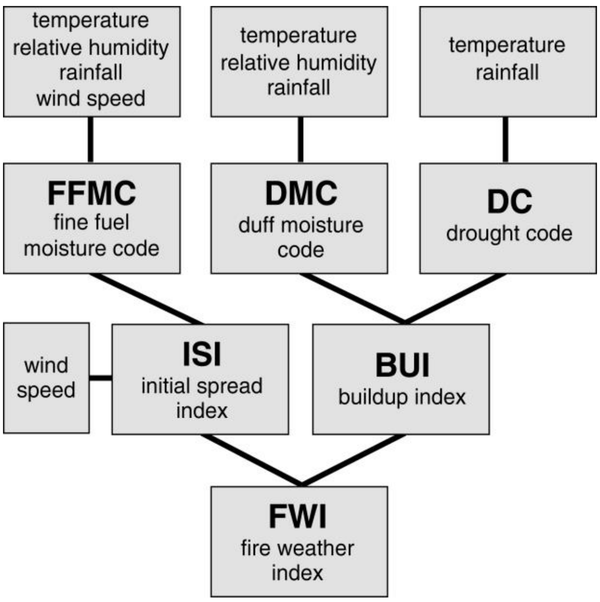

Figure 6: Structure of the Canadian Forest Fire Weather Index System, after van Wagner (1987).

The FFMC is calculated based on the moisture content of a 1.2 cm deep, 0.25 kg/m² dry fuel load litter/fine fuel layer with a water capacity of 0.6 mm and a time lag of ~0.67 days (at 21.1°C and 45% relative humidity, van Wagner 1987). This is modelled using a bookkeeping system integrating the previous day's moisture content, drying as defined by equilibrium moisture content and the relative humidity-, wind speed- and temperature-dependent log drying rate (cf. chapter 1.2.3). Wetting calculations are made using a log wetting rate similar to the log drying rate, as well as a rainfall routine depending on the initial moisture content and amount of rainfall, corrected by 0.5 mm of interception (van Wagner 1987). Due to psychological reasons, FFMC and the other moisture indices were built to increase with increasing dryness (i.e. decreasing fine fuel moisture content). According to Wotton (2009), FFMC can be expected to correlate with the moisture content of many different fine fuels, such as grass, small branches as well as leaf and needle litter. As the moisture of fine surface fuels is also linked to their ignitability, FFMC can be used as an indicator of human-caused fire occurrence with additional influences, however, from forest type and human activities (Wotton 2009).

DMC represents the moisture content of the subjacent layer of decaying litter (7 cm deep, 5 kg/m² fuel load, 15 mm water capacity and 12 days time lag at 21.1°C and 45% relative humidity) and is calculated in a similar way as the FFMC (van Wagner 1987). However, equilibrium moisture content is kept constant (20%) and the drying rate is not depending on the wind speed but additionally on day length (van Wagner 1987). In Canada, DMC has been found well correlated to the number of fires per lightning strike, as the lightning discharge often ignites organic material near the tree trunks and the ground surface, and also to the depth of burn in experimental fires (Wotton 2009).

Moisture of deeper and denser organic layers (nominally 18 cm depth, 25 kg/m² fuel load, 100 mm water capacity and 52 days time lag at 21.1°C and 45% relative humidity, van Wagner 1987) is simulated by the DC. This is the slowest-reacting moisture index of the system and is calculated based on effective rainfall (reduced, amongst others, by 2.8 mm interception) and potential evapotranspiration as calculated from temperature and day length (van Wagner 1987). Because of the slow response time, the influence of the previous year's weather conditions on the starting value in the following year (overwintering) also needs to be considered (van Wagner 1987).

The ISI combines the FFMC and wind speed to a dimensionless measure of fire spread (van Wagner 1987; Wotton 2009). While it is a good indicator for Canadian fuel types in general, largely different correlations could be found from one fuel type to the other (Wotton 2009).

The moisture levels of fuels covered by the DMC and DC are integrated in the BUI in order to represent the amount of fuel available (i.e. dry enough) to be consumed by surface fire (Wotton 2009). Although its calculation is somewhat complex, BUI is essentially a harmonic mean of the DMC and weighed DC (Wotton 2009).

FWI, the final and main index of the Canadian Fire Weather Index System, provides a measure of the potential intensity of a spreading fire per unit of fire perimeter (Wotton 2009). It is analogue to Byram's fireline intensity (Eq. 3).

$$I = Hwr \qquad \textbf{(Eq. 3)}$$

Where I is the fire intensity as described above, H is the heat yield of combustion (energy per fuel mass), w is the weight of available fuel and r is the rate of spread (Davis *et al.* 1959). FWI uses BUI and ISI as indicators for the amount of fuel consumed (w) and the rate of spread (r), respectively (Wotton 2009). While it gives an indication of the general fire potential and is used for public warnings (in the form of fire danger levels), fire management agencies in Canada mostly rely on its sub-indices for operational planning (Wotton 2009). It should be noted that in addition to the Canadian Fire Weather Index system, the superordinate Canadian Forest Fire Danger Rating System has been introduced that provides additional fuel moisture models (e.g. increased temporal resolution and stand-specific moisture conversion) as well as fire occurrence and behaviour prediction systems (Wotton 2009).

1.3.3 Waldbrandgefahrenindex

Recently, a novel index called 'Waldbrandgefahrenindex' (WBI) has been developed and put into operational use by the German Meteorological Service (Deutscher Wetterdienst – DWD, Wittich & Bock 2014, Wittich *et al.* 2014, DWD 2016). This index combines aspects of several other systems (Baumgartner *et al.* (1967), M-68 (Käse 1969), CFWIS (van Wagner 1987)) and has a largely physical modelling/process-oriented rather than a fire occurence or an empirical basis. Similar to the FWI, it is also using Byram's fireline intensity for the main index (cf. Davis *et al.* 1959, Eq. 3) and there are internal components for the moisture of litter and soil, as well as for the rate of spread (DWD 2016). Wetting and drying are modelled using water balance equations for the canopy, litter and soil, with the foliage and litter intercepting part of the rainfall and the canopy also reducing radiation levels (DWD 2016). The litter layer has a nominal depth of 12 mm and is described using a dedicated process-based litter moisture model (Wittich 2005), e.g. taking differential heat- and water-transfer equations into account. The rate of spread (parameter r in Byram's fireline intensity, Eq. 3) is determined using litter moisture and wind speed, following an algorithm from the Canadian Fire Behaviour Prediction System (DWD 2016). Soil moisture can be calculated for three different forest types (coniferous with a coarse-grain soil and low water capacity, deciduous with a fine-grain soil and high water capacity, and mixed forests in-between) which also possess different leaf area index (DWD 2016; Wittich *et al.* 2014). This follows the approach of the M-68 index (Käse 1969), where the index calculation is adapted for areas with different forest types/fire susceptibility. Along with litter moisture and leaf area index, soil moisture is used to compute the amount of available fuel (w in Eq. 3, DWD 2016). The index calculation is based on hourly time series of temperature, relative humidity, wind speed, rate of precipitation, amount of snowfall and short- and longwave radiation (DWD 2016). The final model output are danger levels (1 through 5), calibrated using data from few test fires and coherence with other danger indices (FWI, Baumgartner, M-68 and Angstrom (Chandler *et al.* 1983); Wittich *et al.* 2014). The maximum of hourly values in the timespan 12 to 18 h UTC is published (DWD 2016). Due to the choice of wind speed-dependent fireline intensity and the inclusion of the litter layer, the index is more responsive than the Baumgartner and M-68 indices previously used in Germany (DWD 2016). For example, a change to moist air masses during otherwise dry periods may lower the index even without any precipitation (due to adsorption) and changes in wind speed affect the fireline intensity, thus the final index, directly (Wittich *et al.* 2014).

1.4 Local conditions and previous studies

In addition to the fire danger indices just illustrated (Baumgartner *et al.* 1967; Käse 1969; DWD 2016), research on forest fires and fire danger has been relatively limited in Bavaria, Germany and adjacent areas. This is partially due to the limited overall amount and significance of fires. For example, in the state of Bavaria (forested area 7,055,019 ha, BMEL 2014), an average number of 71 forest fires and a burnt area of 87 ha per year is reached, respectively (2002-2014, including federal forests, data: Federal Office for Agriculture and Food, Bundesanstalt für Landwirtschaft und Ernährung - BLE). The average monthly number of fires and area burnt in the same period is depicted in Figure 7. A very similar seasonality with a spring maximum of fire occurrence was already observed by Julio (1979) and Baumgartner *et al.* (1967), who linked this to the rapid drying of cured ground vegetation (e.g. grass) before green-up. The predominant influence of human ignition causes is apparent even in the large proportion of fires and burnt area in federal forests only representing few percent of the forested area (BMEL 2014), but being used as military training areas and thus subject to increased human-caused ignitions. In recent years, fires in the commonly humid Alpine part of Bavaria have been an increasing cause of concern, since they proved difficult to fight due to steep terrain with limited access and intense fire behaviour. They also occurred in uncommon seasons, including November, December and early March, and burned relatively large areas of protected forests with many functions (e.g. avalanche, debris flow and water protection).

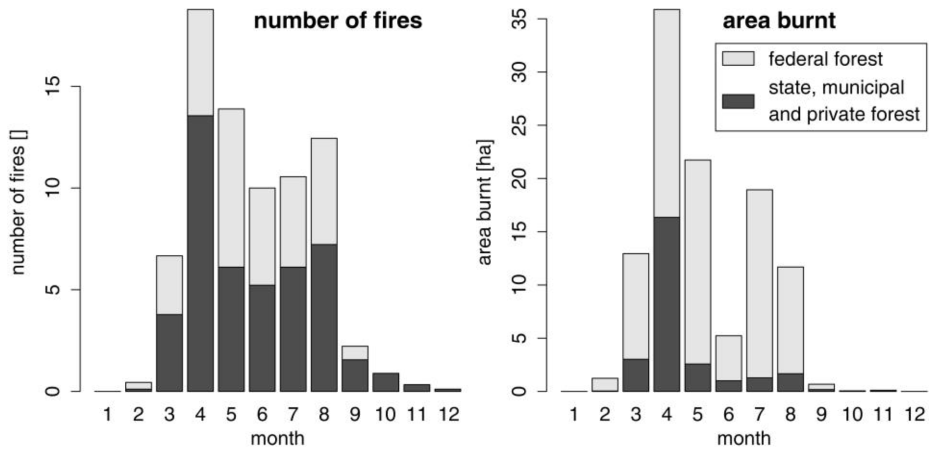

Figure 7: Average number of fires and area burnt in Bavaria 2002-2014 per month. Data source: Federal Office for Agriculture and Food (Bundesanstalt für Landwirtschaft und Ernährung - BLE).

Even before Baumgartner *et al.* (1967), Weck (1947) and Geiger (1948) analyzed fire occurence data, identified potential factors influencing fire occurrence and compiled first ideas for fire danger rating. A first simple, binary index based on relative humidity was proposed by Zieger (1953). Deichmann (1957, 1960) analyzed ignitability of surface fuels and suggested rating fire danger from wind speed, relative humidity and precipitation.

Numeric fire danger index comparisons using fire occurrence data were carried out by Schmidtmeyer (1993), Holsten *et al.* (2013) and Arpaci *et al.* (2013) for Bavaria, Germany and Austria, respectively. In addition, Patzelt (2008) and Kolb *et al.* (2014) qualitatively discussed fire danger index behaviour in case studies.

As part of their research effort, German Meteorological Service tested grass curing observations (Wittich 2011) and the potential of fire ignition by glass fragments (Wittich & Müller 2009).

Fire ecology and the use of prescribed burning in forest protection and conservation have also been investigated, e.g. by Goldammer (1979), Goldammer *et al.* (2012), Hille & den Ouden (2004, 2005).

2 Aims and outline of the thesis

Following the interactions and dependencies outlined in chapter 1, this thesis aims to contribute to a better understanding of recent and future changes of fire danger, as well as its rating in the state of Bavaria, Germany, and the adjacent Alpine area. The chapters outlined below are classified according to their approximate temporal and spatial scale in Figure 8.

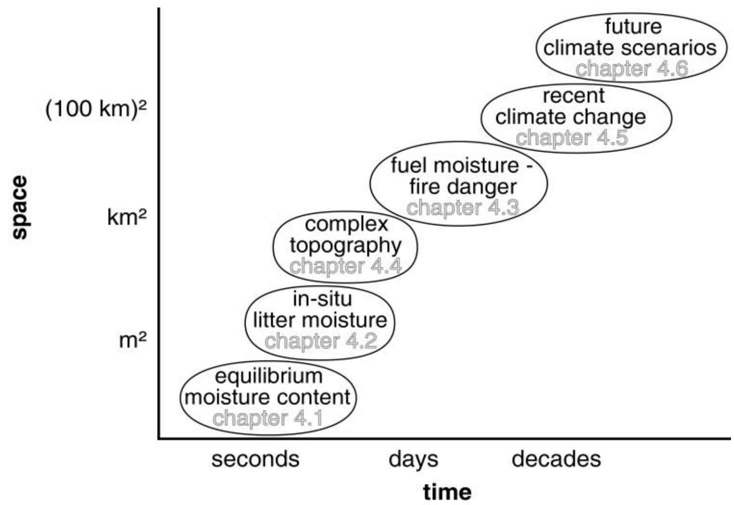

Figure 8: Classification of thesis chapters according to spatial and temporal scale.

Equilibrium moisture content is an intrinsic fuel property that has not been investigated so far for Central European fuels, although it is a basis for many fire danger rating systems (e.g. WBI (DWD 2016), Canadian Fire Weather Index System (van Wagner 1987)). It is analysed for the four main tree species of Germany in chapter 4.1; the data is presented and provided for further modelling and operational use and different techniques for sample conditioning are tested and compared.

In the field, measurements of dead fine fuel (e.g. litter) moisture can provide an independent parameter for fire danger (cf. chapters 1.2.2, 1.2.3 and 1.3). However, the procedures are very cumbersome and labour-intensive (e.g. regular manual sampling in a fixed time interval, laboratory processing) and results can only be obtained after the drying process has finished (typically 24 hours delay, cf. Matthews 2010). Thus a simple technique for obtaining fine fuel moisture content values automatically would be very worthwhile and is investigated specifically in chapter 4.2, as well as in chapter 4.3, using a variety of existing measuring techniques for soil, wood and fuel moisture.

Evaluation of fire danger indices based on fire occurrence has already been attempted for Bavaria, Germany and Austria (cf. Schmidtmeyer 1993, Holsten *et al.* 2013, Arpaci *et al.* 2013). However, these studies are limited by the low frequency of fire occurrence (e.g. Holsten *et al.* (2013) had to work with monthly data, while fire danger changes at a daily or even diurnal scale) and may additionally be affected by human ignition patterns. For example, Wastl *et al.* (2012) stated that in the last 50 years, low fire occurrence in Bavaria in a given year was not necessarily linked to low fire danger (as defined by several fire danger indices), and Wittich & Bock (2014) raised some concern about the results of such analyses. Thus, a different technique for evaluating fire danger indices and differences between species and sites independent of human ignitions and based on litter moisture content is presented in chapter 4.3.

Index performance and accuracy furthermore is of special importance for the Alpine part of Bavaria with its steep topography and the recent fire context (cf. chapter 1.4). The meteorological situation and fire danger index behaviour related one of the recent exceptional fires is analysed in chapter 4.4, with a special view to fire danger index and input data requirements.

While fire danger is currently relatively limited and thus not a major forest protection issue in southern Germany, this may change or already have shifted due climatic changes. Trends of fire danger and occurrence in the recent past (1951-2010) and projected future changes are therefore examined in chapters 4.5 and 4.6, respectively. The whole Alpine area is included in the analysis to show potential differences of the areas surrounding and within the European Alps. The analyses are based on changes of calculated fire danger indices, as fire occurrence is sufficiently limited and not expected to lead to major vegetation cover or climate feedbacks (cf. chapter 1.1). For future projections, influences of using a single regional climate model versus a multi-model approach are shown, thus also adding methodological considerations.

3 Overview of methods

While the methods used as well as the scientific state of the art are fully presented in the publications associated with each of the following chapters, a brief overview is given here.

3.1 Gravimetric moisture content determination and sampling

Gravimetric litter moisture determination (cf. Figure 9) is used in chapters 4.1 to 4.3, as well as for supplementary data in chapter 4.4. The moisture content is calculated from sample wet and oven-dry mass as indicated in Eq. 2. All drying was performed for 24 hours at 105°C, as recommended by Matthews (2010). To avoid buoyancy effects, samples were allowed to cool off in desiccators before the dry mass was determined using balances with a suitable range and accuracy.

Material considered as litter was the O_L layer represented by undecomposed, dead needles and leaves, as well as small branches < 4 mm diameter, inflorescence and fruits. Care was taken to ensure at least a minimum of repetitions and a representative distribution of sampling locations.

In case of the equilibrium moisture content determination in chapter 4.1, sample conditioning was performed in a walk-in climate chamber as well as exsiccators and a special sorption device over saturated salt solutions. Wet mass was measured repeatedly for different relative humidities and temperatures before the samples were dried.

Field samples taken in chapters 4.2 to 4.4 were put in air-tight polypropylene bottles and brought or shipped to the laboratory as soon as possible (i.e. within a few days). During most of the studies, it was aimed to perform the fuel moisture sampling between 11:00 and 13:00 h LST to account for diurnal variations, although this was not always possible. Depending on the study and site considered, sampling was carried out daily to weekly, or based on staff availability and prevailing weather conditions.

3.2 Automated moisture measurements

In addition, techniques for automated litter or fuel moisture measurements were tested and used in 2010 and 2013 (chapters 4.2 and 4.3, respectively). While a direct measurement at the litter layer/fuel particle level was attempted in 2010, using various frequency domain and electrical resistance sensors; commercially available, standardized 10-hr fuel moisture sticks by Campbell Scientific, Inc. were used in 2013 (cf. Figure 9). The automated measurements were related to concurrent gravimetric litter moisture values in order to determine calibration equations for litter moisture (chapters 4.2 and 4.3) and the stability of those over the course of a season (chapter 4.2). 10-hr fuel moisture was also used to explain whether differences in litter moisture behaviour of two different forest types are due to within-stand microclimate or differences in the litter layer and underlying soil (chapter 4.3).

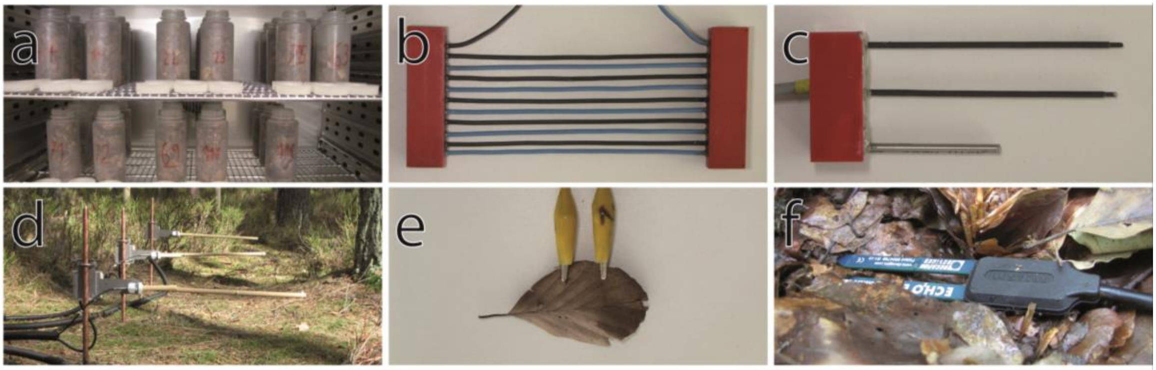

Figure 9: Methods of moisture content determination: a) gravimetric/oven drying; b), c) and f) frequency domain sensors; d) 10-hr fuel moisture sticks; e) electrical resistance sensor.

3.3 Meteorological data sources and models

As a basis for fire danger index computations and direct comparisons, meteorological measurement and model data was necessary.

For present and historical analyses (chapters 4.3 to 4.5), open-air station observations were used, with data supplied by the network of forest climate stations of the Bavarian State Forest Institute (Landesanstalt für Wald und Forstwirtschaft - LWF), the German Meteorological Service (Deutscher Wetterdienst - DWD), the Central Institute of Meteorology and Geodynamic in Austria (Zentralanstalt für Meteorologie und Geodynamik - ZAMG), MeteoFrance, MeteoSwiss, the Environmental Agency of the Republic of Slowenia, the Aeronautical Service Agency Italy, the Venice Institution of Science and a station run by the Professorship of Ecoclimatology. This data was at a temporal resolution of 10 min to 1 day, depending on the parameter and data provider. In chapter 4.4, data from an altitudinal gradient of within-forest temperature-humidity data loggers (run by the Professorship of Ecoclimatology within 'KLIMAGRAD' project), as well as radiosonde soundings (obtained from NOAA's Integrated Global Radiosonde Archive) were used to illustrate the vertical profiles of temperature and humidity during inversion.

Future projections of meteorological parameters (chapter 4.6) were derived from a single regional climate model as well as multi-model outputs. The single model used was the non-hydrostatic regional climate model COSMO-CLM (Böhm *et al.* 2008), with input from the coupled atmosphere-ocean global circulation model ECHAM5/MPIOM (Jungclaus *et al.* 2006). A single step was used to dynamically downscale the ≈200 km-resolution global model to ≈18 km (0.2°) horizontal resolution.

In contrast, the multi-model consisted of 7 different regional climate models (HIRHAM5, REGCM3, HadRM3Q0, RM4.5, CLM, RACMO2 and REMO) selected to represent the variety of leading global and regional climate models. Depending on the parameter and training data available, the model outputs were combined using different techniques. For temperature and precipitation, it was possible to compute so-called ‘Multimodel SuperEnsembles’, where a training period with reference observations from the E-OBS dataset (Haylock *et al.* 2008) is used to weigh the model outputs for ECMWF ERA-40 reanalysis data and to reduce their biases. While the standard Multimodel SuperEnsembe technique was used for temperature, a novel probabilistic Multimodel SuperEnsemble Dressing (Cane & Milelli 2010) was applied to precipitation. For wind speed and relative humidity, no reference observations were available and thus a simple averaging of the models was performed. Spatial resolution of the regional climate models used in the multi-model was adapted to the reference measurement resolution, 25 km, with a simple bi-linear interpolation.

COSMO-CLM and multi-model data for SRES scenario A1B and a reference (1991-2010) as well as a scenario (2031-2050) period were selected for further analysis.

3.4 Fire danger index computations

Fire danger index calculation in chapters 4.3 to 4.6 was based on the data described above and carried out with a FORTAN program purpose-written by colleague Dr. Clemens Wastl. The computable indices and sub-indices are listed in Table 1; note that not all of these indices were used in the specific chapters and that they may represent radically different aspects of fire danger (cf. chapter 1.3). Additionally, for some indices and chapters, data sources had to be merged to enable the necessary computations (e.g. for the M-68 index (Käse 1969) in chapter 4.3 that requires phenological and snow data not determined at the forest climate stations). For chapter 4.4, Mc Arthur’s forest fire danger index as well as the Canadian FFMC were also calculated at an hourly resolution, following Noble *et al.* (1980) and van Wagner (1977), respectively. As the calculation method of the novel 'Waldbrandgefahrenindex' (WBI, cf. chapter 1.3.3) is not yet fully published, this could not be included in the analyses.

Table 1: Fire danger indices computable.

acronym	index name	country of origin	input data	reference
Baumgartner	Baumgartner	Germany	T, H, P, U	Baumgartner *et al.* (1967)
M-68	M-68	Germany	T, H, P, U, S, Phenology	Käse (1969)
Nesterov	Nesterov	Russia	T, H, P	Nesterov (1949)
Angstrom	Angstrom	Sweden	T, H	Chandler *et al.* (1983)
FWI	fire weather index	Canada	T, H, P, U	van Wagner (1987)
DSR	daily severity rating	Canada	T, H, P, U	van Wagner (1987)
ISI	initial spread index	Canada	T, H, P, U	van Wagner (1987)
BUI	buildup index	Canada	T, H, P	van Wagner (1987)
FFMC	fine fuel moisture code	Canada	T, H, P, U	van Wagner (1987)
MC	fine fuel moisture content	Canada	T, H, P, U	van Wagner (1987)
DMC	duff moisture code	Canada	T, H, P	van Wagner (1987)
DC	drought code	Canada	T, P	van Wagner (1987)
KBDI	Keetch-Byram drought index	US	T, P	Keetch and Byram (1968)
DF	drought factor	US	T, P	Keetch and Byram (1968)
FFWI	Fosberg's Fire Weather Index	US	T, H, U	Goodrick (2002)
McArthur / FFDI	McArthur's Forest Fire Danger Index	Australia	T, H, P, U	Noble *et al.* (1980)

3.5 Comparison to fire occurrence data

In chapters 4.5 changes in fire occurrence and burnt area are related to long-term trends in meteorological fire data, provided by the Swiss Federal Institute for Forest, Snow and Landscape Research (Eidgenössische Landesanstalt für Wald, Schnee und Landschaft - WSL) and the Bavarian State Ministry for Food, Agriculture and Forestry (Bayerisches Staatsministerium für Ernährung, Landwirtschaft und Forsten - StMELF). Furthermore, a large fire occurrence dataset is used for fire danger index selection based on a comparison of fire/no-fire days in the future projection study (chapter 4.6). This dataset was supplied by the Regional Agency for Environmental Protection of Piedmont (Agenzia Regionale per la Protezione dell'Ambiente del Piemonte - ARPA Piemonte).

4 Abstracts of and contributions to individual publications

4.1 Equilibrium moisture content of dead fine fuels of selected central European tree species

Christian Schunk, Clemens Leutner, Michael Leuchner, Clemens Wastl and Annette Menzel (2013), *International Journal of Wildland Fire 22: 797-809*, doi: 10.1071/WF12105.

Fine fuel moisture content is a key parameter in fire danger and behaviour applications. For modelling purposes, equilibrium moisture content (EMC) curves are an important input parameter. This paper provides EMC data for central European fuels and adds methodological considerations that can be used to improve existing test procedures. Litter samples of Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.), European beech (*Fagus sylvatica* L.) and pedunculate oak (*Quercus robur* L.) were subjected to three different experiments using conditioning in a climate chamber and above saturated salt solutions. Climate chamber conditioning yielded the best results and can generally be recommended, however saturated salt solutions are able to produce lower relative humidities, which are relevant to forest fire applications as they represent the highest fire danger. Results were within the range of published sorption isotherms for forest fine fuels. A fairly clear gradation was present with higher EMC values in leaf litters than in needle litters. These differences are in accord with values from the literature and suggest general differences in the sorption properties of leaves and needles, which may be caused by differing chemical and physical properties. The influence of temperature on EMC described in the literature could be confirmed.

Contributions:

I designed the study, acquisitioned the fuel samples and arranged for the necessary lab facilities (contact to Chair of Wood Science, repairs of climate chamber etc.). *Clemens Leutner*, a Bachelor student under my guidance, performed much of the lab work and an initial analysis for his related thesis. *Michael Leuchner* provided practical and methodological assistance and together with *Clemens Wastl* helped with the analysis and writing of the manuscript. *Annette Menzel* supported analysis of the data and manuscript writing. The TUM Chair of Wood Science provided a special sorption device, as well as sample preparation facilities and technical assistance. About 75% of the work was done by myself.

4.2 Comparison of different methods for the in situ measurement of forest litter moisture content

Christian Schunk, Bernhard Ruth, Michael Leuchner, Clemens Wastl and Annette Menzel (2016), *Natural Hazards and Earth System Sciences 16:* 403-415, doi: 10.5194/nhess-16-403-2016.

Dead fine fuel (e.g., litter) moisture content is an important parameter for both forest fire and ecological applications as it is related to ignitability, fire behavior and soil respiration. Real-time availability of this value would thus be a great benefit to fire risk management and prevention. However, the comprehensive literature review in this paper shows that there is no easy-to-use method for automated measurements available. This study investigates the applicability of four different sensor types (permittivity and electrical resistance measuring principles) for this measurement. Comparisons were made to manual gravimetric reference measurements carried out almost daily for one fire season and overall agreement was good (highly significant correlations with 0.792< =r <=0.947, p <0.001). Standard deviations within sensor types were linearly correlated to daily sensor mean values; however, above a certain threshold they became irregular, which may be linked to exceedance of the working ranges. Thus, measurements with irregular standard deviations were considered unusable and relationships between gravimetric and automatic measurements of all individual sensors were compared only for useable periods. A large drift in these relationships became obvious from drought to drought period. This drift may be related to installation effects or settling and decomposition of the litter layer throughout the fire season. Because of the drift and the in situ calibration necessary, it cannot be recommended to use the methods presented here for monitoring purposes and thus operational hazard management. However, they may be interesting for scientific studies when some manual fuel moisture measurements are made anyway. Additionally, a number of potential methodological improvements are suggested.

Contributions:

I had the idea for and designed the study. *Bernhard Ruth* provided his non-commercial soil moisture sensors and valuable comments and interpretation in the data analysis and publication phase. *Michael Leuchner* and *Clemens Wastl* provided methodological support and together with *Annette Menzel* helped in data analysis and writing of the manuscript. About 85% of the work was done by myself.

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

Christian Schunk, Clemens Wastl, Michael Leuchner and Annette Menzel, submitted to: *Agricultural and Forest Meteorology*, 06 April 2016.

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, since fire danger is expected to be linked to micrometeorology and dead fine fuel moisture, the use of litter and 10-hr 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-hr 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.

Contributions:

The study was planned and carried out by myself, with conceptual help from *Annette Menzel*, *Michael Leuchner* and *Clemens Wastl*. Field sampling was carried out with the help of several colleagues and external sampling staff under my guidance. Most of the laboratory work was done by me and an additional student assistant. *Clemens Wastl's* fire danger index calculator was used and the analysis supported by *Annette Menzel*. All of the co-authors reviewed the draft manuscript before submission. About 90% of the work was done by myself.

4.4 Forest fire danger rating in complex topography – results from a case study in the Bavarian Alps in autumn 2011

Christian Schunk, Clemens Wastl, Michael Leuchner, Christina Schuster and Annette Menzel (2013), *Natural Hazards and Earth System Sciences 13: 2157-2167*, doi: 10.5194/nhess-13-2157-2013.

Forest fire danger rating based on sparse meteorological stations is known to be potentially misleading when assigned to larger areas of complex topography. This case study examines several fire danger indices based on data from two meteorological stations at different elevations during a major drought period.

This drought was caused by a persistent high pressure system, inducing a pronounced temperature inversion and its associated thermal belt with much warmer, dryer conditions in intermediate elevations. Thus, a massive drying of fuels, leading to higher fire danger levels, and multiple fire occurrences at mid-slope positions were contrasted by moderate fire danger especially in the valleys. The ability of fire danger indices to resolve this situation was studied based on a comparison with the actual fire danger as determined from expert observations, fire occurrences and fuel moisture measurements.

The results revealed that, during temperature inversion, differences in daily cycles of meteorological parameters influence fire danger and that these are not resolved by standard meteorological stations and fire danger indices (calculated on a once-a-day basis). Additional stations in higher locations or high-resolution meteorological models combined with fire danger indices accepting at least hourly input data may allow reasonable fire danger calculations under these circumstances.

Contributions:

Annette Menzel had the idea of investigating meteorological conditions that lead to the fire at Sylvensteinspeicher reservoir and helped with data analysis and writing of the manuscript. *Clemens Wastl, Michael Leuchner, Christina Schuster* and I set up and operated the climate station at Felsenkanzel. *Clemens Wastl* furthermore implemented the fire danger index calculation and helped perform the fuel moisture measurements soon after the fire took place. *Christina Schuster* contributed the altitudinal gradient temperature and humidity data, as well as to the creation the map in Fig. 2. All co-authors were involved in the final publication process. About 80% of the work was done by myself.

4.5 Recent climate change: Long-term trends in meteorological forest fire danger in the Alps

Clemens Wastl, Christian Schunk, Michael Leuchner, Gianni B. Pezzatti and Annette Menzel (2012), *Agricultural and Forest Meteorology 162-163: 1-13*, doi: 10.1016/j.agrformet.2012.04.001.

Climate change is one of the key issues in current scientific research. In this paper we investigate the impacts of rising temperatures and changing precipitation patterns on meteorological forest fire danger in the Alps. Our analysis is based on daily meteorological observations from 25 long-term stations in six Alpine countries. The selected stations are distributed more or less uniformly over the whole Alpine area and represent the different climate regions in this complex terrain. Stations with similar climatological conditions were grouped into regions. These were: Western Alps, Northern Alps, inner Alpine area and Southern Alps. The meteorological forest fire danger in the time period 1951–2010 was assessed on the basis of different forest fire danger indices (FWI, Nesterov, Baumgartner, etc.) calculated on a daily basis. A statistical percentile analysis revealed different impacts of recent climate change in the four regions. A significant increase in forest fire danger occurred at the stations in the Western Alps and even more strongly in the Southern Alps. Here, the yearly averaged fire danger increased during the past six decades. Additionally, in recent years the number of days with elevated forest fire danger (indices above a predefined threshold) has also increased. A comparatively weak increase was observed in the Northern Alps and no clear signal was evident at the stations in the inner Alpine valleys. In order to analyze extreme events (highest index value per year and region) extreme values statistics was applied. It was shown that the return period of extraordinarily high index values has decreased significantly over the past decades, especially in the Western and Southern Alps. For three pilot areas (Valais in the Western Alps, Bavaria in the Northern Alpine region and Ticino in the Southern Alps) a comparison with observed historical fire data is shown. In Valais, a region in the Western Alps with a generally low fire hazard, a weak trend toward more forest fires and more area burned could be found. The correlation between calculated indices and observed fires was quite low in this region. In Bavaria (Northern Alps) this correlation was higher, but while the trend of forest fires in Bavaria was decreasing in terms of number and burned area, the meteorological fire danger in contrast increased. Reasons for this contrasting trend may be related to altered anthropogenic factors such as less military activities, technical progress, and higher awareness. The correlation between indices and forest fires south of the Alps

(Ticino) was considerably lower because here most forest fires occurred in winter when the meteorological fire danger is usually lower than in summer. In this region a positive trend in meteorological fire danger over recent decades was also counterbalanced by decreasing anthropogenic ignitions.

Contributions:

Clemens Wastl initiated the study, acquired the necessary data and performed much of the calculations and writing. I helped in the data acquisition, analysis and especially interpretation and writing phases, e.g. obtaining the fire occurrence data for Bavaria, part of the meteorological dataset, describing the observed changes in fire danger and occurrence and supplying the map in Fig. 1. *Gianni B. Pezzatti* contributed fire occurrence data from Ticino and Valais, as well as interpretation regarding their patterns and correlation to fire danger. *Michael Leuchner* and *Annette Menzel* helped during the layout and analysis phases of the study, and all authors reviewed the draft manuscript that was written by *Clemens Wastl* and me. About 40% of the work was done by myself.

4.6 Projection of fire potential to future climate scenarios in the Alpine area: some methodological considerations

Daniele Cane, Clemens Wastl, Simona Barbarino, Luisa A. Renier, Christian Schunk and Annette Menzel (2013), *Climatic Change 119: 733-746*, doi: 10.1007/s10584-013-0775-7.

In Europe, wildfires are an issue not only for the Mediterranean area, but also in the Alpine regions in terms of increasing number of events and severity. In this study we evaluate the impact of climate change on the fire potential in the Alps in the past and in future scenarios. The Fine Fuel Moisture Code (FFMC) of the Canadian Forest Fire Danger Rating System, which successfully distinguishes among recorded fire/no fire events, is applied to projections of Regional Climate Models (RCMs) calculated on the SRES scenario A1B. We compare two different techniques: 1) a single model run of the COSMO-CLM RCM at 18 km resolution, and 2) a combination of 25-km resolution RCMs from the ENSEMBLES project, combined with the Multimodel SuperEnsemble technique and a new probabilistic Multimodel SuperEnsemble Dressing. The single-model RCM allows for a greater coherence among the input parameters, while the Multimodel techniques permit to reduce the model biases and to downscale to a higher resolution where long term records of observations are available. The projected changes with the

Multimodel in the scenario give an estimation of increasing wildfire potential in the mid XXI century. In particular the frequency of severe wildfire potential days is shown to increase dramatically. The single (independent) COSMO model gives a weaker signal and in some regions of the study area the predicted changes are opposite to the ones by the Multimodel. This is mainly due to increasing precipitation amounts simulated especially in the northern parts of the Alps. However, there are also some individual models included in the Multimodel ensemble that show a similar signal. This confirms the ambiguity of any impact study based on a single climate model due to the uncertainty of the projections of the climate models.

Contributions:

Daniele Cane, *Clemens Wastl* and I had the idea for the study. The Italian partners *Daniele Cane*, *Simona Barbarino* and *Luisa A. Renier* produced the multi-model and the code for the main data analysis. They also gathered the fire occurrence and reanalysis data. *Clemens Wastl* ran the COSMO-CLM model and I adapted the data analysis code to run with the COSMO-based fire danger indices. The manuscript was mainly written by *Daniele Cane*, with major contributions and adjustments (in several submissions and revisions) by me and *Clemens Wastl*. About 35% of the work was done by myself.

5 Discussion

The aims of the present thesis and the publications linked to it are to better understand fire danger, its rating, as well as recent and future climate changes in Bavaria and the European Alps. In addition to the discussions presented in the individual publications, this chapter constitutes a general and unifying discussion of the results.

5.1 Differences among species and sites

One of the main motives for the experimental moisture studies (chapters 4.1, 4.2 and 4.3) was to reveal differences between forest types made up of different species and at different locations.

Chapter 4.1 examined the equilibrium moisture content of litter from four important Central European tree species (Norway spruce (*Picea abies* [L.] Karst.), Scots pine (*Pinus sylvestris* L.), European beech (*Fagus sylvatica* L.) and pedunculate oak (*Quercus robur* L.)). A clear ranking could be found with EMC decreasing from beech to oak, spruce and pine, for both adsorption and desorption. Differences between leaf-needle combinations from climate chamber measurements were generally significant, with additional significant differences within the coniferous and deciduous species (depending on adsorption/desorption, humidity and whether individual measurements or models were compared). EMC ranges and curve shapes were similar to the literature (e.g. in comparison to King & Linton 1963, Blackmarr 1971, van Wagner 1972, Britton *et al.* 1973, Anderson 1990, Anderson *et al.* 1978, Nelson 1984, Lopes *et al.* 2014), with similar differences between needle and leaf litters for many cases (e.g. Blackmarr 1971 and Anderson 1990). This agreement is an indication for a general difference in needle and leaf sorption that may be based on the different chemical and physical properties these litters certainly have. While the sequence of EMC matches well with observed fire occurrence in Bavaria (highest for pine and spruce stands and much lower for deciduous stands), it has to be considered that due to permanently changing meteorological conditions, EMC is never reached in the field (Pyne *et al.* 1996). Additionally, the differences between sorption isotherms (<5% fuel moisture) are well below the standard deviation usually found when dead fine fuel moisture content is determined in the field. However, EMC is a critical determinant of dead fine fuel moisture especially in very dry conditions and thus may have an influence on ignitability and fire behaviour during (somewhat infrequent) prolonged drought in Bavaria or in areas with less precipitation.

In chapter 4.3, litter moisture was determined repeatedly for different forest stands/species across Bavaria and analysed using its interrelation with fire danger indices. Since the indices take prevailing weather conditions into account, data from the various locations and two years of sampling could be compared. Interestingly, leaf litter again tended to show higher moisture content than needle litter, with differences generally decreasing for increasing fire danger. Wotton (2009) showed very similar results for various litters and other fine fuels in Canada. Decreasing differences for higher fire danger index values could be explained with fuel moisture levels generally becoming more uniform during prolonged drying (Wotton & Beverly 2007; Wotton 2009). In addition, different time lags (cf. chapter 1.2.3) of the individual litter layers may also influence the litter moisture found for different tree species at a given fire danger index value. As the conditions in Bavaria (and generally north of the European Alps) are characterized by frequent precipitation events followed by shorter or longer dry periods, differences in litter moisture after rain and in the early stages of drying (medium fire danger) can be expected to have a substantial influence on the overall fire danger of different species. Thus, the actual fire hazard for a given fire danger level has to be expected to vary from forest type/species to species. It should be noted that most fire danger indices neither take forest type or species into account (cf. chapter 1.3), nor is this reasonable since fire danger rating maps would then become too detailed and complex to be useful on a broad scale. Forest type- and species-specific fire hazard thus has to be considered when interpreting fire danger rating system outputs. However, information about the danger level in different forest types may be helpful for the identification of areas with special fire prevention needs (e.g. compilation of firefighting maps, deployment of helicopter buckets, hose layer units etc.).

In addition, a comparison of litter to automated 10-hr fuel moisture measurements revealed that the species-specific differences found were only present for litter and not for standardized fuel moisture sticks. Both types of fuel were exposed to similar conditions (within-stand temperature, relative humidity, precipitation, radiation etc.) and only differed in their structure/intrinsic properties and the connection to subjacent organic/soil layers (in contrast to the litter layer, 10-hr fuel moisture sticks are mounted 30.5 cm above the forest floor). Thus, missing differences of 10-hr fuel moisture sticks indicate similar drying conditions in the two forest stands considered, whereas the differences of litter moisture had to be caused by different fuel structure and time lag. This is not surprising when considering that the pine litter sampled consisted of individual needles scattered on top of moss and bare soil, whereas the beech leaves formed a litter layer of several cm depth and exhibited a distinct drying from top to bottom. The increased interception and delayed drying of leaf litter thus explains much of the lower fire danger found in deciduous forest stands, potentially in addition to growing areas with different climate conditions and differences in within-stand meteorological conditions.

5.2 Evaluation of fire danger indices and index weaknesses

The choice of fire danger index in chapter 4.6 was justified using standard comparisons of fire danger index values on days with and without fires (cf. Andrews *et al.* 2003, Arpaci *et al.* 2013), however, this was done for the fire-susceptible region of Piedmont, Italy that also possesses a large fire occurrence database.

As both of those factors do not exist in Bavaria, using litter moisture for fire danger index performance assessment is proposed in chapter 4.3. This is possible since all fire danger indices must show a response to fuel moisture (cf. chapters 1.2.2, 1.2.3 and 1.3), regardless of the physical variables they represent. Furthermore, Wotton (2009) and Beverly & Wotton (2007) stated that fuel moisture content is actually well-related to human and lightning-caused fire occurrence in Canada and prediction of fire occurrence is a key reference to and the main purpose of fire danger rating in Bavaria. However, different indices may show a non-linear response to litter moisture and Spearman’s rank correlation is therefore used. Employing non-parametric techniques for fire danger index comparisons follows the fundamental logic of Eastaugh *et al.* (2012), who stress that fire danger index comparators have to be insensitive to different index frequency distributions. Using litter moisture for fire danger index performance assessment furthermore is a sensible addition to the existing techniques based on fire occurrence (cf. Andrews *et al.* 2003, Eastaugh *et al.* 2012), monthly aggregated fire occurrence (Dolling *et al.* 2005) and fire behaviour (Haines *et al.* 1983) data. Although litter moisture sampling and analysis is quite labour-intensive, it can - at least theoretically - be carried out in any region, stand type and season of interest, is independent from highly variable human-caused ignitions and enables a more robust statistical approach than fire occurrence data. Litter or fuel moisture determination may be simplified using automated methods further discussed in chapter 5.4.

In addition to this general assessment of fire danger index performance, their ability to resolve temperature inversion in complex terrain was explored in chapter 4.4. This feature of mountain meteorology and its importance for fire danger rating is well known (McRae & Sharples 2011; Sharples 2009), however, no dedicated analysis of its influence on fire danger index calculations was carried out before. In order to correctly account for fire danger in the case study, both meteorological (observation or model) input data from relevant elevations, as well as hourly or higher resolved fire danger indices are needed. Typical meteorological stations found in the valleys are not subjected to the same, steadily warm and dry conditions, and indices calculated from early afternoon values only (as is the case with most fire danger indices) are affected by the disintegrating temperature inversion at this time of day and therefore do not produce correct ratings of fire danger. These are problems that fire managers in most mountainous areas worldwide are faced with. Fortunately, the WBI index currently in use in Bavaria provides hourly calculations (DWD 2016; Wittich & Bock 2014; Wittich *et al.* 2014). However, in contrast to the 'RAWS' stations in use for fire danger rating in the US, which are located at mid-elevation south-facing slopes (Cohen & Deeming 1985; Holden & Jolly 2011), German Meteorological Service (Deutscher Wetterdienst - DWD) stations are almost exclusively limited to the valley floors.

5.3 Climatic changes

Influences of recent and potential future climatic changes on forest fire danger in the Alpine area were analysed in chapters 4.5 and 4.6, respectively. It should be noted that these studies were based on the fire danger presented by meteorological conditions (as expressed by fire danger indices) alone and that they did not incorporate any interactions of fires/fire emissions and the vegetation/climate system (as e.g. in Thonicke *et al.* 2010, Sitch *et al.* 2003 and Thonicke *et al.* 2001). This was not considered necessary as the number of fires is relatively limited and no major feedbacks are expected.

In the meteorological station data from 1951-2010 used in chapter 4.5, significant ($p<0.02$) temperature increases could be detected for the whole Alpine arc (mean regional increase 1.1 to 1.7°C), whereas absolute values and trends of precipitation proved highly variable. The only significant changes in precipitation were found in the Southern Alps region, with a decrease of annual precipitation by 8% or 100 mm ($p=0.02$) and a reduction of days with gaugeable precipitation by 9% or 12 days per year ($p=0.04$). These trends are consistent with the studies by Schmidli & Frei (2005) and Rebetez (1999). When fire danger indices were calculated from the station data, median fire danger (50th percentile) showed a significant increase for many stations; with the highest percentage of significant stations and indices again located in the Southern Alps. Some decreasing trends could be found for station-index combinations in all regions; however, most of those were not significant. The highest numbers of decreasing trends, including some significant ones, were detected in the Inner and Northern Alps. Changes of exceptionally high fire danger (95th percentile) were more pronounced, usually showing an increase (except for some station-index combinations in the Inner and Northern Alps) and the proportion of significant trends was higher. This confirms a stronger increase in extremes rather than in mean values, and similar effects were found by Clarke *et al.* (2013) in Australia. Number of days with a high fire danger index value (> 95^{th} percentile of the whole period) increased in the whole Alpine area, however only very slightly and not significantly in the Western and Inner Alps, whereas significant increases could be found for the Northern (8 days in 60 years, $p=0.03$) and Southern (22 days in 60 years, $p<0.01$) Alps. Extreme value statistics also indicate a decrease in return periods for given fire danger index values from the sub-periods 1951-1980 to 1981-2010, mostly in the Western and Southern Alps. It should be noted that fire danger indices incorporate many more parameters than commonly analysed in climate change studies (e.g. relative humidity, wind speed) and that highly temperature-dependent indices (e.g. Baumgartner and M-68) tended to show a higher proportion of significant and more pronounced correlations than indices depending more on relative humidity and precipitation (e.g. McArthur and Angstrom). A comparison with fire occurrence data from Bavaria, Valais and Ticino revealed complex interactions with human influences on an annual scale. While trends for both fire danger and occurrence (number of fires and area burnt) show a slight increase in Valais, occurrence trends are not significant and other research (Pezzatti *et al.* 2013) suggests that these are partially due to land use changes. In Bavaria (whole period) and Ticino (1971-2010), number of fires and burnt area even decreased over time, indicating a reduction in human ignitions and higher effectivity of the detection and firefighting systems. This could be verified using multiple regression, showing a significant positive influence of meteorological fire danger and a significant negative influence of the variable time (i.e. changing social and technological factors) on fire occurrence. In addition, years with low fire occurrence in Bavaria did not match years with a low index value. Thus low fire occurrence does not necessarily imply low fire danger in a given year, justifying the approach taken in chapter 4.3, where fire danger indices are validated and compared using litter moisture rather than fire occurrence data.

Future changes (periods 2031-2050 vs. 1991-2010) projected from a multi-model of 7 different regional climate models (chapter 4.6) suggest a rough continuation of the trends found in the past, including the more pronounced changes for exceptionally high fire danger (95^{th} percentile) than for median conditions. However, the single COSMO-CLM regional climate model also used gives different and in many cases even opposite results than the multi-model. This phenomenon will be discussed in chapter 5.4.

After the studies in chapters 4.5 and 4.6 were completed, it became more and more obvious that fires also start to occur during autumn, spring and even winter in the Alpine part of Bavaria (cf. chapter 1.4). This is a well-known phenomenon south of the Alpine ridge (Conedera *et al.* 1996; Moretti 2002; Moretti *et al.* 2004) that may begin to influence the Northern Alps as circulation patterns change and extreme events become more frequent. It might also be explained by a general increase in fire season length (cf. Jolly *et al.* 2015, Clarke *et al.* 2013).

5.4 Methodological considerations

Apart from the factual findings presented and discussed so far, a range of existing and novel methods were also tested and compared within the scope of this thesis. These are discussed in this chapter.

Equilibrium moisture content (chapter 4.1) was determined using both conditioning over saturated salt solutions (similar to King & Linton 1963, Blackmarr 1971, van Wagner 1972, Anderson *et al.* 1978, Nelson 1984 and Anderson 1990) and in a climate chamber (as in Britton *et al.* 1973, Weise 2007 and Lopes *et al.* 2014). Saturated salt solution conditioning was carried out with small (typically 0.8 g) samples in a special sorption device and larger (10-25 g) samples in exsiccators. In the climate chamber, only large samples were used. While climate chamber conditioning usually provides enough space for the simultaneous processing of numerous samples, relative humidity generation is limited to values above 10-20% at 23°C, in most cases. This precludes a determination of EMC at very low relative humidity that is important for (extremely) high fire danger. Additionally, technical control cycles involved in the temperature/relative humidity generation do not allow the same constant conditions as over saturated salt solutions and may affect absolute EMC values as well as hysteresis. However, absolute hysteresis and hysteresis ratios from our climate chamber measurement match with our saturated salt solution measurements and those done by Anderson (1990) and Nelson (1984). While saturated salt solutions can produce relative humidities down to 3.6% at 23°C, they are often corrosive or even hazardous and can usually only be used for conditioning air in a relatively confined space. The special sorption device offered conditioning to 10 different relative humidities at the same time. However, samples had to be partitioned representatively and individual sample mass was very small, leading to weighing errors. At very high relative humidities, a deviation of special sorption device from climate chamber measurements could be noted, probably due to condensation taking place over the saturated salt solutions. Use of climate chamber conditioning with a relatively large sample mass (>10-20 g) and a high number of repetitions (>5-15) can thus be recommended for general use. If measurements at low humidities are required, special technical drying systems or saturated salt solutions have to be used.

Considering methods for the automated measurement of litter moisture content at the original fuel particle level, electrical resistance and three different types of frequency domain sensors were tested in chapter 4.2. The results therein indicate that the latter have to be calibrated against manual gravimetric measurements frequently in order to account for the highly dynamic and variable litter layer, while further fine-tuning of electrical resistance measurements would be necessary that were also affected by limited measuring range. Other studies (Conedera *et al.* 2012; Ferguson *et al.* 2002) also report difficulties calibrating permittivity sensing devices in litter and duff, however this is mostly related to low coefficients of determination and not to seasonal influences on the calibration equations. In addition, recently developed sensor types and techniques (OZ probe, Canone *et al.* 2009; TDT method, Blonquist *et al.* 2005), as well as near-fuel relative humidity measurements, have not been included in the tests. Although these may perform better, based on the results of chapter 4.2 the conclusion has to be maintained that litter moisture content and variation cannot be easily measured automatically at the original fuel level. In addition to this it should be noted that many forest types even do not produce a litter layer deep and consistent enough that would allow for the placement of any automated sensor type (e.g. pine litter described in chapter 4.3, consisting of individual needles scattered on top of moss or bare soil). Borken *et al.* (2003) and Sheridan *et al.* (2014) used the electrical resistance of a basswood veneer placed inside the litter layer and permittivity sensing techniques in an artificial 'litter pack' successfully, however. 10-hr fuel moisture used in chapter 4.3 and described in more detail in Schunk *et al.* (2014) provides a standardized fuel (1.3 cm diameter and 50.8 cm length Ponderosa pine stick) that can be automatically measured and used independently of the local litter layer. This greatly facilitates a comparison of drying conditions in different stand types, however it should be noted that the absolute moisture content measured, timelag and drying behaviour of the 10-hr fuel sticks will differ from that of the litter layer in most cases. Chapter 4.3 for example shows differences between the litter moisture to 10-hr fuel moisture relationship for pine and beech litter.

Projected fire danger based on a single regional climate model and a multi-model was compared in chapter 4.6 and the large differences encountered have already been mentioned above. These differences are chiefly based on high uncertainty in the projection of precipitation by the different regional climate models (COSMO-CLM and the ones used in the multi-model calculation), whereas e.g. temperature projections are relatively reliable. Frei *et al.* (2006) as well as Heinrich & Gobiet (2012) also found a high projection uncertainty for precipitation near the European Alps. The latter furthermore also reported increasing dryness south of the Alps and an uncertain signal north of them, based on an A1B-scenario multi-model. Thus using a multi-model approach or otherwise accounting for the high variability of (precipitation) projections from different regional climate models is necessary for projecting future fire danger and drought. While some authors used single models in the past (e.g. Carvalho *et al.* 2006, 2010, 2011), Moritz *et al.* 2005 and Parks *et al.* (2016) are two examples that included multiple regional climate models in their analyses.

6 Outlook

The present thesis has established a range of novel facts and techniques for fire danger rating and climatic change assessment in temperate Europe and the adjacent Alpine space. While not all of the assessed techniques proved useful (e.g. automated dead fuel measurements at the fuel particle level, projection of fire danger from a single regional climate model), many others are sensible additions to existing knowledge, especially in an area where relatively few studies have been carried out to date. Several new aspects and data (e.g. equilibrium moisture content and species-specific fire danger as determined from litter moisture measurements) can be used operationally in the calculation or interpretation of fire danger indices. However, their implementation is not within the domain of research; it has to be adopted by the meteorological service and forest/fire management agencies. The problems associated with fire danger rating in complex topography have in the meantime been proven and highlighted by yet another exceptional forest fire within the thermal belt (ignited December 30, 2015, approximately 0:30 h probably by human causes and less than 100 m from 'Felsenkanzel' climate station used in chapter 4.4). Action is now being taken both from the research and operational perspective to further improve understanding and rating of fire danger in the Alpine part of Bavaria.

7 References

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Wittich, K.-P.; Bock, L.; Zimmermann, L. (2014): Neuer Waldbrandgefahrenindex des Deutschen Wetterdienstes (2). Der WBI und dessen Anwendung auf bayerische Waldbrände. *AFZ-Der Wald* **69**, 22–25.

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8 Tables and figures

Appendix

A Curriculum vitae

Persönliche Daten

Name:	Christian Schunk
Geburtsdatum:	31.03.1984
Geburtsort:	Fürth
Adresse:	Dr.-Hans-Eisenmann-Straße 1 85354 Freising
E-Mail:	schunk@wzw.tum.de
Familienstand:	ledig
Staatsangehörigkeit:	Deutsch
Religion:	Evangelisch

Schulausbildung

1990-1994	Grundschule Soldnerstraße, Fürth
1994-2003	Hardenberg-Gymnasium Fürth Abschluss: *Allgemeine Hochschulreife*

Hochschulausbildung

2004-2009	Studium der Forstwissenschaften Technische Universität München Vertiefungsbereiche: Forstbetriebssteuerung, Naturschutz, Holzwirtschaft Diplomarbeit: ‘Untersuchungen zu dämmstoffrelevanten Materialeigenschaften spanmorphologisch optimierter Frässpäne ausgewählter Holzarten‘ Akademischer Grad: *Diplom-Forstingenieur (univ.)*
2009-2016	Promotion Technische Universität München, Professur für Ökoklimatologie ‘Contributions to the assessment of past, present and future forest fire danger in Bavaria and the Alpine region’

Ausgewählte Tätigkeiten

08.2003-05.2004	Zivildienst Stadt Fürth, Ordnungsamt, Abteilung Umwelt- und Naturschutz
08.2007-10.2007	Praktikum Department of Natural Resources, Fairbanks Area Forestry, Fairbanks, Alaska, USA
05.2009-05.2016	Wissenschaftlicher Mitarbeiter Technische Universität München, Professur für Ökoklimatologie

Auszeichnungen

26.06.2009	Preis des Oberbürgermeisters der Stadt Freising

Freising, den 6. April 2016

B List of publications, conference contributions, and teaching

B1 Peer-reviewed publications

Publications marked with an asterisk (*) are part of this thesis.

Christian Schunk, Sebastian Treml and Fritz Tröger (2009): Lose Dämmstoffe aus Holz – Wärmeleitfähigkeit von speziell hergestellten Fräßspänen ausgewählter Holzarten. *European Journal of Wood and Wood Products*, 67: 487-488, doi: 10.1007/s00107-009-0354-9.

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Christian Schunk, Clemens Wastl, Michael Leuchner, Christina Schuster and Annette Menzel (2013): Forest fire danger rating in complex topography – results from a case study in the Bavarian Alps in autumn 2011. *Natural Hazards and Earth System Sciences 13: 2157-2167*, doi: 10.5194/nhess-13-2157-2013.*

Daniele Cane, Clemens Wastl, Simona Barbarino, Luisa A. Renier, Christian Schunk and Annette Menzel (2013): Projection of fire potential to future climate scenarios in the Alpine area: some methodological considerations. *Climatic Change 119: 733-746*, doi: 10.1007/s10584-013-0775-7.*

Clemens Wastl, Christian Schunk, Marvin Lüpke, Giampaolo Cocca, Marco Conedera, Eva Valese and Annette Menzel (2013): Large-scale weather types, forest fire danger, and wildfire occurrence in the Alps. *Agricultural and Forest Meteorology 168: 15-25*, doi: 10.1016/j.agrformet.2012.08.011.

Anna Bock, Tim H. Sparks, Nicole Estrella, Nigel Jee, Andrew Casebow, Christian Schunk, Michael Leuchner and Annette Menzel (2014): Changes in first flowering dates and flowering duration of 232 plant species on the island of Guernsey. *Global Change Biology 20: 3508-3519,* doi: 10.1111/gcb.12579.

Michael Leuchner, Sonja Gubo, Christian Schunk, Clemens Wastl, Manfred Kirchner, Annette Menzel and Christian Plass-Dülmer (2015): Can positive matrix factorization help to understand patterns of organic trace gases at the continental Global Atmosphere Watch site Hohenpeissenberg? *Atmospheric Chemistry and Physics* 15: 1221-1236, doi: 10.5194/acp-15-1221-2015.

Michael Leuchner, Homa Ghasemifard, Marvin Lüpke, Ludwig Ries, Christian Schunk and Annette Menzel (2016): Seasonal and diurnal variation of formaldehyde and its meteorological drivers at the GAW Site Zugspitze. *Aerosol and Air Quality Reseach 16: 801-815,* doi: 10.4209/aaqr.2015.05.0334.

Christian Schunk, Bernhard Ruth, Michael Leuchner, Clemens Wastl and Annette Menzel (2016): Comparison of different methods for the in situ measurement of forest litter moisture content. *Natural Hazards and Earth System Sciences 16:* 403-415, doi: 10.5194/nhess-16-403-2016.*

B2 Submitted for peer-review

Christian Schunk, Clemens Wastl, Michael Leuchner and Annette Menzel (2016): Fine fuel moisture for site- and species-specific fire danger assessment in comparison to fire danger indices. Submitted to: *Agricultural and Forest Meteorology*, 06 April 2016.*

Ludwig Bothmann, Annette Menzel, Bjoern H. Menze, Christian Schunk and Göran Kauermann (2016): Automated processing of webcam images for phenological classification. Submitted to: *PLOS ONE*.

Hannes Seidel, Christian Schunk, Michael Matiu and Annette Menzel (2016): Diverging drought resistance of Scots pine provenances revealed by infrared thermography. Submitted to: *Frontiers in Plant Science*.

In preparation

Laura Stratopoulos, Christian Schunk, Karl-Heinz Häberle, Christian Blanck, Uwe Stilla, Konrad Eder and Annette Menzel: Close range remote sensing techniques for tracking of phenology and drought stress of common beech (*Fagus sylvatica* [L.]) in Upper Bavaria.

B3 Other publications

Christian Schunk, Michael Leuchner and Annette Menzel (2009): Waldbrand – Historische, aktuelle und zukünftige Bedeutung in Bayern. *LWF aktuell* 72: 30-31.

Christian Schunk, Clemens Leutner, Michael Leuchner and Annette Menzel (2010): Methods for equilibrium moisture content determination. *In: Proceedings of the VI International Conference on Forest Fire Research* (Ed. D.X. Viegas). 10 pp.

'Wie Forscher die Waldbrandgefahr erkunden', radio report in: IQ: Wissenschaft und Forschung, Bayern 2, 18.07.2011.

Christian Schunk, Clemens Leutner, Michael Leuchner and Annette Menzel (2012): A method to estimate the ignition characteristics of forest litter. *In: Modelling Fire Behaviour and Risk* (Eds. Donatella Spano, Valentina Bacciu, Michele Salis, Costantino Sirca), p. 41-46, ISBN: 978-88-904409-7-7.

'Brandgefahr in den Alpen', TV report in: Hilfe, es brennt!, [w] wie wissen, Das Erste, 05.05.2013.

'Waldbrandgefahr', TV report in: Schön grün, Alles Wissen, HR Fernsehen, 22.05.2013.

Christian Schunk, Michael Leuchner, Christian Kölling, Lothar Zimmermann and Annette Menzel (2015): Mit Holzstäben Waldbrandgefahr beurteilen - Neuartige Messgeräte zur

Abschätzung und Bewertung der Waldbrandgefahr an Waldklimastation getestet. *LWF aktuell* 105: 46-47.

Christian Schunk, Michael Leuchner and Annette Menzel (2014): Evaluation of a system for automatic dead fine fuel moisture measurements. *In: Advances in Forest Fire Research* (Ed. D.X. Viegas), Imprensa da Universidade de Coimbra, Coimbra, Portugal, ISBN: 978-989-26-0884-6, p. 1115-1123, doi: 10.14195/978-989-26-0884-6_121.

'Forschung zur Waldbrandgefahr', TV report in: Unser Land, Bayerisches Fernsehen, 14.08.2015.

B4 Conference contributions

B4.1 Presentations

The presenting author is identified by **bold** *print.*

Clemens Wastl, Christian Schunk and Annette Menzel (2011): Climate change impact on meteorological forest fire danger in the Alpine region. *EGU General Assembly 2011*, Vienna, Austria 03.-08. April 2011.

Christian Schunk, Clemens Wastl, Michael Leuchner and Annette Menzel (2011): Evaluation of fire danger rating systems in moderate fire regimes. *Ninth Symposium on Fire and Forest Meteorology*, Palm Springs, USA, 18.-20. October 2011.

Clemens Wastl, Christian Schunk and Annette Menzel (2011): Projections of future meteorological forest fire danger in the European Alps. *Ninth Symposium on Fire and Forest Meteorology*, Palm Springs, USA, 18.-20. October 2011.

Christian Schunk, Michael Leuchner and Annette Menzel (2014): Evaluation of a system for automatic dead fine fuel moisture measurements. *VII International Conference on Forest Fire Research*, Coimbra, Portugal, 14-21. November 2014.

Michael Leuchner, Homa Ghasemifard, Marvin Lüpke, Ludwig Ries, **Christian Schunk** and Annette Menzel (2015): Diurnal variation of formaldehyde and its meteorological drivers at UFS Schneefernerhaus. *VAO Symposium 2015*, Salzburg, Austria, 27.-30. October 2015.

B4.2 Posters

Christian Schunk, Clemens Leutner, Michael Leuchner and Annette Menzel (2010): Methods for equilibrium moisture content determination. *VI International Conference on Forest Fire Research*, Coimbra, Portugal, 15.-18. November 2010.

Christian Schunk, Bernhard Ruth, Michael Leuchner, Clemens Wastl and Annette Menzel (2011): Methods for the automated in-situ measurement of dead fine fuel moisture dynamics. *EGU General Assembly 2011*, Vienna, Austria, 03.-08. April 2011.

Clemens Leutner, Christian Schunk, Michael Leuchner and Annette Menzel (2011) A method to estimate the ignition characteristics of forest litter. *International Conference on Fire Behaviour and Risk Modelling*, Alghero, Italy, 4-6 October 2011.

Christian Schunk, Clemens Wastl, Michael Leuchner, Christina Schuster and Annette Menzel (2012): Forest fire danger indices under extreme meteorological conditions in a complex topography – the situation in the Bavarian Alps in autumn 2011. *EGU General Assembly 2012*, Vienna, Austria, 22.-27. April 2012.

B5 Teaching

B5.1 Supervision

Methoden zur Bestimmung der Gleichgewichtsfeuchte von Waldstreu als Beitrag zur Abschätzung der Waldbrandgefährdung. Clemens Leutner, *Bachelor thesis in 'Forstwissenschaft und Ressourcenmanagement'*, Technische Universität München, 2010.

Abschätzung der Entzündungs- und Brandcharakteristik von Waldstreu. Clemens Leutner, *Master thesis in 'Forst- und Holzwissenschaft'*, Technische Universität München, 2012.

Entzündungs- und Brandverhalten künstlich erzeugter Waldstreuauflagen. Tobias Schula, *Bachelor thesis in 'Forstwissenschaft und Ressourcenmanagement'*, Technische Universität München, 2013.

Bestimmung der Trockengeschwindigkeit verschiedener Laub- und Nadelstreu. Julia Asam, *Bachelor thesis in 'Forstwissenschaft und Ressourcenmanagement'*, Technische Universität München, 2014.

Harvesting fog in southwestern Morocco: Water chemistry and wind field. Simeon Max, *Bachelor thesis in 'Forstwissenschaft und Ressourcenmanagement'*, Technische Universität München, 2014

Experimental test and hydrodynamic theory of five different fog materials. Stephan Wunderlich, *Bachelor thesis in 'Engineering Science'*, Technische Universität München, 2014.

Bewertung der Dürreresistenz verschiedener Kiefernherkünfte mittels IR-Thermografie. Stefanie Weindler, *Master thesis in 'Forst- und Holzwissenschaft'*, Technische Universität München, 2014.

Messung und Analyse von atmosphärischen Spurengasen auf der Zugspitze. Julia Mendler, *Study project 'Environmental Engineering'*, Technische Universität München, 2014.

Fog harvesting in Morocco: Comparison of nets yields. Antoine Tranchet, *Study project 'Environmental Engineering'*, Technische Universität München, 2015.

Bestimmung des Emissionsgrades an Kiefernsetzlingen. Marina Gabler, *Projektarbeit 'Umweltplanung und Ingenieurökologie'*, Technische Universität München, 2015.

Zeitliche und räumliche Analyse historischer Waldbranddaten. Sebastian Klopfer, *Master thesis in 'Forst- und Holzwissenschaft'*, Technische Universität München, 2015.

Set up and operation of a system for automatic fuel moisture measurement. Subash Chandra Sapkota Study, *Study project 'Environmental Engineering'*, Technische Universität München, 2015.

Use of close range remote sensing techniques for the tracking of phenological events and the detection of drought stress of common beech (*Fagus sylvatica* [L.]) in Upper Bavaria. Laura Stratopolous, *Master thesis 'Umweltplanung und Ingenieurökologie'*, Technische Universität München, 2015.

B5.2 Lectures

Waldbrände. Contribution to: lecture series 'Ursachen und Auswirkungen des Klimawandels', Technische Universität München, Programmes *'Forst- und Holzwissenschaft' (M.Sc.)* and *'Umweltplanung und Ingenieurökologie' (M.Sc.), 2011-2015.*

Gebirgsklimatologie. Contribution to: lecture series 'Ökologie des Gebirgswaldes', Technische Universität München, Programme *'Forst- und Holzwissenschaft' (M.Sc.), 2013-2015.*

Abiotische Umwelt. Contribution to: lecture series 'Konzepte und Forschungsmethoden in Ökologie und Sozioökonomie', Technische Universität München, Programme *'Forst- und Holzwissenschaft' (M.Sc.), 2012, 2014, 2015.*

Fortgeschrittene Methoden der Forst- und Agrarmeteorologie. Contribution to: 'Probenahme zum Stoffhaushalt und fortgeschrittene Methoden der Forst- und Agrarmeteorologie', Technische Universität München, Programme *'Forst- und Holzwissenschaft' (M.Sc.), 2010, 2013, 2014, 2015.*

Klimatischen Gegebenheiten. Contribution to: 'Große Geländeübung Waldstandorte Bayerns', Technische Universität München, Programme *'Forst- und Holzwissenschaft' (M.Sc.),2011, 2013, 2015.*