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Experimental studies on the fire behaviour and smoke toxicity of German pine vegetation (*Pinus sylvestris*)

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Abstract

The mechanisms of fire and smoke spread in forest and vegetation fires have not been fully investigated. Most numerical models often only consider the topography of the area and climatic influences such as wind and temperature. There is a need to understand the fire behaviour of specific vegetation in order to predict how the fire and smoke will spread during a fire incident. Understanding the mechanisms and behaviour of fire is therefore important for both, preventing and fighting fires. The European research project DRYADS and the associated German pilot project "Fire research in forest fires and derivation of safety measures" deal with these problems. Therefore, several measurement campaigns were carried out to study safety-relevant parameters, fire behaviour, fire spread and spontaneous combustion processes of specific German vegetation and soil samples. The research objectives of the studies focused on the characterisation of fire development and spread as well as smoke composition.

1. Introduction

Common pine vegetation (Pinus sylvestris) is involved in approximately 75% of wildfires in Germany. Over the past five years, the German regions of Saxony-Anhalt and Brandenburg have been particularly affected, with an increase in the number, severity and area affected by fires. It is essential to understand the mechanisms of vegetation-specific fire behaviour and smoke production in order to develop effective fire fighting measures. To achieve this, fire experiments are conducted on 0.25 m² soil samples to characterize the ignition proteries and fire spread in ground fires. In addition, self-ignition amd smouldering tests of the local soil and vegetation samples were conducted in a DIN tube furnace and the resulting smoke gases were measured and analysed by FT-IR spectrometry. Furthermore, the self-ignition behavior of soil samples was investigated by thermal storage tests, performed in the SEDEX-oven. Also here the smoke gases were measured by FT-IR. The results provide an comprehensive overview of typcial fire behavior and smoke compositions and characterize essential factors influencing ground fires.

Previous studies (Huand & Rein, 2014; Morandi & Silvani, 2010; Martin et al, 1993; Tihay et al, 2016) (selection) already show characteristic processes of fire spread in forest soils; the present series of experiments is intended to determine regional characteristics. In addition the results provide the basis for large-scale tests and numerical simulations within the DRYADS-project.

2. Small-Scale Fire Tests

2.1. Experimental Setup

The small scale (real scale) fire experiments were conducted in 25 x 50 x 50 cm plexiglass boxes outdoors. Samples were taken from natural vegetation (52°23'04.8"N, 11°14'11.8"E) and dried under ambient conditions, to obtain low moisture levels. The ignition was performed by placing a heat-conditioned metal cylinder (approximately 650°C, pre-heated in the Muffeloven) on the dry litter layer of organic material. Temperatures were measured at different locations and depths of the sample to characterize the intensity of the ground fires. The fire spread was recorded with a thermal imaging camera, and mass loss was tracked using a burn scale. To

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measure the temperatures, thermocouples were mounted at a depth of 5 cm (TC 2 to 10) and 10 cm (TC 11 to 14). As the intensity of the fire tests was significantly influenced by the wind, the prevailing wind speeds were recorded with a weather station.

Figure 1 – Burning Soil Sample

2.2. Results

Due to the high dryness (soil moisture <15%), the organic litter layer ignited when the cylinder was placed on top. The dry components of the upper layer burned with the appearance of flames. After 5 minutes, a smouldering fire is established on the entire surface of the specimens. Horizontal and vertical heating of the entire sample occurs. Selected measured temperatures and the mass lass of one specimen are shown in Figure 2.

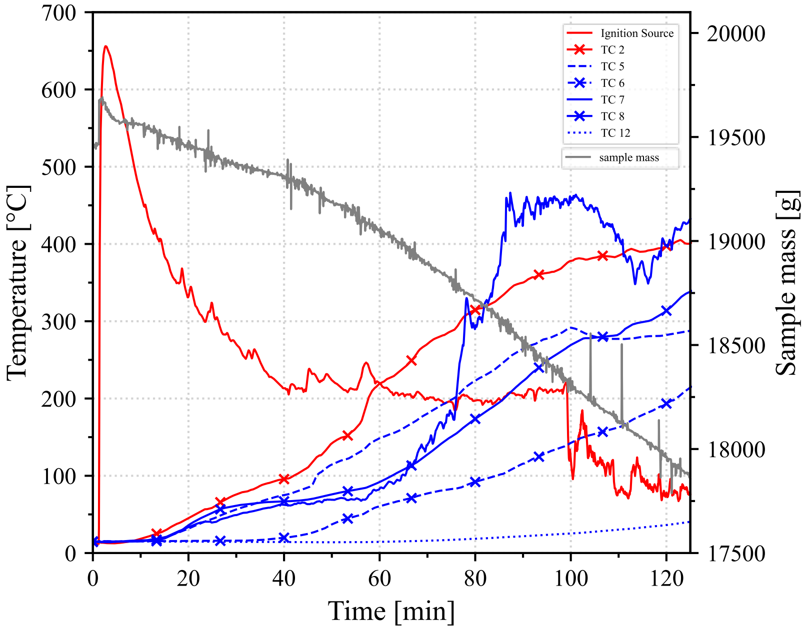

Figure 2 - Temperature curves and mass decrease of pine soil sample

The smouldering fire led to the slow combustion of the organic material of the soil, also recognizable by a steady mass decrease. Furthermore, the classical combustion processes of forest soil (preheating, drying, pyrolysis, oxidation), as described by Huang & Rein (2013) among others, could be observed. The smouldering fire is maintained by the heat generated in the reaction zone. It also provides energy to fuel the drying, preheating and pyrolysis processes. It was also shown that previously ignition-resistant components (e.g. mosses) could be thermally conditioned by the addition of heat, and if sufficient pyrolysis gases were produced, flaming combustion could be initiated at a later stage. The heat of the metal cylinder just only delivers the initial energy, to start the tests. The thermocouple (TC 1) under the metal shows a constant temperature after about 40 minutes, so it could be stated, that from this point on the combustion is no longer influenced by the energy of the ignition source.

The studies show that all of the ground fires investigated spread independently and persistently after initial ignition. All tests showed fully developed smoldering fires, which constantly heated the soil samples to over 300°C (also up to 400°C) after two hours. Figure 3 shows typical temperature curves (measurement 5 cm below litter layer) of different soil samples. It can be seen that the samples from the coniferous forests show a much faster and significantly more severe temperature rise over the experimental time.

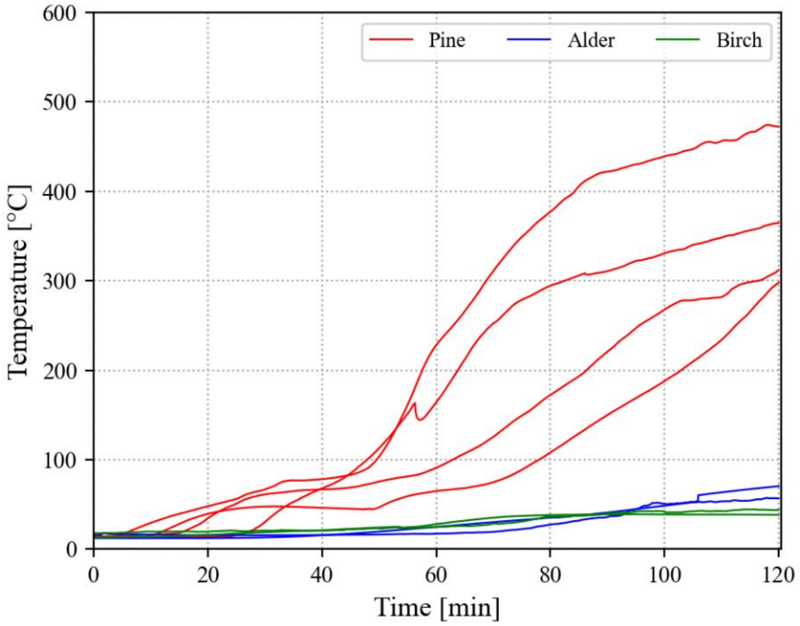

Figure 3 - Comparison of maximum soil temperatures of different samples

The intensity of the fires varied with the composition and moisture of the soils, the possibility of air entry into the soil layer and the duration of the tests. In general, the test stand is very suitable for investigating the characteristic fire behaviour of certain soil samples and the inter-soil fire spread. It should be noted that as the scale is increased, the influence of fire thermic increases (e.g. radiant heat, greater turbulence) and affects aboveground fire behaviour. The experiments show the danger of the rapid horizontal fire spread and the intensive heating of the soil layers, which pose major challenges for the firefighters during large-scale forest fires and can irreversibly damage the vegetation.

3. Experiments on Smoke Toxicity

3.1. Experimental Setup

The DIN tube furnace is suitable for creating optimal and reproducible smouldering conditions. This is to be understood as thermal oxidative decomposition without flame formation. For the tests in the DIN tube components (5g each) of the organic litter layer were taken. In another test series a thermal storage furnace (SEDEX-oven) was used to study spontaneous ignition behaviour. Heterogenous samples of soil (100g) were heated until the pre-set maximum temperature was reached. By measuring the temperature with a thermocouple, it is possible to detect any spontaneous ignition.

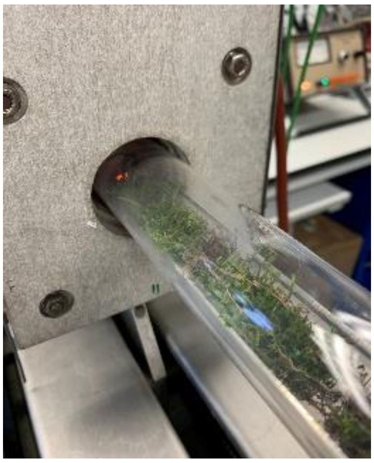

Figure 4 – DIN tube furnace with 5g soil sample

Figure 5 – SEDEX-Oven with 100g soil sample

Both, the DIN tube furnace and the SEDEX-oven were coupled with an FT-IR spectrometer to determine combustion products of the smouldering fires. The FT-IR were calibrated to different typical smoke components, which can be identified and quantified in respect to their concentration. By this determination, approaches to the evaluation of the hazard from smoke in regional ground fires should be made.

3.2. Results

3.2.1. Smouldering Test in the DIN Tube Furnace

In the comprehensive series of experiments, samples of moss, leaves, needles, bark, branches, soil, wood fragments, sand and pine cones in different compositions were investigated. Due to the heterogeneity of the samples, the composition of the smoke gases also varied.

The displayed sample in figure 4 contained small branches, as well as a proportion of sand, moss, needles and bark. Figure 6 and 7 show typical measured concentrations of this specimen 1.1 of hydrogen cyanide and sulfur dioxide, which are classified as toxic gases. The black line shows the medium concentration of two trials of a measurement series while the red line shows the average concentration during the whole experiments.

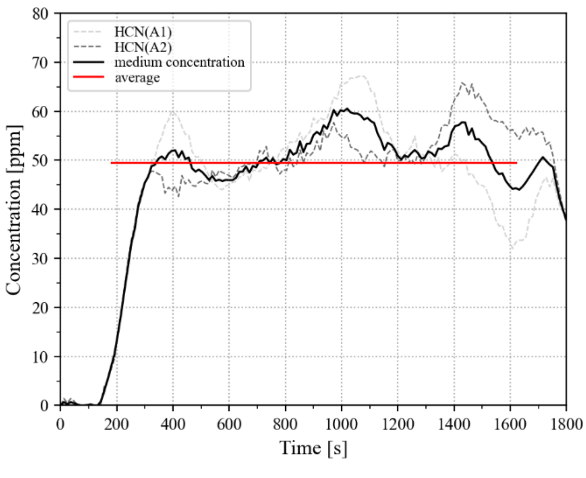

Figure 6 - Concentration of hydrogen cyanide (sample 1)

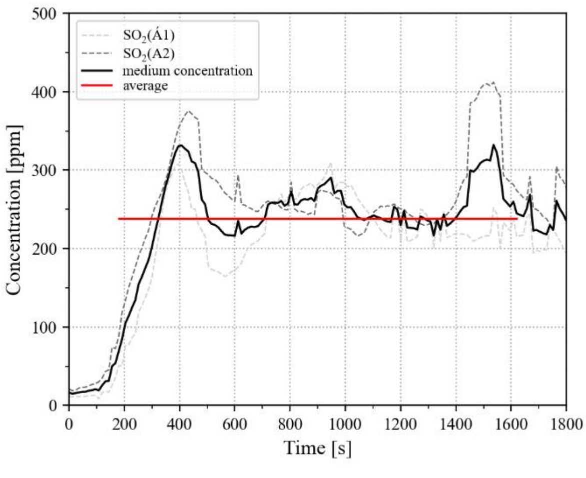

Figure 7 - Concentration of sulfur dioxide (sample 1)

The graphs rise continuously at the beginning when the heating ring of the DIN tube furnace initiates smouldering. During the course of the experiment, a relatively constant release of the toxic gases is established. The averaged released values are 50 ppm for HCN and 240 ppm for SO_2. The following table presents the average concentrations of typical measured product from different experiments.

Table 1 – Average concentrations (medium of two tests each) of different samples in [ppm]

SOIL SAMPLE	HCN	SO_2	C_3H_4O	C_2H_6O	CO	NH_3	CH_4
A	48	236	24	77	2940	13	640
B	45	276	29	79	3095	22	958
C	99	217	9	58	4280	25	545
D	36	301	54	86	5818	16	1064
E*	21	417	120	364	4316	10	4524

*(only needles)

The comparison shows the similar magnitudes of concentrations for different samples. The experimental setup makes it possible to measure the different components of the smoke gases. In additional experiments, the concentrations will be further quantified and the sources of the hazardous combustion substances can be determined by specific analyses.

3.2.2. Self-Ignition test in the SEDEX-oven

The samples in the SEDEX furnace were heated up to 400°C for 24 hours. Typically, spontaneous combustion occurred after 9-10 hours at temperatures of 180°C. The self-ignition of the organic material leads to a sudden increase of the temperature up to 440°C and initiates a burning process inside the oven.

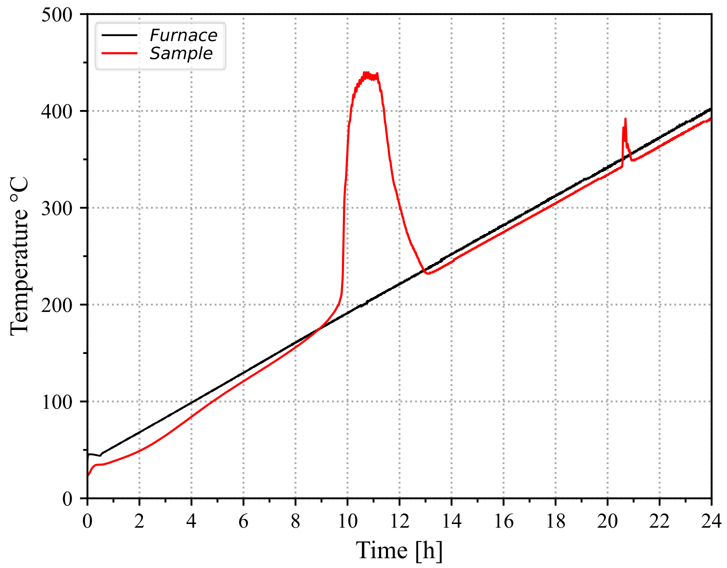

Figure 8 – Self-Ignition of sample from organic pine vegetation

During the experiments, analogous to the smoldering tests, the composition of the smoke was analyzed. The combustion products in the smoke are the similar to those of the other determination. The emissions of the

By the end of the self-ignition tests, complete combustion of the organic material can be assumed, leaving behind non-combustible components, such as heavy metals. Both the amount of mass loss and the level of concentrations of smoke depend on the composition of the sample. Due to the heterogeneity of the samples, further test series will be carried out to compare the values in order to determine a generally valid quantification of the hazards.

3.3. Evaluation of the smouldering tests

The inhalation of the harmful substances contained in the fire smoke can represent a not inconsiderable health hazard for people at the appropriate concentration. The experimental setup offers the possibility to determine the smoke compositions of different samples and to quantify them by comparison. The experiments provide knowledge in the area of basic research on the concentration of pollutants in fire smoke under smoldering conditions typically encountered in ground fires. The study of local vegetation provides specific insights into hazards from fire smoke, which must be considered in terms of fire suppression.

4. Conclusions

The fire tests and smoldering experiments are to be used to investigate the vegetation-specific fire behavior of local forest soils. The measured temperatures in the soil und the detected smoke compositions show the possible, high damaging effects of soil fires. Furthermore, the rapid and extensive spread of fire can spread to above-ground vegetation and lead to severe fires. The experiments will be expanded to include other vegetation types and in number to provide quantitative information on specific hazards.

Small and medium scale experiments are the basis to develop a numerical model capable of predicting the fire propagation. The combination of experiments and numerical investigation allows a quantitative assessment of the influence of the different heat transfer modes and therefore will significantly improve the understanding of fire propagation in these fires. In addition, by analyzing possible combustion products in the smoke, hazards for first responders and further, for the civil population can be determined and protective measures can be derived.

5. Acknowledgments

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