

RESEARCH ARTICLE

Self-ignition of forest soil samples demonstrated through hot storage tests

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Abstract

The increasing threat of forest fires on a global scale is not only a matter of concern due to the potential harm they may cause to both human and animal life but also due to their significant role in exacerbating climate change. In light of these circumstances, one might inquire as to whether forest soil can self-ignite and, if so, under what conditions and at what temperatures this phenomenon may occur. This question is being addressed in the German pilot “Fire science of wildfires and safety measures” of the EU project TREEADS, and the first results are presented below. The importance of basic research into the self-ignition of forest soil cannot be underestimated, as it provides crucial knowledge to prevent forest fires and protect human and animal health. Furthermore, mitigating the occurrence of forest fires can also play a role in reducing greenhouse gas emissions, contributing to global efforts to combat climate change. The procedure of the hot storage test is an effective means of determining whether a material can self-ignite. During the investigation of six soil samples, it was found that five of them were indeed capable of self-ignition. In addition to determining whether the material ignites, the modified hot storage test also analyzed the resulting smoke gases and measured their concentration. The research question of whether regional forest soil is capable of self-ignition can be answered with yes based on these initial tests. Further experiments are needed to determine if self-ignition causes forest fires.

KEYWORDS

FTIR spectroscopy, hot storage oven, ignition behavior, soil, wildland fire

1 | INTRODUCTION

Forests are an essential component of our ecosystem and serve a variety of functions, such as preserving biodiversity, providing wood and other resources, and protecting the soil and climate. However, forest fires pose a significant threat to forests and human life.

Forest soil fires can spread rapidly and cause significant damage, not only in terms of the destruction of ecosystems and biodiversity, but also in

terms of the health and lives of people living near forest areas. An example of highly destructive ground fires are the so-called “zombie fires” in the Arctic. Fires occurring in boreal forests can result in the release of more carbon than fires in regions like California or Europe, due to the presence of old, carbon-rich peat in the soil. Last year, Arctic fires released approximately 250 megatons of carbon dioxide, equivalent to half the annual emissions produced by human activity in Australia, and 2.5 times the amount released during California's unprecedented wildfire season in 2020.¹

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The issue of forest fires has been a concern in Germany for decades, not just since the major fires in 2017 and 2022. Large forest fires were already recorded in Lower Saxony in 1975 and during the 1990s. The effects of such fires are devastating, as they not only destroy large amounts of forest and vegetation, but can also lead to strong smoke development that can still be perceived up to 100 km away in some cases.²

Since 2022, the risk of forest fires in Germany has continued to increase, and between January 1st and June 25th alone, 2800 ha of forest area were destroyed by fires. Additionally, forest fires can have economic impacts by affecting forestry and tourism. Over the past 30 years, Germany has seen an average estimated damage of 1.76 million euros per year on an area of approximately 776 ha caused by forest fires.³ However, forest fires in Germany are not a new phenomenon, as the German Research Network for Natural Disasters (DFNK) already pointed out in 2004 that forest fires, along with earthquakes, floods, and storms, are one of the four natural hazards in Germany.⁴

According to Liu et al.,⁵ various literature studies have shown that the smoke from vegetation fires can cause higher levels of air pollution and respiratory diseases.

Therefore, it is of great importance to understand the causes and effects of forest fires and to take preventive measures to prevent or at least minimize such disasters. This includes basic research, insights into the origin and spread of fires, as well as into smoke gases, which are essential to be able to make recommendations.

In 2021, the cause of about half of all forest fires in Germany could not be determined, with most of these fires attributed to unknown causes. Known causes can be attributed to human actions or natural influences such as lightning strikes. Only 1.3% of forest fires in 2021 were attributed to natural causes.³

The question arises whether self-ignition of the soil can be considered as one of the unknown causes of forest fires. In particular, it is being investigated under which conditions and at what temperatures the soil can self-ignite and whether it is sufficient for a fire to roll over dry ground in order to cause a later flare-up of the fire.

In July 2022, a soil fire and the resulting smoke from a forest fire in eastern Germany can be seen in Figure 1. Here in this case, it is also of interest to know whether the underlying soil layer has ignited, is smoldering, or if the heat emitted from the fire was insufficient to initiate the ignition process.

In the case of self-ignition of soil, the smoke gases that are produced are also of interest. The low temperatures suggest incomplete combustion and therefore a higher concentration of CO in the smoke gas. Whether and at what temperatures soil samples ignite will be presented in this paper, along with an examination of the resulting smoke gases.

It is important to better understand the phenomenon of self-ignition in forest soil in order to develop effective measures for the prevention and control of forest fires. Research into the causes and mechanisms of self-ignition in forest soil, as well as the development of appropriate prevention and control strategies, is crucial to minimize the risks of forest fires and ensure the safety of both humans and nature.



FIGURE 1 July 2022 in Lieberose, Germany: Spreading of ground fire and consequent emission of smoke gases.

To achieve this objective, a comprehensive methodology was implemented under the EU project TREEADS, focusing on the experimental examination of forest and vegetation samples. The methodology, shown in Table 6, encompassed elemental analysis, thermogravimetric analysis (TGA), DIN tube furnace testing, assessment of organic content, and analysis using a hot storage oven. The findings on self-ignition behavior and the resulting smoke gases are incorporated into the project as fundamental research (Table 1).

In general, TREEADS is a project that focuses on the development of a holistic fire management ecosystem for prevention, detection, and restoration of environmental disasters. It involves collaboration with 47 partners from Europe and Taiwan, the German Pilot including, among others, the Otto-von-Guericke University Magdeburg, the Bundesanstalt fuer Materialforschung und -pruefung (BAM), RISE Fire Research Norway, and Schmitz One Seven GmbH. The project is a response to the increasing number of environmental disasters, particularly the growing number of wildfires worldwide due to climate change.⁶

Overall, the aim of this present study is to expand the knowledge about the behavior of ordinary forest soils regarding self-ignition and to contribute to the overall research on forest fires and their causes. The findings of this investigation will contribute to obtaining a more comprehensive understanding of the fire behavior of soils in forest areas and could potentially open up new perspectives for forest protection and management.

2 | FUNDAMENTALS OF SELF-IGNITION PROCESS

The Frank-Kamenetskii theory of ignition criticality has been widely used in research to study self-ignition characteristics of materials.⁷⁻⁹ The theory states that for a given sample size, heat generation from exothermic reactions is proportional to the volume of the sample,

TABLE 1 Experimental investigation systematic of forest and vegetation samples, X = Investigation completed, (X) = not fully completed, - = planned/implementation follows.

Specimen	Organic content (%)	HO/HU (kJ/kg)	Elemental analysis	Self-ignition + smoke analysis	Smouldering + smoke analysis	Ignition + temperatures	TGA
Pine (soil, needles, cones, bark)	X	X	X	X	X	X	X
Spruce (soil, needles, cones, bark)	X	X	X	(X)	X	X	(X)
Alder (soil, leaves, fruit, bark)	X	X	X	(X)	X	-	(X)
Beech (soil, leaves, fruit, bark)	X	X	X	(X)	X	X	(X)
Oak (soil, leaves, fruit, bark)	X	X	X	(X)	X	X	(X)
Moss	X	X	X		X	-	(X)
Grass	-	X	X		X	-	(X)

Abbreviation: TGA, thermogravimetric analysis.

while volumetric heat loss is proportional to the surface area. This means that as the size of the sample increases, the critical ambient temperature required for self-ignition decreases. The theory can be used to predict self-ignition for larger sizes, assuming the mechanism of heat generation remains the same.^{7,9} The theory assumes that the material is reactive and 1-D, with heat release from a 1-step exothermic reaction containing many chemical and biological elemental reactions. Organic materials usually have two sources of heat generation, a chemical process at higher temperatures and a biological process at lower temperatures caused by micro-organisms.¹⁰⁻¹²

It is common for self-ignitions during the storage of bulk materials to be investigated as there is a risk of self-ignition in such cases. The causes of self-ignitions lie in exothermic processes that can also occur at low temperatures. However, temperature plays an important role in the speed of these processes as the reaction rate increases with increasing temperature.¹³ In addition to chemical oxidation reactions that contribute the largest exothermic component to the overall process, physical and microbiological processes also play a role in the heat regulation of biomass bulk materials. For example, the adsorption of water onto relatively dry solid surfaces can also lead to an increase in temperature as adsorption heat is released.¹⁴ Microbiological processes can accelerate processes, particularly in the temperature range up to approximately 80°C and can vary greatly depending on environmental conditions.¹⁵

Similar to biomass bulk materials, forest soil can be viewed as an inhomogeneous, porous medium that is exposed to environmental factors such as temperature, rain, humidity, and air movement. It is therefore reasonable to assume that similar processes as those observed in bulk materials can also occur in forest soil.

A self-ignition can be graphically represented during continuous measurement. However, it must be distinguished whether the sample material only heats up or actually ignites. The turning point of the sample body temperature graph, which must be above the oven temperature (see Figure 2, hot storage test C), is decisive.¹⁶

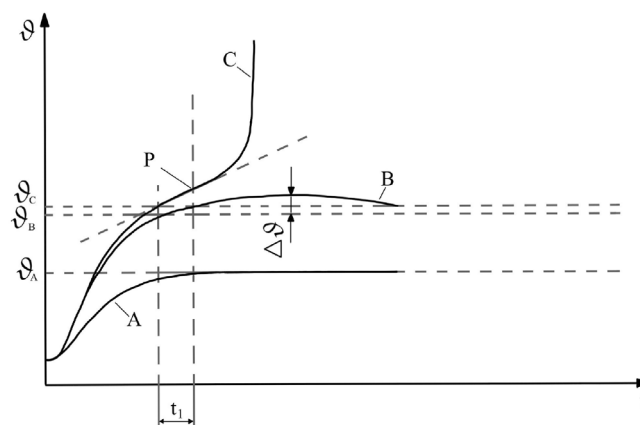


FIGURE 2 Idealized temperature curves over time in dust samples of the same volume at hot storage temperatures according to DIN EN 15188:2020.¹⁶ θ = temperature of the environment (for tests this is the oven temperature): shown with dashed lines; t = duration of the test; P = turning point; t_1 = induction time (for curve C): described with dashed and dotted lines. From the time when the temperature of the sample crosses the oven temperature (θ_C) and ends at the turning point. A = Hot storage test A. B = Hot storage test B. C = Hot storage test C.

According to Figure 2, it can be seen that there is no ignition at temperature θ_A and that the temperature difference at temperature θ_B is less than 60 K, indicating only warming but not ignition. The turning point p is relevant here, as self-ignition only occurs when it is exceeded. The turning point is not fixed at a specific temperature, but is reached when the oven and sample have a temperature difference greater than 60 K.¹⁶

Based on the fundamental principles of the stationary theory of thermal explosion, the self-ignition of solid substances can be theoretically understood. In practical laboratory experiments, the effect is exploited that the self-ignition temperature is dependent on the

TABLE 2 Summary of the main publications in the subject area around self-ignition of soil and forest or vegetation species.

Type of biomass	References
Peat (i.a. moss, dust, drained)	12,18–28
Grass	19,29
Eucalyptus soil litter	30
<i>Pinus halepensis</i> , <i>Pistacia lentiscus</i>	31
<i>Cupressus sempervirens</i>	
<i>Olea europaea</i> , <i>Cistus incanus</i>	

volume-to-surface area ratio (V/A). An intriguing method involves plotting the reciprocal absolute self-ignition temperature against the logarithm of the volume-to-surface area ratio ($\log(V/A)$) on a graph. In this process, the points exhibit a linear arrangement, enabling the determination of technically relevant volumes through extrapolation. This method yields satisfactory results, particularly for simple geometric shapes such as the cube, sphere, or cylinder.¹⁷

By utilizing this approach, a safe storage temperature for large quantities of a substance can be estimated. Hence, further studies are already being conducted using pine soil and various V/A -ratios (cube width/length/height: 6, 7.5, and 10 cm) to calculate the self-ignition temperature and subsequently extrapolate to larger scales.

In the past, other research teams have already delved into the topic of spontaneous combustion of biological materials, primarily focusing on peat soil. The following table aims to provide an overview of the current state of research on soil self-ignition. However, it does not claim to be exhaustive (Table 2).

After conducting this literature review, it was found that previous research has mainly focused on peat and other carbon-rich soils. However, there have been no investigations concerning ordinary forest soils, and as a result, the question of whether this type of soil can self-ignite and, if so, at what temperatures, remains unanswered.

The focus of this work is not on the determination of the self-ignition temperature, but on the study of the phenomenon itself and whether this ordinary forest soil is capable of self-ignition at all. The determination of the parameters will be the subject of further studies. Furthermore, the resulting smoke gases are measured and analyzed.

3 | EFFECTS OF COMPONENTS IN WILDFIRE SMOKE

The number of individual compounds present in smoke reaches into the thousands. Smoke composition depends on several factors, including fuel combustion efficiency, fuel type and moisture content, fire temperature, wind conditions, and other weather-related influences, as well as the freshness of the smoke and other variables. Different types of wood and vegetation consist of varying amounts of cellulose, lignin, tannins and other polyphenols, oils, fats, resins, waxes, and starches, which produce different compounds that are released as smoke when burned.³²

Generally smoke comprises two types of components: first particulates which include soot, semi-volatile organic compounds (SVOCs), and solid inorganic compounds, and second non-particulates which include very volatile organic compounds, volatile organic compounds, as well as liquid and gaseous inorganic compounds.³³

Wildfire smoke is a complex mixture that includes fine particles, volatile organic compounds, and other pollutants that can cause various health effects. Short- and long-term exposure to particle pollution from wildfire smoke can cause respiratory tract irritation, exacerbation of asthma and heart failure, and premature death. Fine particles can lead to coughing, wheezing, difficulty in breathing, and pulmonary inflammation. Short-term exposures to wildfire smoke can increase the risk of respiratory and cardiovascular disease exacerbation, as well as premature mortality.³⁴

During the combustion of forest and vegetation samples, smoke gases are typically released, including acetaldehyde, acetone, acrolein, ammonia, benzene, hydrogen cyanide, formaldehyde, ethanol, ethene, sulfur dioxide, and nitrogen oxides. Additionally, carbon dioxide and carbon monoxide are produced during every fire. These smoke gases have a narcotic and irritant effect, which can cause oxygen deprivation and, in severe cases, death.

Carbon monoxide and hydrogen cyanide affect cell respiration and oxygen transport in the blood, which can lead to death by suffocation at high concentrations. Carbon dioxide can intensify physiological effects at high concentrations and increase the amount of toxins that can be inhaled over a specific period. A reduction in the oxygen content in the air can have harmful effects on health and restrict the possibility of self-rescue.³⁵

Benzene is a well-known chemical compound often associated with the combustion of plastics or petrol. However, it can also be produced in forest fires, releasing as a highly flammable and toxic gas. Benzene is classified as carcinogenic to humans and can increase the risk of leukemia. Long-term exposure to benzene can lead to serious health problems, including liver and kidney damage, changes in blood composition, damage to the nervous system, and prolonged exposure can even cause death.³⁶

There are more irritant gases than narcotic gases, including inorganic acid gases such as HF, SO₂, and NO_x; organic irritant gases such as acrolein, acetaldehyde, and formaldehyde, as well as other inorganic gases such as ammonia, chlorides, and phosgene. Acrolein is one of the strongest irritant gases and can be deadly within a few minutes at concentrations above 10 ppm. Formaldehyde is produced under similar combustion conditions as acrolein and is also a common smoke product when burning many polymers and plastics. Sulfur dioxide irritates the respiratory system and can cause constriction, while nitrogen oxides such as nitric oxide and nitrogen dioxide are present as mixtures in combustion atmospheres and can cause lung damage when inhaled. Acetaldehyde is an irritating and carcinogenic substance, mainly known as an intermediate product in alcohol breakdown in the human body and as a component of cigarette smoke. Ammonia is a highly irritating gas that is corrosive to the respiratory system and eyes and can cause breathing difficulties.³⁵

In this study, the effects of fine particulate matter (PM) were not considered as the apparatus used did not allow for their investigation or determination. However, Reisen et al.³⁷ and Wegesser et al.³⁸ impressively describe the impact of these particles on health. It was also shown that fine PM from wildfires is more toxic than ambient particles.

4 | PRESENTATION OF THE FOREST SOIL SAMPLES

Six soil samples of different tree species are examined, with three trials conducted per sample. The samples were taken from a woodland area near Magdeburg and were dug out with a spade to a depth of 15 cm, then dried for 1 week under laboratory conditions in open plastic containers. Nonetheless, the samples had varying levels of moisture content during the trials.

The oak soil (WP 3) contains predominantly sandy soil in addition to leaves and branches. This sample was taken from an artificially planted oak forest, and the results cannot be generalized to all oak forests since the sand content in the soil is very high in the Börde region.

Therefore, a second examination of oak soil (WP 4) from the Grauingen region was conducted, with probably a higher organic and lower sandy content in the soil. Figure 3 reveals how the samples were layered: the majority of the sample mass is soil, and then a layer of litter follows. The depictions in Figure 3C,F illustrate the condition of the specimens after the experiments were conducted.

Due to the different composition of the samples, self-ignition may occur during the hot storage tests. However, it is also possible that no combustion occurs and there is no temperature difference between the oven and the sample material. Moreover, due to the heterogeneity of the organic sample material, a different composition of smoke gases is to be expected.

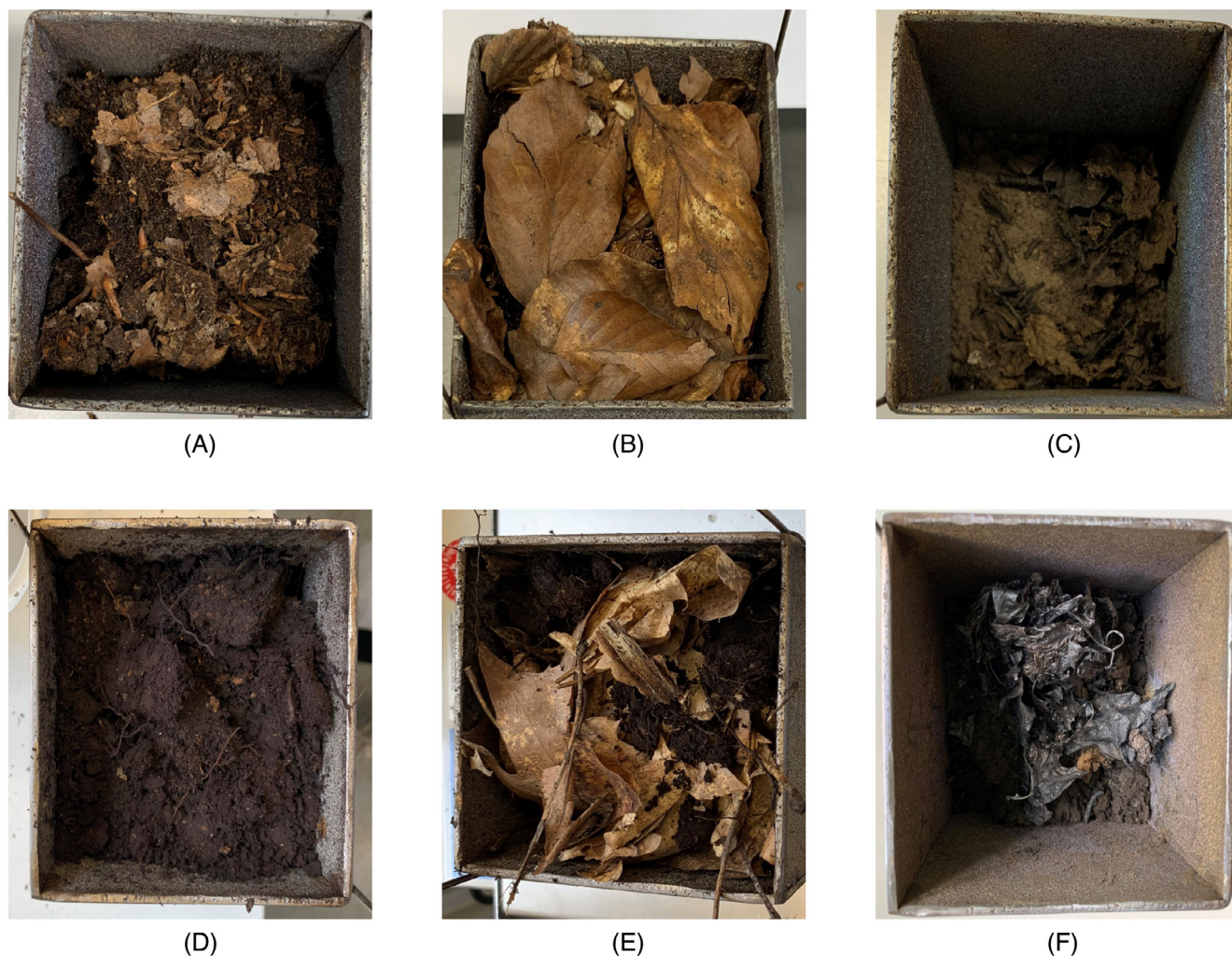


FIGURE 3 Beech and oak soil samples collected before and after the hot storage tests, top view (A) Beech WP 2, location: Grauingen (Calvörde), soil layer. (B) Beech WP 2, before testing, with soil layer with litter. (C) Beech WP 2, after testing. (D) Oak WP 4, location: Grauingen (Calvörde), soil layer. (E) Oak WP 4, before testing, with soil layer with litter. (F) Oak WP 4, after testing.

5 | MEASUREMENT TECHNOLOGY AND EXPERIMENTAL METHOD

To investigate the self-ignition behavior, a hot storage oven is used. The samples are heated until the preset maximum temperature is reached. By measuring the temperatures using two thermocouples, type K, an assertion about self-ignition can then be made. This method is mainly used for dust samples, but it is also possible to investigate other samples such as bulk materials. The basis for this is DIN EN 15188:2020 Determination of the self-ignition behavior of bulk materials.¹⁶

Samples must be filled into sample basket (10 cm × 10 cm × 10 cm → $V = 1000 \text{ cm}^3$, $A = 100 \text{ cm}^2$) made of wire mesh (see Figure 4A), with closed bottoms and open tops, and the use of a furnace with air inlets and outlets and temperature control between 35 and 300°C is recommended. The TSC 511-SEDEX furnace from Systag is an example of such an oven, as can be seen in Figure 4B. Two thermocouples are necessary to measure and record temperatures in both the oven and the sample, and in this experiment, the Voltcraft model K202 was used to record two temperature data simultaneously.

The furnace is controlled by the FlexySys software, which divides the experiment into conditioning and temperature step phases (see Figure 5). The Fourier-transform infrared spectroscopy (FTIR) is connected to the oven to measure and record the components and concentrations of the smoke gases, but it should be noted that the concentrations must be multiplied by a factor of 10 due to air dilution. In this experiment, the initial temperature of the test series is 40°C, with an initial ramp of 70 K/h, while the temperature change is 360°C, the temperature ramp is 15 K/h, and the final temperature is 400°C, resulting in a total test duration of 24 h (Table 3).

The apparatuses presented above are part of the experimental setup. The oven, thermocouples with temperature recording equipment, and computer with control software are adjusted accordingly and require no further preparation (see Figure 6). The setup is

supplemented by the FTIR, which is connected to the oven and calibrated before each test. This is used to measure the type and concentration of the resulting smoke gases.

FTIR spectroscopy is based on collecting and analyzing infrared absorption of gas sample components. Several wavelengths within the infrared spectrum are used simultaneously. Molecules are absorbing energy in a characteristic spectrum, caused by stimulated molecular vibrations. Thus identification and concentration measurement of gas samples are possible. The measuring device Gasett DX4000 is used as FTIR within the experimental setup. Its infrared light sources cover a wave number range from 900 to 4200 cm^{-1} . The sensor technology is based on mercury cadmium telluride (MCT) semiconductors.³⁹

Before starting the experiment, the sample mass is always documented. Due to the higher moisture content of alder (WP 1), the average mass is 250 g. The LP4200S balance from Satorius is used for mass measurement. The storage conditions for the first six experiments were 1 week under laboratory conditions. The remaining samples were allowed to dry for 6 weeks. After the filled basket has been placed in the oven, the thermocouples must be placed. The thermocouple that measures the interior temperature is placed midway between the outer wall and the sample basket. The second thermocouple is inserted into the center of the sample, and then the temperature logger recording is started. After all parameters have been entered into the software, the oven door is closed, the oven fan is turned on, and the experiment is started. The FTIR starts measuring the smoke gases at the same time, and the procedure is identical to that of the smoldering experiments. After the experiment, the sample is removed, weighed, and photographed for documentation.

6 | RESULTS AND DISCUSSION

As explained in the Introduction the primary research question was whether forest soil ignites at all and what types of smoke gases are

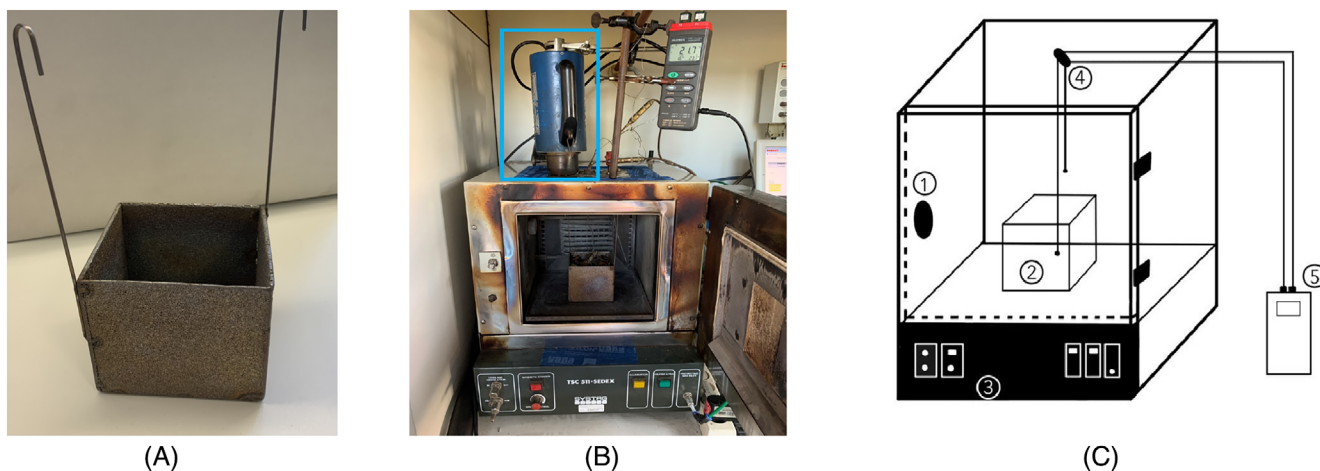


FIGURE 4 Test setup of the hot storage oven. (A) Stainless steel test basket for hot storage tests, 10 cm × 10 cm × 10 cm. (B) Hot storage oven with temperature logger and in blue framed the FTIR heater with collecting sensor. (C) Sketch of hot storage furnace with (1) door, (2) basket, (3) fan control unit, (4) thermocouples, (5) temperature logger.

FIGURE 5 Presentation of the two experimental phases during the hot storage test.

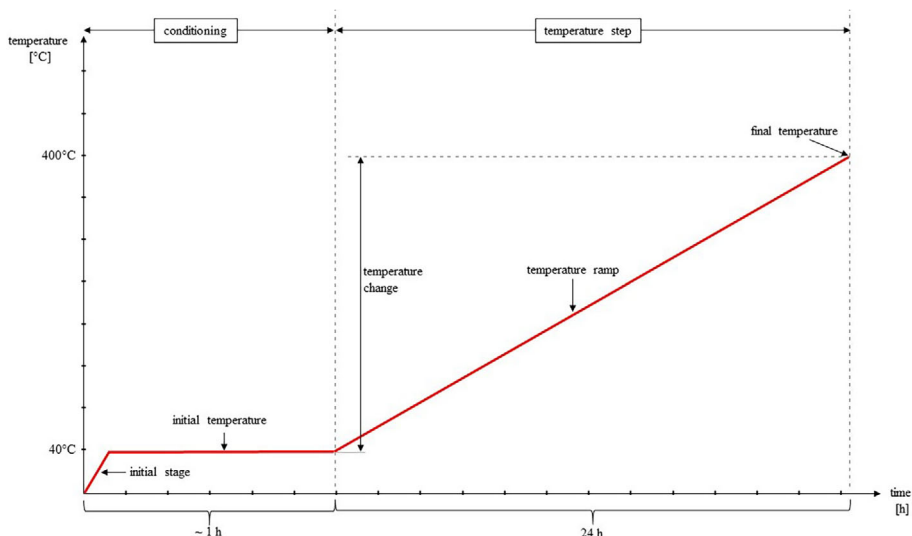


TABLE 3 Overview of hot storage furnace settings and general setup.

Parameter	Hot storage furnace
Test conditions	Controlled temperature increase of the furnace with parallel monitoring Sample temperature to determine spontaneous ignition
Furnace temperature	Up to 400°C, 15 K temperature increase per hour, initial temperature = 40°C
Cube size	100 × 100 × 100 mm
Specimen mass	WP 1-WP 4: 250 g WP 5: 125 g WP 6: 100 g
Test duration	24 h and ≈1 h conditioning (see Figure 5)
Experiment number	Three per specimen
Measured quantities	Temperature, gas concentrations
Toxicity assessment FTIR spectroscopy	Yes
Standards	DIN EN 15188:2020

Abbreviation: FTIR, Fourier-transform infrared spectroscopy.

released in the process. To address this question, initial experiments were conducted using various forest soil samples, with each sample utilizing a specific V/A ratio (volume to area ratio). The results of these initial experiments were obtained, and further investigations are now planned, where the V/A ratios will be varied to analyze the scalability of the findings.

Drawing on the foundation (refer to Figure 2), the data collected can be used to infer the presence or absence of self-ignition. Table 4 shows an overview of the most important temperatures during the hot storage tests and also the starting points of the self-ignition processes.

Significant fluctuations in sample temperature ϑ_s within a given soil type are evident, as shown in Table 4. The intuitive assumption of

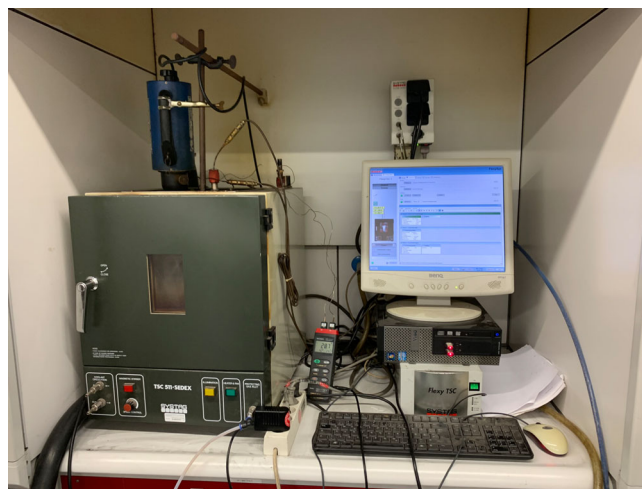


FIGURE 6 Test setup hot storage test, incl. part of the Fourier-transform infrared spectroscopy device (blue cylinder), front view.

higher mass loss at elevated temperatures cannot be confirmed, as the calculated mass losses do not correlate with the temperatures (cf. Table 5). This implies that a high mass loss in an experiment does not necessarily equate to a high sample temperature, and vice versa. Further research is needed at this juncture. Nevertheless, it remains possible that the approach to mass loss is accurate, as it has been determined thus far through weighing the sample before and after the experiment, with no data available regarding mass loss over time.

Figure 7 displays temperature curves for a single test per soil sample for illustration. It depicts the onset of self-ignition, which occurs when the sample temperature surpasses the oven temperature and continues to escalate. Figure 7C, on the other hand, presents no indication of self-ignition. Although the sample temperature briefly exceeds the oven temperature, it does not escalate further but rather descends back below the oven temperature before rising in parallel with it, without surpassing it.

TABLE 4 Overview of the six materials with the oven temperature (ϑ_F), the sample temperature (ϑ_S) leading to the maximum temperature difference ($\Delta\vartheta_{\max}$) between oven and sample in °C during the hot storage test, and the averaged starting points of the self-ignition processes.

	Test nr.	ϑ_F	ϑ_S (°C)	$\Delta\vartheta_{\max}$ (°C)	Averaged start of the self-ignition process
Alder WP 1	V 1	213°C	398	185	≈10 h at 189°C
	V 2	219°C	461	242	
	V 3	222°C	383	161	
Beech WP 2	V 1	214°C	431	217	≈9 h and 40 min at 186°C
	V 2	215°C	500	285	
	V 3	215°C	386	171	
Oak WP 3	V 1				
	V 2	No self-ignition, only continuous warming of the sample			
	V 3				
Oak WP 4	V 1	266°C	486	220	≈11 h and 27 min at 211°C
	V 2	289°C	686	397	
	V 3	258°C	547	289	
Spruce WP 5	V 1	223°C	491	268	≈8 h and 39 min at 169°C
	V 2	210°C	418	208	
	V 3	211°C	419	208	
Pine WP 6	V 1	182°C	332	150	≈8 h and 55 min at 175°C
	V 2	200°C	440	240	
	V 3	201°C	456	255	

TABLE 5 Overview of the mass loss of the six materials with the highest sample temperature (ϑ_S).

	Test nr.	ϑ_S (°C)	Mass loss (%)
Alder WP 1	V 1	398	49.6
	V 2	461	44.6
	V 3	383	19.2
Beech WP 2	V 1	431	32.9
	V 2	500	31.1
	V 3	386	15.2
Oak WP 3	V 1		11.4
	V 2		7.9
	V 3		6.7
Oak WP 4	V 1	486	86.0
	V 2	686	85.1
	V 3	547	84.1
Spruce WP 5	V 1	491	55.3
	V 2	418	56.6
	V 3	419	29.8
Pine WP 6	V 1	332	71.0
	V 2	440	54.1
	V 3	456	62.6

That is not surprising because as mentioned at the beginning of the publication, the oak samples (WP 3) are samples from an artificially created forest area with very sandy soil and little organic litter

layer. Therefore, the experiment was repeated with a different oak soil sample (WP 4) to check whether WP 3 was an exception or if oak soil generally does not ignite. It can be clearly stated at this point that WP 3 is an exception, as the second oak soil sample (WP 4) did ignite.

The sample mass for the pine soil (WP 6) was only 100 g, not 250 g like for the alder and beech. However, the sample mass does not seem to have a significant influence on the time to ignition or the ignition temperature. The ignition temperature is only on average 7.6°C higher for WP 1–WP 4, despite having a 1.5 times greater mass.

The temperature graphs of the soil samples (see Figure 7B,D) also clearly showed the influence of soil moisture on the temperature profile. Soil samples with short drying times exhibit a typical drying process. As soon as the sample temperature reaches 100°C and the remaining water has evaporated, the soil temperatures rise rapidly. The samples with longer drying times do not show this initial low temperature profile, but instead rise almost proportionally with the oven temperature.

During the hot storage tests of spruce and pine (WP 5 and WP 6), probably a second self-ignition can also be observed (see Figure 7E,F). After approximately 19 or 21 h, the furnace temperature is once again exceeded by more than 60 K. Parts of cones were included in the tested soil sample, and these may be responsible for the second self-ignition as sufficient organic material remained, which ignites at >325°C. Another reason would be ignition of residues on the thermocouple. Whether this is indeed a second self-ignition by the soil needs to be investigated with further experiments.

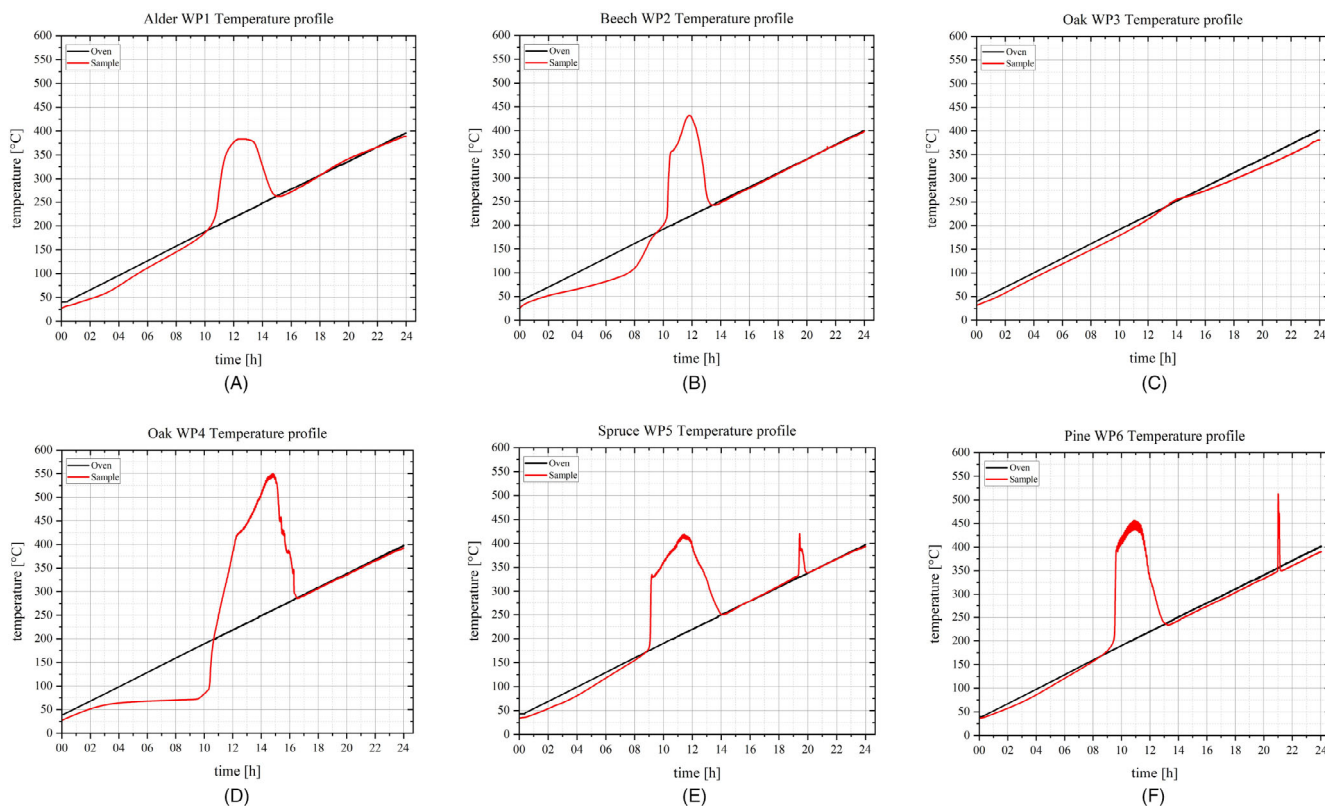


FIGURE 7 Exemplary temperature profiles of one of the experiments per soil sample, black line shows the oven temperature and the red line shows the sample temperature. (A) Alder WP 1 (test nr. 3). (B) Beech WP 2 (test nr. 1). (C) Oak WP 3 (test nr. 2). (D) Oak WP 4 (test nr. 3). (E) Spruce WP 5 (test nr. 2). (F) Pine WP 6 (test nr. 3).

In principle, it is important to discuss the aspects of repeatability and potential inaccuracies. The execution of three trials for each test specimen already reveals a fundamental commonality, namely their self-ignited, with the exception of Oak WP 3. Nevertheless, significant differences can be observed both in terms of the maximum sample temperatures compared to the furnace temperatures and in regard to the measured mass loss (see Tables 4 and 5). There are already specific plans in place to conduct further experiments in order to expand the dataset and validate the existing results.

By integrating FTIR into the experimental apparatus (see Figures 4B and 6) and measuring the type and concentration of smoke gases, additional information about the smoke gases generated during self-ignition can be obtained. This allows differences between the smoke gases from wildfires and fires in urban or industrial areas to be identified. In addition, the main components in wildfire smoke can be confirmed.

In addition to temperature diagrams, there are other indications of self-ignition that can be derived from smoke gas concentration diagrams. During the beginning of the self-ignition process, the concentrations rapidly increase, and then fall again, as can be seen when the temperature curve is overlaid over the concentration curve (see Figure 8).

The gases analyzed are listed in Table 6, and the maximum concentrations of the smoke gas components averaged over the three

experiments are presented for each sample. A 24-h time averaging is not performed, as the concentration peaks mostly occur during self-ignition, and pollutant concentrations are otherwise very low.

The graphs (see Figure 8) clearly show the parallel course between the self-ignition process and the increase in smoke gas concentrations. This correlation was already to be expected. In addition, the pine graph WP6 Figure 8C shows that there is again a CO concentration peak during the second self-ignition.

It would be expected that the maximum temperature of the sample would result in the maximum production of smoke gases. However, this was not the case for all smoke gas components. Particularly, ammonia stands out as its concentration peak occurs only toward the end of the experiment (see Figure 9). This progression of gas concentration can be found in all six soil samples. Figure 9A shows the direct comparison of temperature curves between the furnace and the sample for NH_3 concentrations from the third experiment of alder. It is important to further investigate this phenomenon and to understand which processes occur during the formation of ammonia in order to explain these trends.

The low concentrations for WP 3 were expected as no self-ignition occurred. The high ammonia value and relatively increased sulfur dioxide value are surprising. Although there is no self-ignition, the sample body is degassing, and it is assumed that oak leaves and branches are mainly involved in this process.

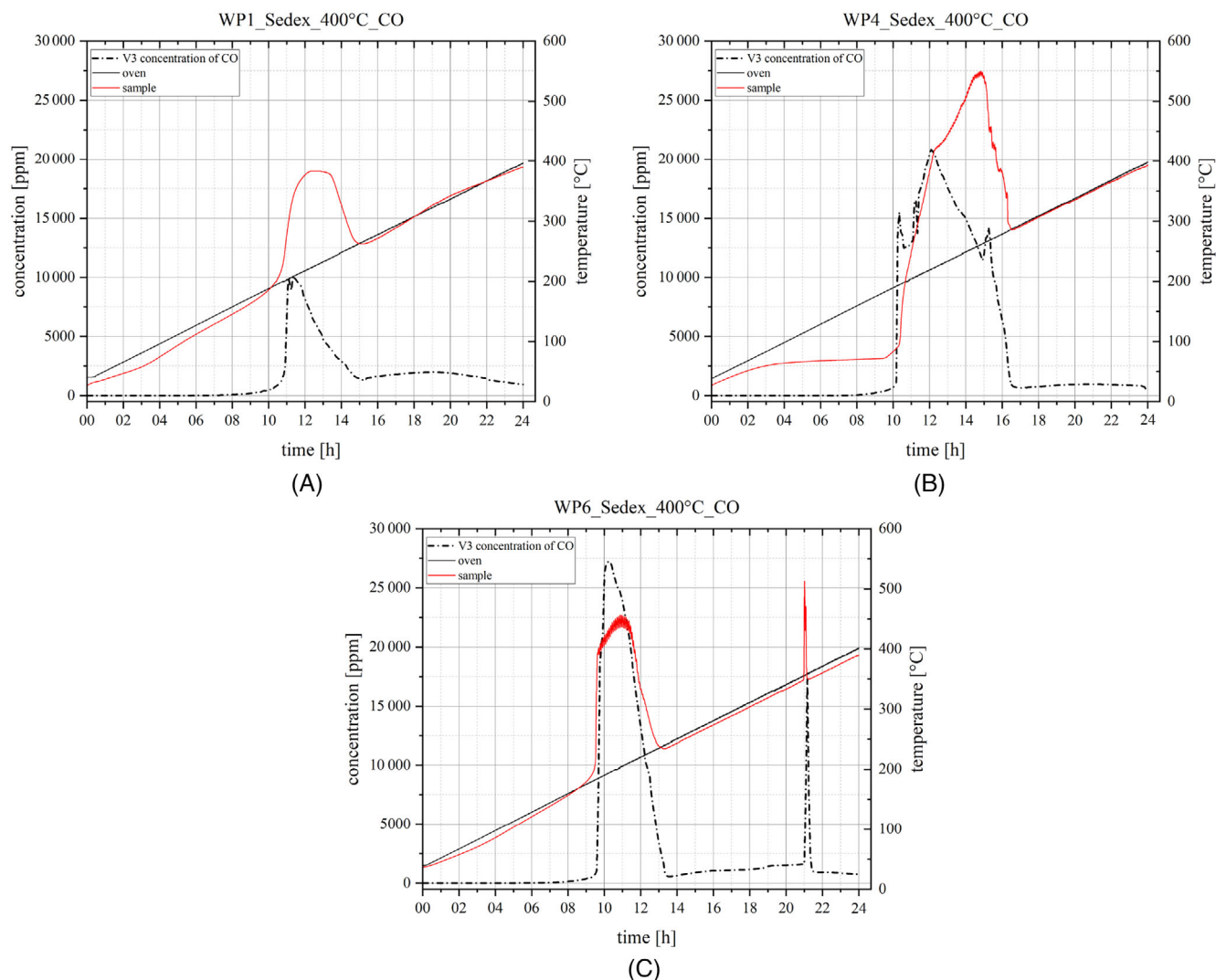


FIGURE 8 Measured concentration of CO from alder WP 1, oak WP 4, and pine WP 6 during hot storage tests (in ppm) (dashed line), compared to the temperature curves of the sample (red line) and oven (black line). (A) Alder WP 1—CO concentration and temperature curve. (B) Oak WP 4—CO concentration and temperature curves. (C) Pine WP 6—CO concentration and temperature curves.

	Alder	Beech	Oak	Oak	Spruce	Pine
Smoke gas (in ppm)	WP 1	WP 2	WP 3	WP 4	WP 5	WP 6
Acetaldehyde	967	333	69	479	1243	786
Acetone	913	876	155	592	1023	379
Acrolein	2337	815	271	535	1999	1590
Ammonia	349	157	196	270	878	558
Benzene	332	186	15	166	294	348
Hydrogen cyanide	258	235	24	482	249	408
Ethanol	1907	217	17	935	3003	3210
Ethene	389	233	31	83	532	22
Formaldehyde	180	208	77	212	182	254
Carbon monoxide	12 997	12 016	2617	17 724	15 631	26 027
Methane	13 084	3289	173	6760	17 299	12 112
Sulfur dioxide	7548	14 381	3476	11 200	22 345	10 307
Toluene	37	49	5	437	572	496
Carbon dioxide (vol%)	9	6	2	12	11	17

TABLE 6 Averaged maximum smoke gas concentrations WP 1–WP 6 (in ppm), red numbers show the highest concentration, orange numbers are specific for WP 3 and underline that this is not the lowest concentration.

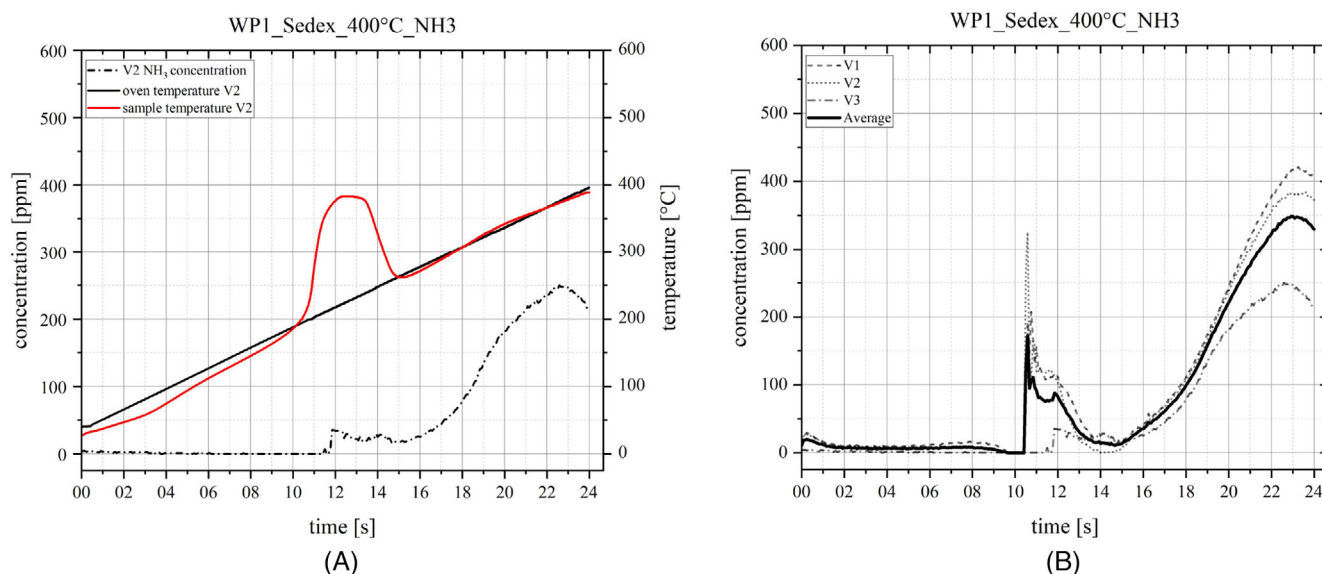


FIGURE 9 Measured concentration of ammonia from alder WP 1 (V 1–V 3) during hot storage tests (in ppm) and left-hand side the ammonia concentration of the second test (V2) compared to the temperature development of the sample and oven. (A) Alder WP 1 V 2—ammonia concentration and the temperature graphs of oven and sample. (B) Alder WP 1, all tests—ammonia concentration (in ppm).

WP 5 and WP 6 contained spruce and pine cones, respectively. These two sample bodies also show the highest concentrations of smoke gases (12/14), which is highlighted in red shown in Table 6. It is plausible that the cones have an influence on the concentration levels, which would need to be further investigated in another series of experiments.

The ammonia and ethene concentrations are colored in orange for oak WP 3 since, despite no self-ignition occurring, the smoke gas concentration is not the lowest. This suggests that even without self-ignition, ammonia and ethene can be present at higher concentrations than when the material ignites.

The loss of mass is determined mathematically by measuring the masses before and after the experiment. Therefore, it is not possible to make any statements about the progression of mass loss. The available data shows significant differences in mass loss between the individual samples. While oak WP 3 only shows a mass loss of 8%, this is the highest in oak WP 4 with 85%. The other samples also show clear differences. A high mass loss rate can be attributed to various factors, such as the moisture content of the product and the organic content. Here are all mass loss rates listed:

Alder	WP 1	38%	Oak	WP 4	85%
Beech	WP 2	26%	Spruce	WP 5	56%
Oak	WP 3	8%	Pine	WP 6	63%

A high mass loss rate does not allow conclusions to be drawn about the level of smoke gas concentrations. Although, for example, oak WP4 has the highest mass loss, the data (see Table 6) show that it does not produce the highest smoke gas concentrations.

7 | CONCLUSION AND PROSPECTS

This study was conducted as part of the German Pilot of the EU TREEADS project. The central research question was whether different types of forest soil can self-ignite. The TSC 511-SEDEX hot storage oven from Systag was chosen as the experimental apparatus, and the forest soil sample was exposed to a temperature increase of 15 K per hour, starting from an initial temperature of 40°C, for 24 h. The focus was also on the resulting smoke gases, which were measured and their concentrations were determined using FTIR spectroscopy. The mass loss was subsequently calculated, but only a statement regarding the overall mass loss can be made, as no information was collected on the mass reduction over time.

In summary, this paper demonstrates that self-ignition is possible for different kind of forest soil as long as the organic content is high enough. It is now necessary to determine the inorganic content and mathematically determine the self-ignition temperatures like Restuccia et al.¹² demonstrated it for peat soil. The calculated self-ignition temperatures can help determine if self-ignition of the soil is a cause of forest fires and can serve as a control value for post-extinguishing measures. If the soil temperature is below the calculated value, it can be assumed that the risk of self-ignition and reignition of vegetation is low. However, if the soil temperature is above this value, further extinguishing or cooling measures could be initiated to minimize the risk of forest fires.

The available data shows that the basic composition of smoke gases in forest samples is similar, but the concentrations vary significantly. Therefore, when developing technologies to improve forest fire early detection, the worst-case scenario should be considered to ensure that any type of ground fire in the forest can be reliably

detected. The determined smoke gases and their concentrations can now help optimize forest fire sensors. This knowledge can be used to make technology and software more sensitive and precise. The results of the smoke gas measurement show that significant concentrations of ammonia and ethene were measured even in the absence of self-ignition. Therefore, these gases should be considered in early detection of fire, in addition to the usual gases such as carbon monoxide and hydrogen. Moreover, the data can be used to train artificial intelligence and improve its use in fire detection, as is done with the Dryad technique.⁴⁰

A major challenge is the placement of sensor technology in the forest. Real experiments should be conducted to determine the height above the ground at which sensors should be installed. This would contribute to more precise recommendations for optimal positioning and thus improve early detection of forest fires.

Summarized further research is clearly needed to answer the following questions:

- What self-ignition temperatures result from the calculation? Are these realistic in nature or can spontaneous combustion of the soil be excluded as a reason for forest fires?
- What factors (soil moisture, organic content) promote self-ignition, and conversely, at what levels does self-ignition of this regional forest soil no longer occur?
- What is the reason for temperature θ_s variations within a specific type of soil?
- At which smoke gas concentrations can a ground fire be assumed, and are there certain gases and concentrations that contribute significantly to detection?

Currently, studies are being conducted to answer some of these questions. The initial conditions of the experimental setup are being adjusted. The temperature ramp now increases by 30 K per hour instead of 15 K, and the maximum temperature is set at 200°C instead of 400°C. These changes are based on the findings that the turning point for four out of five samples that ignited was below 200°C.

Additionally, a switch to larger hot storage ovens is being made to analyze larger samples. The initial conditions will remain the same for the time being to ensure comparability.

The temperature profiles of the soil samples reveal that those with shorter drying times exhibit a typical drying pattern, while samples with longer drying times demonstrate a nearly proportional increase in temperature with the oven temperature. Ultimately, self-ignition tends to occur once the soil sample temperature reaches a critical point. To determine the conditions that enable or prevent ignition, further analysis of the soil samples is necessary. For this reason, now the samples are being conditioned differently. A climate chamber is used to “stress” the samples with humidity levels typical for the wildfire season and temperatures ranging from 20 to 30°C. This aims to answer the question of whether and to what extent the dry months affect the time to self-ignition.

The sensor technology was tested during real fire experiments in September 2023, with sensors being positioned both on humans and in vegetation. After evaluating the results of these experiments, insights can be shared and recommendations on sensor placement may be provided.

Generally these observations provide valuable information about the self-ignition process and can help improve the safety. Analysis of smoke gas concentration graphs makes it possible to identify potential sources of danger and take preventive measures to avoid uncontrolled spontaneous combustion. However, the focus should not only be on self-ignition, but also always consider the resulting smoke gases. At this point, no concrete recommendations can be made, as further research and the answering of the questions listed above are necessary. However, this is an important step toward fundamental research on the ignition of organic porous media, here in the form of forest soil.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

1. Borunda A. Zombie fires in the arctic are linked to climate change. *National Geographic*. 2021. <https://www.nationalgeographic.com/environment/article/zombie-fires-in-the-arctic-are-linked-to-climate-change>
2. dpa. Waldbrände in brandenburg: Hoffen auf Regen und Gewitter. *Volksstimme*. 2022. <https://www.volksstimme.de/panorama/waldbrande-in-brandenburg-hoffen-auf-regen-und-gewitter-3394535>
3. B. für Landwirtschaft und Ernährung. *Waldbrandstatistik der Bundesrepublik Deutschland für das Jahr 2021 Bonn*. 2022. Accessed May 5, 2023. <https://www.ble.de/SharedDocs/Downloads/DE/BZL/Daten-Berichte/Waldbrandstatistik/Waldbrandstatistik-2021.html>
4. Hirschberger P. *Wälder in Flammen: Ursachen und Folgen der weltweiten Waldbrände*. 5th ed. Eigenverlag; 2011.
5. Liu Z, Murphy JP, Maghirang R, Devlin D. Health and environmental impacts of smoke from vegetation fires: a review. *J Environ Prot*. 2016;7:1860-1885.

6. Hofmann-Böllinghaus A. *Treedads*. 2020. Accessed May 3, 2023. <https://treedads-project.eu/>
7. Drysdale D. *An Introduction to Fire Dynamics*. 3rd ed. John Wiley and Sons; 2011.
8. Restuccia F, Ptak N, Rein G. Self-heating behavior and ignition of shale rock. *Combust Flame*. 2017;176:213-219.
9. Gray B. Spontaneous combustion and self-heating. *SFPE Handbook of Fire Protection Engineering*. Springer; 2002:211-228. <https://www.sfpe.org/publications/handbooks/sfpehandbook>
10. Nelson MI, Marchant TR, Wake GC, Balakrishnan E, Chen XD. Self-heating in compost piles due to biological effect. *Chem Eng Sci*. 2007; 62:4612-4619.
11. Hogland W, Marques M. Physical, biological and chemical processes during storage and spontaneous combustion of waste fuel. *Resour Conserv Recycl*. 2003;40:53-69.
12. Restuccia F, Huang X, Rein G. Self-ignition of natural fuels: can wildfires of carbon-rich soil start by self-heating? *Fire Saf J*. 2017;91: 828-834.
13. Hensel W, Krause U, Löffler U. In: Steen H, ed. *Selbstentzündung fester Stoffe (einschließlich Stäube)*, *Handbuch des Explosionsschutzes*. Weinheim; 2000.
14. Lohrer C, Schmidt M, Krause U. A study on the influence of liquid water and water vapour on the self-ignition of lignite coal-experiments and numerical simulations. *J Loss Prev Process Ind*. 2005; 18:167-177.
15. Ferrero F, Malow M, Schmidt M, Krause U. Leitfaden zur brandvermeidung bei der Lagerung von Biomasse. *BAM Bundesanstalt für Materialforschung Und -prüfung*. 2009:1-22.
16. D. I. für Normung e.V. *DIN EN 15188: Bestimmung des Selbstentzündungsverhaltens von Staubschüttungen – Deutsche Fassung EN 15188*. Beuth Verlag GmbH; 2020.
17. Steen H. *Handbuch des Explosionsschutzes*. Wiley-VCH Verlag GmbH; 2000.
18. Frandsen WH. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. *Can J for Res*. 1987;17:1540-1544.
19. Frandsen W. Ignition probability of organic soils. *Can J for Res*. 1997; 27:1471-1477.
20. Hanninen KI. A chemical mechanism for self-ignition in a peat stack. *Environ Ecol Res*. 2017;5(1):6-12.
21. Półka M. Analysis of susceptibility of peat on its spontaneous heating and self-ignition properties. *MATEC Web Conf*. 2018;247:6.
22. Cui W, Hu Y, Rein G. Experimental study of the ignition conditions for self-sustained smoldering in peat. *Proc Combust Inst*. 2022;39: 4125-4133.
23. Yuan H, Restuccia F, Rein G. Spontaneous ignition of soils: a multi-step reaction scheme to simulate self-heating ignition of smoldering peat fires. *Int J Wildland Fire*. 2021;30(6):440-453.
24. Gnatowski T, Ostrowska-Ligeza E, Kechavarzi C, Kurzawski G, Szatylowicz J. Heat capacity of drained peat soils. *Appl Sci*. 2022;12:1-17.
25. Ranneklev SB, Bååth E. Use of phospholipid fatty acids to detect previous self-heating events in stored peat. *Appl Environ Microbiol*. 2003; 69(6):3532-3539.
26. Hadden RM, Rein G, Belcher CM. Study of the competing chemical reactions in the initiation and spread of smoldering combustion in peat. *Proc Combust Inst*. 2012;34(2):2547-2553.
27. Palamba P, Ramadhan ML, Perdana LR, et al. Experimental investigation of smoldering combustion of tropical peat layer under stratified moisture content. In: *Proceedings of 11th Asia-Oceania Symposium on Fire Science and Technology 2020*.
28. Arief AT, Elwit E. Self-ignition temperature of peat. *J Phys Conf Ser*. 2018;1198:042021.
29. Font R. Analysis of spontaneous ignition of grass: chemical oxidation and water vapor sorption. *Fire Technol*. 2022;58:1363-1390.
30. Jones JC, Ramahti H, Fowler D, Vorasuyakarnt J. The self-heating and thermal ignition propensity of forest floor litter. *J Fire Sci*. 1990; 8(3):207-223.
31. Liodakis S, Bakirtzis D, Dimitrakopoulos A. Ignition characteristics of forest species in relation to thermal analysis data. *Thermochemica Acta*. 2002;390(2022):83-91.
32. U. E. P. Agency, U. F. Service, U. C. for Disease Control, Prevention, and C. A. R. Board. *Wildfire Smoke, a Guide for Public Health Officials*. U. E. P. Agency, U. F. Service, U. C. for Disease Control, Prevention, and C. A. R. Board; 2016. <https://oehha.ca.gov/media/wildfiresmoke2016.pdf>
33. Newman JS, Yee GG, Su P. Smoke characterization and damage potentials. In: Hurley MJ, Gottuk D, Hall JR, et al., eds. *SFPE Handbook of Fire Protection Engineering*. Springer; 2016:724-744. <https://www.sfpe.org/publications/handbooks/sfpehandbook>
34. US EPA and OAR. *Health Effects Attributed to Wildfire Smoke*. US EPA and OAR; 2022. <https://www.epa.gov/wildfire-smoke-course/health-effects-attributed-wildfire-smoke>
35. Wakefield JC. *A Toxicological Review of the Products of Combustion*. HPA; 2010. <https://assets.publishing.service.gov.uk/government>
36. Schimming E. *Die Belastung des Menschen durch Benzol und andere aromatische Kohlenwasserstoffe unter besonderer Berücksichtigung des Beitrages der Innenraumluft*. Cuvillier Verlag; 1998.
37. Reisen F, Durán S, Flannigan M, Elliott C, Rideout K. Wildfire smoke and public health risk. *Int J Wildland Fire*. 2015;24:1029.
38. Wegesser TC, Pinkerton KE, Last JA. California wildfires of 2008: coarse and fine particulate matter toxicity. *Environ Health Perspect*. 2009;117(6):893-897.
39. gasset. *Gasset DX4000*. 2023. Accessed June 12, 2023. <https://www.atecorp.com/atecorp/media/pdfs/datasheets/gasset-dx4000-datasheet.pdf?ext=.pdf>
40. Brinkschulte C. *Silvanet Wildfire Sensor*. Eberswalde; 2023. Accessed May 8, 2023. <https://www.dryad.net/wildfiresensor>

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