

Effects of prescribed fire on topsoil properties: a small-scale straw burning experiment

Tailin Li¹, Jakub Jeřábek¹, Jan Winkler², Magdalena Daria Vaverková^{3,4}, David Zumr^{1*}

¹ Department of Landscape Water Conservation, Faculty of Civil Engineering, Czech Technical University in Prague, 16629, Prague, Czech Republic.

² Department of Plant Biology, Faculty of AgriSciences, Mendel University in Brno, Zemědělská 1, 61300 Brno, Czech Republic.

³ Department of Applied and Landscape Ecology, Faculty of AgriSciences, Mendel University in Brno, Zemědělská 1, 61300 Brno, Czech Republic.

⁴ Institute of Civil Engineering, Warsaw University of Life Sciences–SGGW, ul. Nowoursynowska 159, 02-776 Warsaw, Poland.

* Corresponding author. E-mail: david.zumr@fsv.cvut.cz

Abstract: A grassland was burned to investigate how a short prescribed fire affected soil physical and hydraulic properties, soil water balance, and emergent vegetation. Three years before the experiment at Řisuty, Czech Republic, the grassland was re-established on arable soil. At the experimental site there is a weather station and sensors measuring soil temperature and moisture at three different depths. The 5 m × 5 m burned plot was compared to a nearby unburned reference location. The loamy Cambisol soil was not water-repellent. 250 m² of sun-dried grass was raked and burned at the burned plot. The fire lasted approximately 15-minute and reached 700 °C. Soil samples were taken immediately after the fire and weekly to monthly thereafter to quantify organic carbon content, soil structure stability, hydraulic conductivity, bulk density, and texture. According to the research results, it appears that temporary burning improved the hydraulic properties of the topsoil. The fire plot's infiltration capacity was increased, and soil water content was higher than the control plot throughout the year, providing suitable habitat for colonizing vegetation. The results suggest that small-scale controlled biomass burning can be risk-free to the soil ecosystem and may even temporarily improve the hydraulic properties of the upper soil layer.

Keywords: Prescribed fire; Grassland; Topsoil dynamics; Post-fire soil properties.

INTRODUCTION

As extreme weather has become more frequent recently, natural catastrophes such as floods, droughts, and wildfires strike correspondingly (Caon et al., 2014; Chen et al., 2020; Ebel, 2012, 2019, 2020). A case in point, is the summer of 2022 when a fire broke out in the Bohemian Switzerland National Park in the Czech Republic, marking it as one of the worst forest fires in the history of the Czech history. While the scientific literature and media generally focus on forest fires, agricultural field fires also have a significant economic impact over the past few years in the Czech Republic. According to the official records (Fire Rescue Service of the Czech Republic, 2020), over 600 fires occurred in the Czech Republic's agricultural areas in 2019 (almost 2000 in forest areas). Furthermore, among the recorded fires, 140 cases were caused by the self-ignition of crops in 2019 (Žalud et al., 2020). Usually, the fires on farmlands occur while harvesting in the hot and dry summer months, where the contact between harvesters and stones on the soil surface is the main trigger of fires. Such fires often damage crops, reduce yields significantly, and destroy expensive machinery. In 2019, approximately 60 major fire events caused damage exceeding 10 million Czech crowns (EUR 400,000) (Fire Rescue Service of the Czech Republic, 2020). Hence, authorities regard fires as a significant ecological and financial risk; even small-scale straw burning is illegal in the Czech Republic. Although most of the media portray fire as a disaster or a threat to ecosystems and soils, straw burning was historically used by farmers to eliminate weeds, pests, and excess biomass while also fertilizing soils (Fire Rescue Service of the Czech Republic, 2020).

The increased fire risk due to the changing climate and the potential benefits of the prescribed fires highlight the need to understand post-fire processes in soil and their effects on vegetation. The fire's positive or negative effects depend on factors such as vegetation cover, fire intensity, duration, and soil characteristics (Alcañiz et al., 2018). Many studies suggest that wildfires could significantly decrease hydraulic conductivity and saturated volumetric water content (e. g. Ebel and Moody, 2020; Moody et al., 2016) and decrease or increase bulk density (Badía and Martí, 2003; Moody et al., 2016). However, these effects were limited to the uppermost 1 cm of soil profiles (Ebel and Moody, 2020) and the soil recovered within several years (Ebel and Martin, 2017; Ebel, 2020). Ebel (2019) also showed no significant difference in the prescribed fires and wildfires' effects on soil properties.

The impact of wildfires on the soil water balance depends on the severity of the fire (Atchley et al., 2018). Due to the loss of vegetation cover and reduction of transpiration, less severe fires may increase soil moisture content. On the other hand, a higher fire severity may cause a temporal reduction of soil moisture content due to increased surface runoff (Atchley et al., 2018). The fire-induced reduction in water infiltration was attributed to the blocking of macropores by ash. However, DeBano (2000) argued that increased soil water repellence is the main factor. It was shown that the water repellent layer depth depends on the fire severity, and subsoil repellency is less time persistent than soil surface repellency (Chen et al., 2020). The temperature of the fire (and thus the strength of the soil water repellent layer) has a higher impact on decreasing infiltration than the burned vegetation (DeBano, 2000). The soil repellency also alters

infiltration within a single rainfall episode or single tension infiltration experiment (Chen et al., 2020; Imeson et al., 1992). The infiltration rate could decrease exponentially or linearly for soil with no water repellency or first increase and then decrease in time in the case of water-repellent soil (Chen et al., 2020).

Additionally, fires may contribute to a significant reduction of soil organic matter when the soil temperature exceeds 300 °C according to Stoof et al. (2010) or 500 °C according to Badía and Martí (2003). A decrease in soil organic carbon may cause spatial homogenization of soil water retention characteristics (Ebel, 2012). However, it was shown that the effect is temporary as soil organic carbon levels reach pre-fire levels after one year (Badía et al., 2014).

Observing the wildfire effect in nature is complicated since access to the burned areas is dangerous and restricted right after the fire ends. Therefore, fire experiments (Delač et al., 2020; Silva et al., 2006; Stoof et al., 2010; Stoof et al., 2015) or laboratory heating of soil samples (Stoof et al., 2010) are often used to simulate natural wildfire.

Until now, there is limited information about the consequences of fires on tilled soils and the water regime in the Czech conditions. Furthermore, there is little data on post-fire soil water dynamics of former agricultural soils in the Czech Republic, particularly the fire effects on soil water storage. Hence, we conducted a small-scale straw burning experiment in August 2021 on a small Czech farm with long-term monitoring of soil water dynamics, meteorological conditions, and vegetation cover. The key objectives of this study are the evaluation of:

1. The change of physical characteristics of topsoil after a short prescribed fire.
2. The dynamic of topsoil's hydraulic properties after a prescribed fire.
3. The impacts of prescribed fire on soil water retention and soil water content dynamics.
4. The short-term responses of vegetation to prescribed fires.

MATERIALS AND METHODS

Site description

We conducted the burning experiment on a plot at an agricultural field site Řisuty, about 30 km northwest of Prague, Czech Republic, at coordinates 50°13'2.0"N, 14°12'2.2"E (Fig. 1). The elevation of the plot is a range of 310–315 m. a.s.l. The climate is humid continental, with an annual mean temperature of 8 °C and average annual precipitation of 500 mm. The soils are developed on sedimentary rocks composed of claystone, sandstone, and arkose and are classified as Cambisols based on the World Reference Base for Soil Resources (Driessen, 2001). The topsoil consists of 18.3% clay, 33.8% silt, and 47.9% sand and is classified as loam and contains 1.2 to 1.5% organic matter. The pH of the topsoil is around 7.61. The site is on a mild slope of approximately 8%. The site is bordered by larger agricultural fields where a wheat, rape seed, mustard crop rotation takes place.

Two experimental plots, each with a size of 5 m x 5 m, were delineated. One plot was established in the centre of the mown lawn (hereinafter referred to as a burned plot or the fire scenario), and the second plot was in the intact grassland (hereinafter referred to as the reference plot/scenario). The plots were 30 m apart and had the same native grass cover and soil conditions. Each plot had six soil moisture and soil temperature sensors (SMT100, Truebner, Germany). The sensors were horizontally installed in pairs to increase the measurement volume in depths of 10 cm, 20 cm and 30 cm and were connected with a 15 m long buried cable to a datalogger (GreyBox GSM, EMS Brno, Czech Republic). Two sensors in each depth were at least 5 cm apart. After the installation, the readings of the sensors in the same depth were checked. If the measured water content differed by more than 5%, the sensors were reinstalled (similarly to a protocol suggested by Bogen et al. (2010)). The data were recorded in 1-hour time steps. The locality was also equipped with a standard meteorological station recording precipitation intensity, wind velocity and direction, air temperature, air humidity, and net solar radiation.

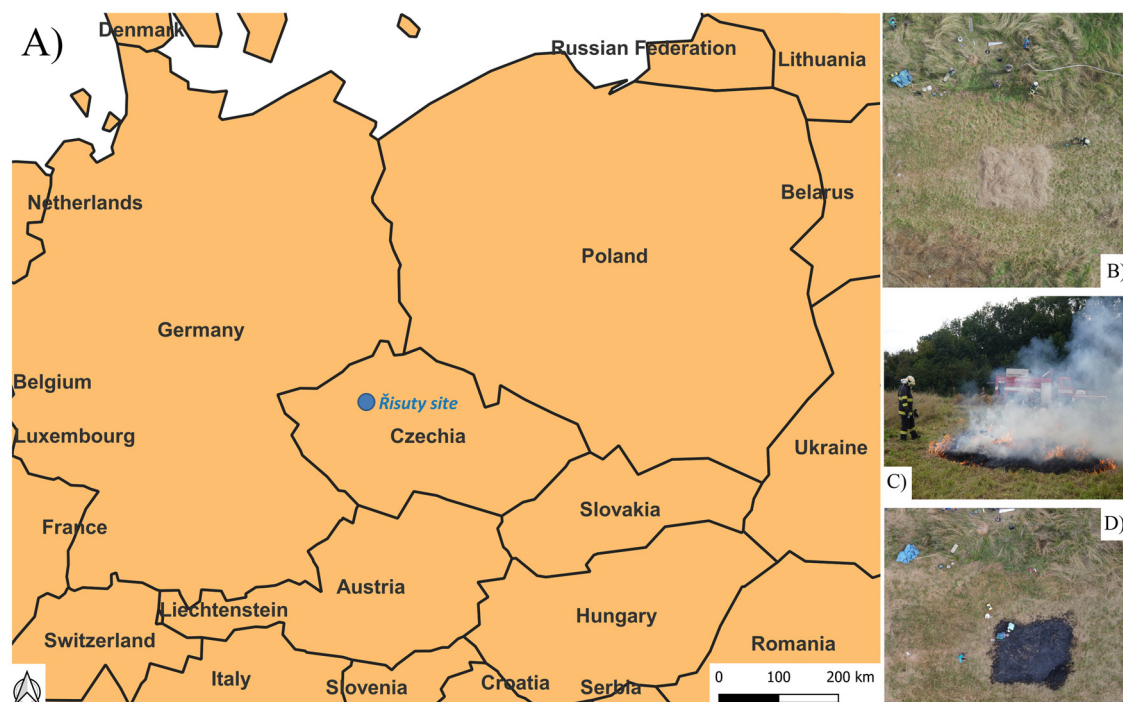


Fig. 1. (A) The location of the Řisuty site and the straw burning experiment. (B) The plot before the fire, (C) during the fire, and (D) after the fire.

Controlled burning

The experiment took place on 18th August 2021, with no substantial antecedent rainfall. The prior-experiment air temperature was 18 °C, the soil water content in the upper 20 cm was 16%, and the topsoil temperature was 17–18 °C.

One week before the burning experiment, the vegetation was cut from the area of ca. 250 m² around the burned plot. The cut vegetation was sun-dried while regularly turned over. The original dry biomass density, which was equal to the biomass density on the reference plot, was 0.47 kg m⁻². On the experiment day, we evenly distributed all the dried straw from the cut area on the fire site before the burning. Subsequently, the total amount of burned biomass was estimated to be 117 kg, corresponding to a density of 4.7 kg m⁻².

The straw was set on fire by firefighters supervising the experiment and preventing the fire from spreading from the intended plot. The fire lasted 16 minutes. After the fire, the firefighters poured water around the burned plot, but the plot itself remained intact. The fire and freshly burned surface temperature (measured by supervising firefighters) using an IR thermometer were closely monitored. When the plot was completely engulfed in flames, the temperature ranged between 599 ± 94 °C and went up to 700 °C at the centre of the burning pile. The soil surface (ash) immediately after the flames disappeared had a temperature of 97 ± 44 °C. The temperatures decrease rapidly with depth; the shallow sensors in 10 cm detected a temperature increase of only 4 °C. The same was also reported by Stoof et al. (2015), where the temperature in 2 cm of depth did not exceed 35 °C while the surface reached 800 °C at some locations. It is therefore expected that the effect of heating would be restricted to 0–2 cm of depth.

Vegetation monitoring

The evaluation of the vegetation in the experimental plot was carried out by using phytocoenological relevés. The first monitoring was conducted before the burning in the summer of 2021. After that, the same monitoring procedure at the exact location in the summer of 2022 (one year after the fire) was repeated. In total, five images were recorded. All vascular plant species on each image were identified, and their cover was estimated.

Additionally, the soil surface images from the height of ca 1 m above the ground were taken to evaluate the temporal development of the surface cover and dead biomass at the burned plot. The images were taken during each postfire sampling campaign (dates shown below). Subsequently, we further evaluated the soil cover using the SOIL COVER web tool to estimate the soil cover of fields (accessible at: <https://soilcover.josephinum.at>).

Soil sampling and laboratory analyses

All soil sampling and later analyses were carried out in two plots described above (burned plot and unburned reference plot). Data were collected before the experimental fire, immediately after the fire, and during the following several months. Altogether eight sampling campaigns were organized. The sampling dates were 18.8.2021, 19.8.2021, 25.8.2021, 10.9.2021, 1.10.2021, 9.11.2021, 21.12.2021, and 9.3.2022.

Three types of samples were collected during each campaign:

- Three to five undisturbed soil cores of 250 cm³ volume (diameter 50 mm, height 60 mm) were collected from the surface on randomly selected spots within the plots. The top edge of the sample was aligned with the soil surface to preserve the integrity of the burned soil surface. The

samples were used for measurements of saturated hydraulic conductivity, actual water content, saturated water content, and bulk density.

- Cross-sectional composite soil samples from 0 to 12 cm were collected with a thin probe on five randomly selected spots. Each cross-sectional sample was separated by 1 cm increments into different sampling containers. The soil samples were utilized for measurements of organic carbon distribution in the soil profile.
- Disturbed soil samples from the uppermost 4 cm were collected on five spots and mixed together. Further, the sampled soil was further used for soil aggregates stability and soil texture analyses.

Additionally, water drop penetration tests (WDPT) were performed on the narrow soil core sample taken up to a depth of 12 cm at several locations in the fire plot. The procedure of (Dekker et al., 2009) was adopted.

Soil organic carbon

The total organic carbon content (TOC) of the sampled soils was measured with the multi-N/C instruments 2100S and HT 1300 (Analytik Jena, Germany). Three replicates were measured for every sampled soil. The measurement procedure consisted of preparing 300 mg of dried soil, adding hydrochloric acid, further drying at 45 °C, high-temperature combustion of the sample and TOC measurement in the N/C 2100S instrument.

Aggregate stability

The aggregate stability was assessed with a wet sieving method according to a protocol suggested by Kemper and Rosenau (1986). Wet sieving apparatus for disturbed soils (08.13, Eijkelkamp, Netherlands) was used. The soil samples were air dried and sieved to an aggregates fraction of a size between 1 mm and 2 mm, and 4 g of the sample was placed on 0.25 mm sieves. Before the test, the soil was pre-wetted with a sprayer to avoid slacking. Then the samples were repeatedly submerged in 100 ml of distilled water. The wet sieving lasted 3 minutes, and the submerge-lift frequency was 34 cycles per minute.

Subsequently, the same procedure was repeated with a dispersion solution until the aggregates were completely broken down (Blakemore, 1972). The aggregate stability was calculated as a ratio between dried undersize soil masses of the dispersed solution sieving and distilled water sieving. Each collected sample had eight repetitions of the analysis.

Saturated hydraulic conductivity and tension infiltration

The saturated hydraulic conductivity (K_s) and unsaturated infiltration were measured using the 250 cm³ undisturbed soil core samples. The falling head infiltration method was used to obtain the K_s values using the Ksat[®] device (METER Group AG, Germany). Each soil sample was saturated in distilled water for 2–5 days before the measurement. Five to thirteen consecutive measurements were conducted at each soil sample.

Before the K_s measurements, the unsaturated infiltration was measured at each 250 cm³ sample using the Minidisk infiltrometer (METER Group AG, Germany). The pressure was set to –3 cm, corresponding to an equivalent pore diameter of 1 mm. Prior to the measurement, the on-site initial soil water content was preserved. Then, a thin layer of fine sand was applied to the sample to keep the infiltrometer in contact with the soil. Each measurement lasted 1 hour. We assumed that the sides of the sample ring affected the infiltration front during the measurement.

Since the conditions of semi-finite space were not met, traditional methods (e.g. Philip equation (Philip, 1957) or Zhang method (Zhang, 1997; Dohnal et al., 2010)) could not be used to evaluate the data. Therefore, only the cumulative values of unsaturated infiltration were evaluated.

Statistical analysis

Monthly soil water dynamics in the fire and reference plots were assessed using statistical analysis. First, the Shapiro-Wilk test (Shapiro and Wilk, 1965) was performed to check for normality of the data distribution. However, neither the monthly dynamics of soil moisture on the fire plot nor the reference plot followed a normal distribution. Since Levene's test (Levene, 1960) can be used for non-normally distributed data sets, we applied it to examine the difference in variation of soil water storage between fire and reference plots for each month and depth (10 cm, 20 cm, and 30 cm). All statistical analyses were performed using the Scipy Python library (Virtanen et al., 2020).

RESULTS

Vegetation

Before the burning, a total of 14 plant species were recorded. The vegetation consisted mainly of grassland species with a predominance of grasses. *Phleum pratense* was the dominant species. Subdominant species were grasses *Festuca pratensis* and *Poa pratensis*. Other species were represented sparsely: *Agrostis stolonifera*, *Alopecurus pratensis*, *Apera spica-venti*, *Bromus sterilis* and *Lolium perenne*. The dicotyledonous species, namely *Cirsium arvense*, *Lactuca serriola*, *Stellaria media*, *Thlaspi arvense*, *Trifolium pratense* and *Tripleurospermum inodorum*, covered only small areas.

In the second assessment in 2022, only four species were found. The dominant species was again *Phleum pratense*. Other

Table 1. Species spectrum of weeds in the experimental plot before and one year after the burning experiment (% cover).

Plant species	Average surface cover (%)	
	Before fire (year 2021)	After fire (year 2022)
<i>Phleum pratense</i>	62.0	66.0
<i>Festuca pratensis</i>	14.8	5.8
<i>Poa pratensis</i>	8.0	3.6
<i>Lolium perenne</i>	1.0	0.4
<i>Cirsium arvense</i>	3.6	0.4
<i>Tripleurospermum inodorum</i>	4.2	0
<i>Stellaria media</i>	0.4	0
<i>Bromus sterilis</i>	1.0	0
<i>Agrostis stolonifera</i>	5.6	0
<i>Lactuca serriola</i>	5.4	0
<i>Alopecurus pratensis</i>	0.6	0
<i>Thlaspi arvense</i>	0.2	0
<i>Trifolium pratense</i>	0.4	0
<i>Apera spica-venti</i>	0.2	0

represented grass species were *Festuca pratensis*, *Poa pratensis* and *Lolium perenne*. From the dicotyledonous species, only *Cirsium arvense* was found. The representation of the species and their coverage is given in Table 1.

As it is shown in Fig. 2, only a little vegetation emerged from the burned soil one week after the experiment. The vegetation soil cover increased in time until November 2021. The decrease in vegetation cover was observed in the second half of December 2021. The after-winter soil cover exhibited no living vegetation and high portion of dead biomass.

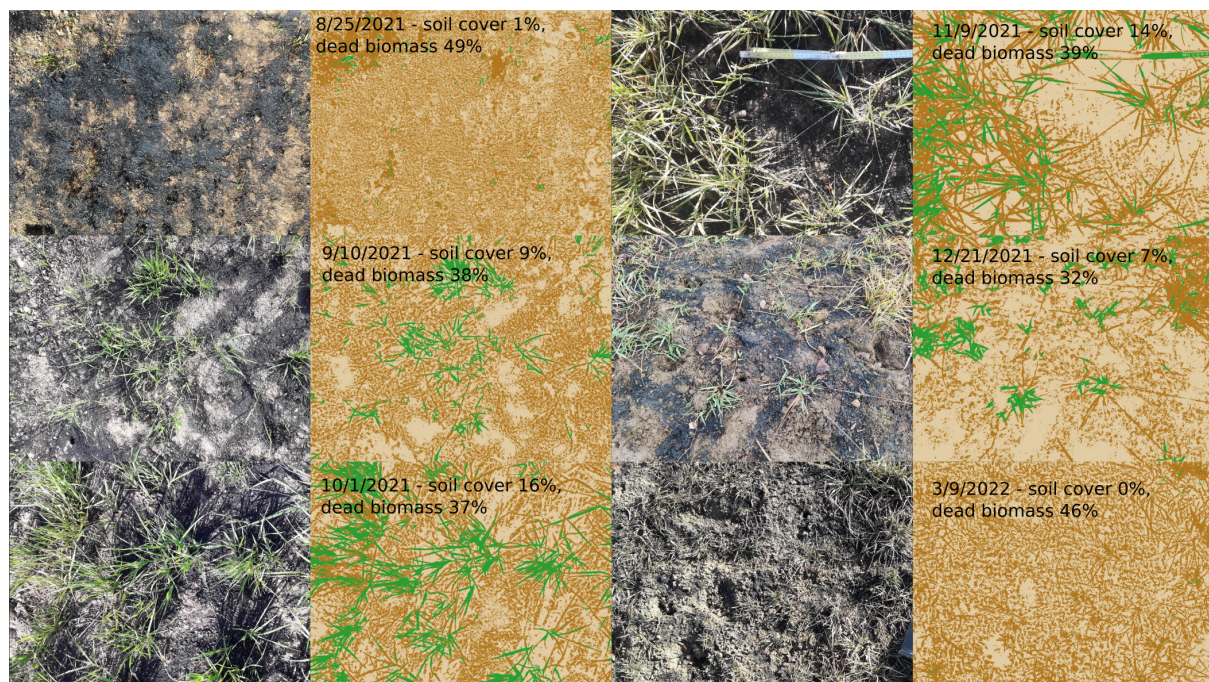


Fig. 2. Temporal changes in soil cover, generated by Soil Cover (soilcover.josephinum.at). The soil cover expresses only the living green vegetation. The dead biomass is not included in the soil cover.

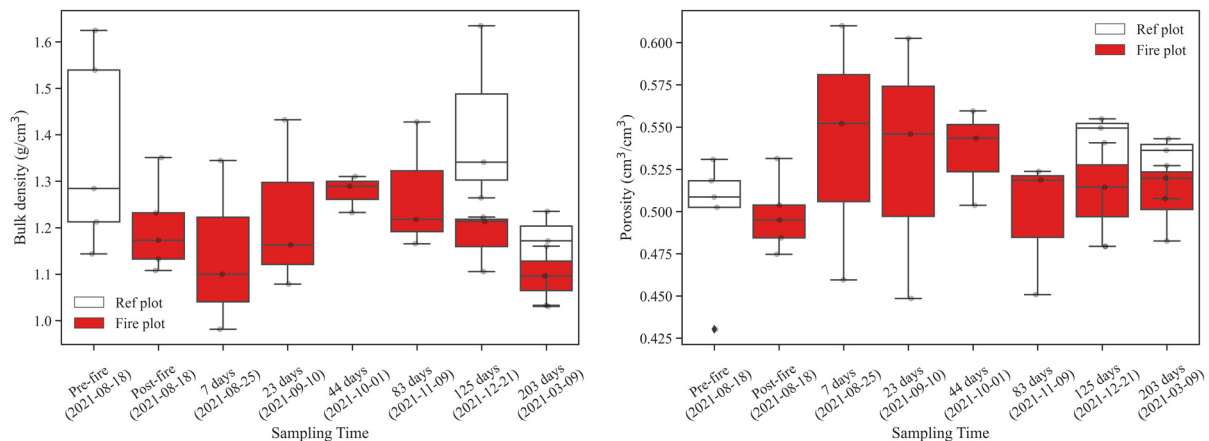


Fig. 3. Temporal changes in soil physical characteristics (left: Bulk density; right: Porosity) before and after the burning experiment. Note that the horizontal axis is not linear but represents sampling days.

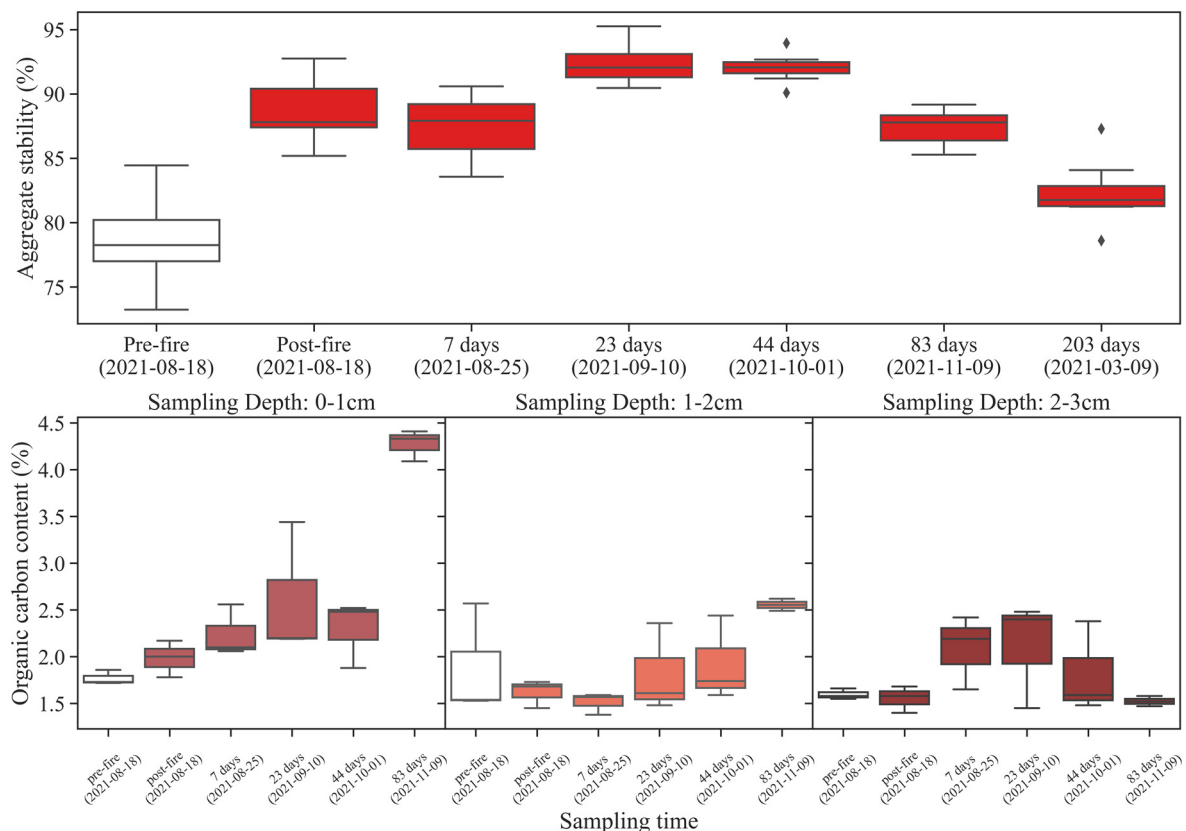


Fig. 4. Temporal variability of the soil aggregates stability (top) and total soil organic carbon in the upper 3 cm of the soil profile (bottom).

Soil physical characteristics

Generally speaking, the bulk density of the soil samples from the reference plot was higher than that of the fire plot. The pre-fire bulk density was 1.28 ± 0.21 g/cm³ with a porosity of 0.51 ± 0.04 cm³/cm³. After the burning, we observed a decline in the soil bulk density and an increase in the porosity (except for the samples with a value of 0.49 ± 0.09 cm³/cm³ just after the fire) (Fig. 3). Furthermore, there was a seasonal variation in bulk density while porosity remained relatively consistent and returned to the initial value of around 0.52 cm³/cm³ within three months.

The reference plot was sampled only 125 and 203 days after the burning. In both cases, the measured bulk density was lower

on the fire plot than on the reference plot, although the difference decreased in time. On the contrary, the porosity on the reference plot was slightly higher than on the fire plot. In addition, WDPT measurements revealed no soil water repellency at any depth or measured location in the fire plot.

Aggregate stability and soil organic carbon

The stability of the aggregates in the topsoil increased immediately after the fire by 11% and reached values around 92% (Fig. 4). Relatively high stability was measured consistently till November (83 days after the fire), and the aggregate stability returned close to the initial value in spring.

The fire substantially influenced total soil organic carbon content (TOC) only in the upper 3 cm of the soil profile (Fig. 4). In the first centimetre, the TOC gradually increased during the first month after the fire from 1.7% to 2.5%. In layers 2 and 3 cm under the surface, the TOC changes were less apparent and varied in time. The measured TOC 83 days after the fire in the top 2 cm exhibited a significant increase compared to previous and pre-fire measurements.

Soil hydraulic conductivity

The saturated hydraulic conductivity of the soil on the reference plot generally remained at the same magnitude with a value of 1–367 cm/d (except for a slight increase on the 203 day, during the spring months with a value of 869 ± 356 cm/d) (Fig. 5). The saturated hydraulic conductivity increased to 334 ± 123 cm/d right after the burning. Subsequently, the saturated hydraulic conductivity of the soil on the fire plot showed an uprising trend after the burning (except for the measured values on day 44), especially the saturated hydraulic conductivity reached the maximum value of 7140 cm/d on day 83 after the burning. Overall, soil samples from the fire plot always had a higher saturated hydraulic conductivity (in 1 order of magnitude more) than the ones from the reference plot. However, the seasonal variation in saturated hydraulic conductivity was also significant (in 1–2 orders of magnitude) from the fire plot. The pre-fire tension infiltration exhibited the lowest values prior to the burning experiment and the highest values approximately one month after the burning (Figure A.1). The tension infiltration exhibited high spatial variability. However, in most cases, the infiltration rate exponentially decreases in a constant value associated with the hydrophilic soils (Chen et al., 2020).

Soil water dynamics and soil temperature

The soil water storage in the fire and reference plots mostly corresponded with the dynamics of potential evapotranspiration (PET) (Fig. 6, Fig. 7). The high soil water storage occurred in winter when the potential evapotranspiration was low, whereas

the insufficient soil water storage occurred in the summer when potential evapotranspiration was high. The reference plot had less soil water storage than the fire plot in all months except October 2021, when the rainfall exceeded PET (Fig. 6). Furthermore, the variation in soil water storage in the reference plot was generally higher than in the fire plot (Fig. 7). However, as the year progressed, the difference in variation of soil water storage between the two plots became smaller. This was consistent with the results of the Levene test: The variation in soil water content (SWC) was significantly different between the fire and reference plots immediately after the experiment. However, as time progressed, the difference in SWC variation tended to become insignificant in the summer months of 2022 (June, July, and August), especially in the upper 10 cm (Table A.1). The top 10 cm soil temperature varied similarly in both plots; however, the fire plot had a higher soil temperature than the reference plot during most months except in December 2021 and January 2022 (Fig. 6).

The monthly average storage in both plots increased by 30 mm when the PET rate fell at the end of 2021 (except for a slight reduction in Oct 2021). The soil water storage then increased by 10 mm until March 2022, with a slight increase (1 mm/d) in the PET rate. After the winter, soil water storage decreased as the PET rate increased during the late spring of 2022. The lowest soil water storage occurred in both plots in June 2022, when the PET rate reached its maximum of 4.4 mm/d (Fig. 7). At the same time, the standard deviation in soil water storage reached high levels during the summer months, when the PET rates also varied widely (Fig. 7).

The soil water content dynamics were flashier at the reference plot in the shallow part of the soil profile as shown in Fig. 8. This behaviour appeared to be the most throughout 2021 and the spring of 2022. Also, the decrease in the SWC was more pronounced in the reference plot in March 2022. During the vegetation season 2022, the difference in the 10 cm SWC dynamics gradually decreased. The rainfall events increased SWC at a depth of 30 cm at the reference plot slightly but significantly, whereas the increase/decrease in SWC at the fire plot happened more gradually, and no reaction to a single rainfall event could be identified.

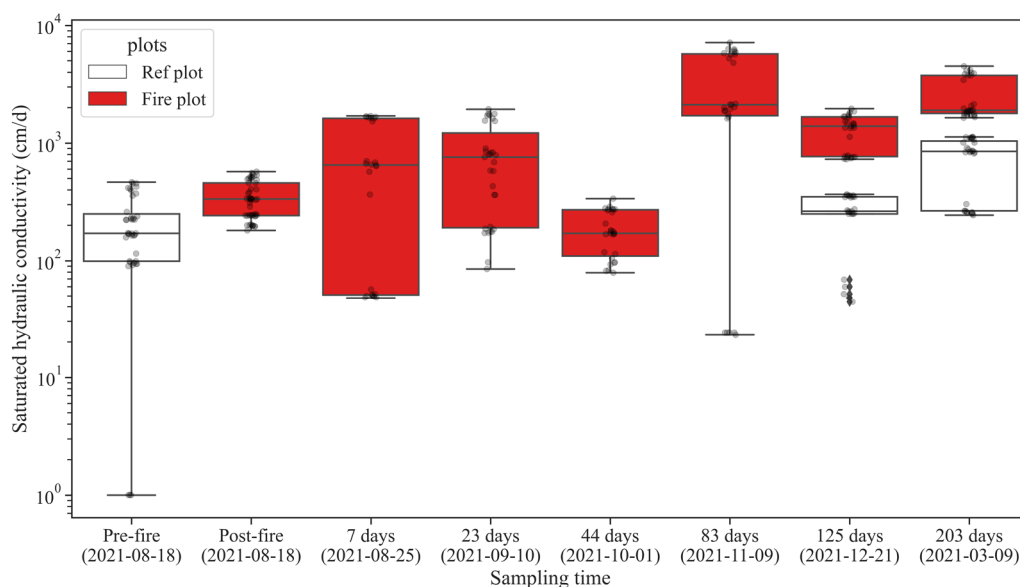


Fig. 5. Temporal changes in the soil saturated hydraulic conductivity before and after the burning experiment.

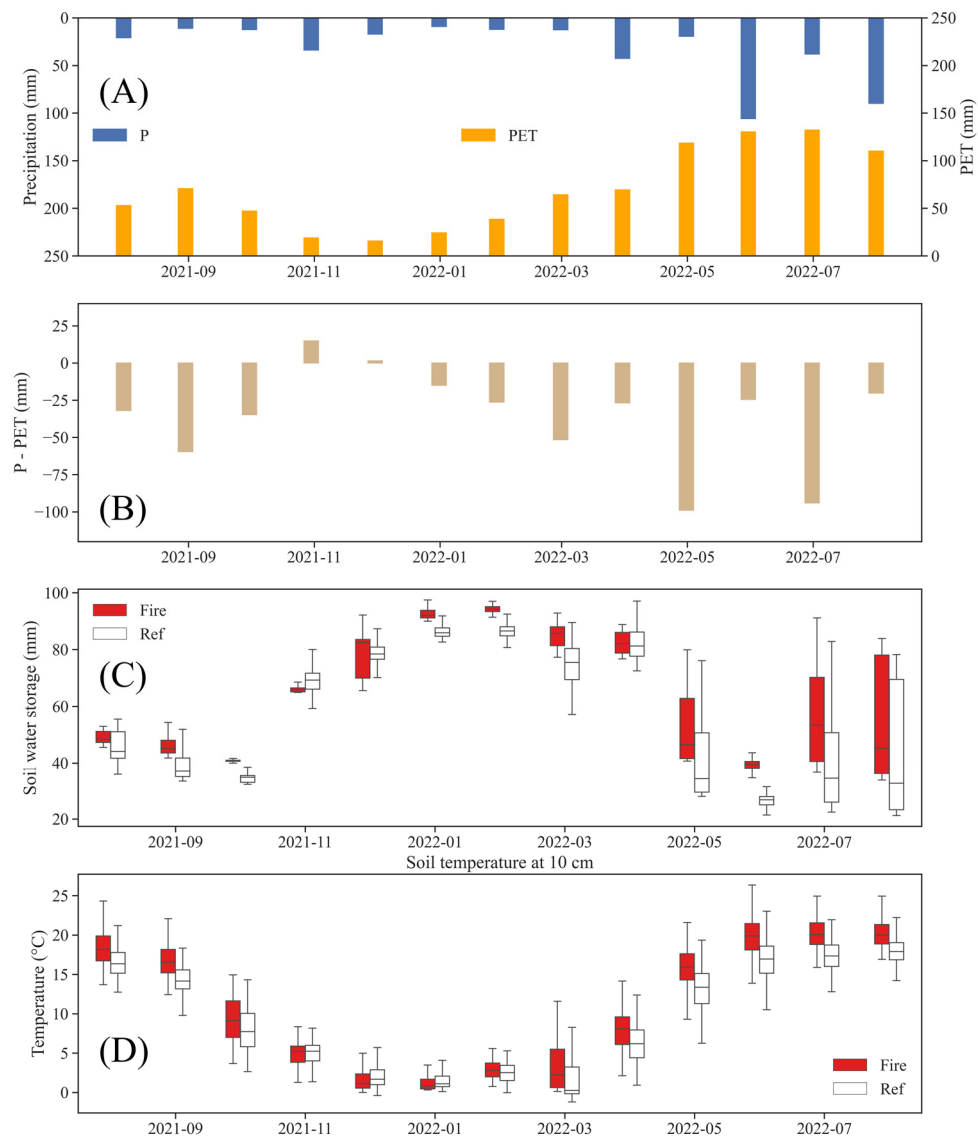


Fig. 6. Monthly dynamics of (A) precipitation and potential evapotranspiration, (B) the difference between precipitation and potential evapotranspiration, (C) soil water storage, and (D) soil temperature at 10 cm.

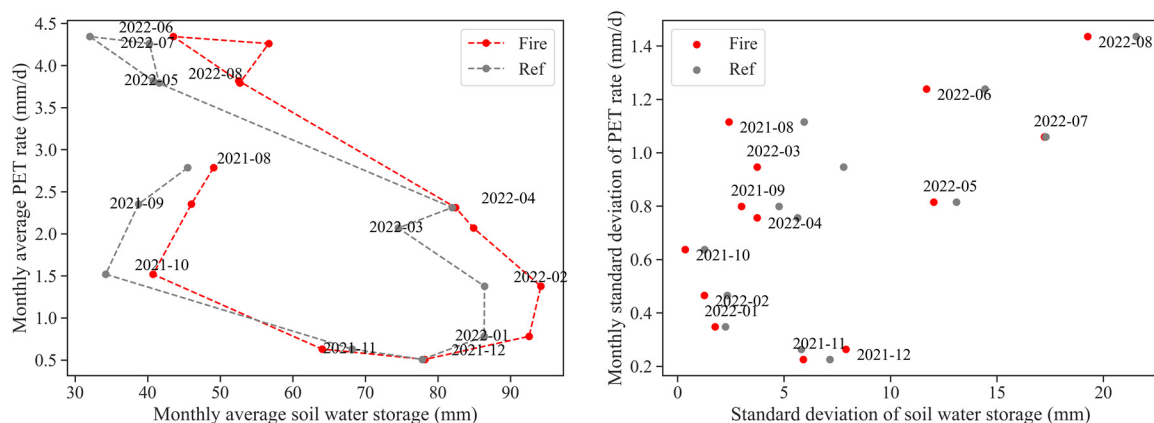


Fig. 7. The monthly averages (left) and monthly standard deviations (right) of soil water storage and potential evapotranspiration. The error bars on the left fig stand for the soil water storage standard deviation.

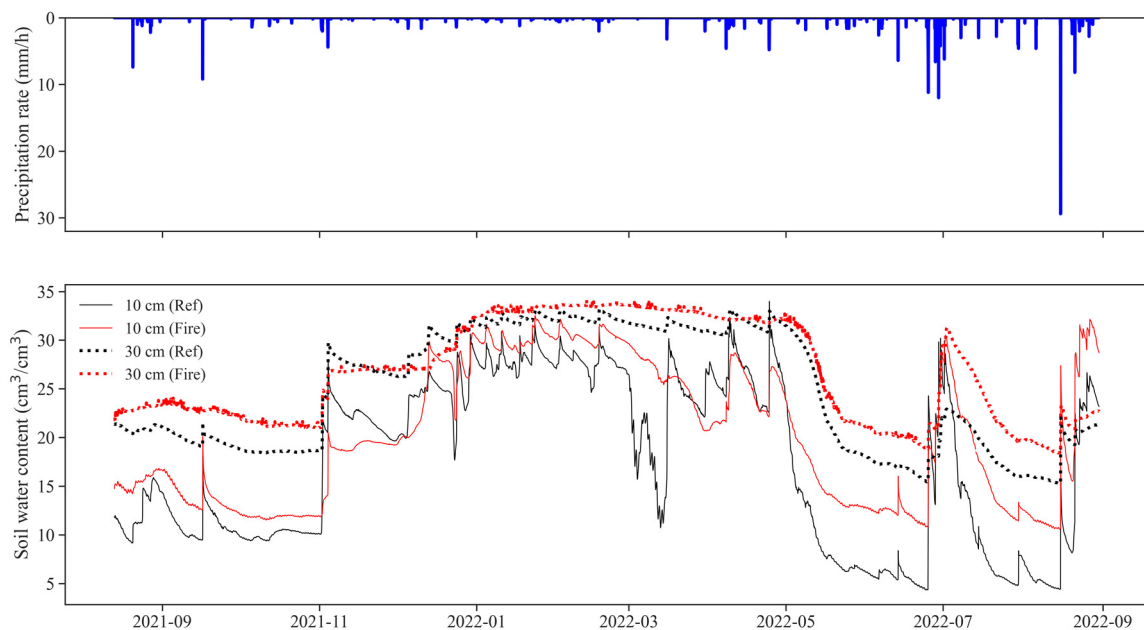


Fig. 8. Precipitation intensity (top) and soil water content dynamics (bottom) at two depths.

DISCUSSION

The vegetation consisted of a species-poor grassland community. The results show that the number of species one year after the fire is significantly lower. Annual plant species were no longer found, and perennial grasses completely dominated. Wind-dispersed species, which have the potential to occupy new habitats rapidly, were not present on the stand. Their absence may be due to high competition from surviving grass species. Our results suggest that the effect of fire on vegetation is long-term. Fire in species-poor grasslands suppresses the occurrence of dicotyledonous species and annual grasses. On the contrary, it enhances the competition of dominant perennial grass species. Besides, the phytotoxicity of the post-fire soil can be responsible for changes in seed germination and root growth inhibition (Barroso and Vaverková, 2020).

After burning, bulk density has been shown to decrease (Brye, 2006; Ebel and Moody, 2020) or increase (Badia and Martí, 2003; Bird et al., 2000; Boyer and Miller, 1994; Godwin et al., 2017). An increase in bulk density could generally be related to the displacement of burned organic matter by higher density mineral soil particles, as well as ash and char infiltration of micropore space (Godwin et al., 2017). On the contrary, a decrease in bulk density could be caused by burning organic matter without displacement or increased subterranean organic matter inputs such as lower-density root biomass and charred soil organic matter (Brye, 2006). In this study, both bulk density and porosity decreased after burning, implying that ash and char infiltration may occur and occupy the micropore space, further decreasing the porosity. Furthermore, the burned straw had a lower density than the soil and covered the ground, likewise a layer of mulching, lowering the bulk density of the uppermost soil layer.

Badia and Martí (2003) showed a decrease in aggregate stability with decreasing organic carbon. On the contrary, Giovannini and Lucchesi (1997) observed an increase in aggregate stability after heating, explaining that the breakdown of organic matter did not affect the cementation of the clay particles at high temperatures. Also, low- to moderate-severity fires can improve

aggregate stability by forming hydrophobic films on aggregate surfaces (Mataix-Solera and Doerr, 2004). The burning above the soil in this study clearly did not cause substantial changes in the organic matter since the organic carbon increased with time. Furthermore, no hydrophobicity in soil was discovered in the study. During the sampling campaigns, however, signs of cementation were observed. As a result, in this study, an increase in aggregate stability may be associated with an increase in organic content and cementation.

Many studies (Badia et al., 2014; Bennett et al., 2014; Bird et al., 2000; Girona-García et al., 2018; Muqaddas et al., 2015; Muqaddas et al., 2016) suggested that the total soil organic carbon (TOC) would decrease after the burning due to thermal decomposition and combustion of the soils organic matter. However, in our study, the 1 cm soil exhibited an increase in TOC immediately after the burning. Similar behaviours (Johnson and Curtis, 2001; Scharenbroch et al., 2012; Taylor and Midgley, 2018) were found after short, low-intensity prescribed fires. The increases in C shortly after burning could be due to the fact that the temperatures in burned soils were never high enough to cause oxidation of soil organic matter (Scharenbroch et al., 2012); incorporation of biochemically protected unburnt residue into mineral soil; or transformation of fresh residues to more recalcitrant forms (Johnson and Curtis, 2001). Furthermore, in this study, we use extra sun-dried grass as a fuel to ignite the fire, which can be considered as an additional source of carbon input.

The saturated hydraulic conductivity K_s was shown to decrease in many literature sources, as shown in a meta-analysis by Ebel (2019), which contradicts this study's findings. Only a few studies, such as Rab (1996), show increased K_s after a fire. In Wieting et al. (2017), the K_s decreased for low-temperature fires and increased for high-temperature fires. A decrease in saturated hydraulic conductivity is usually associated with increased soil water repellency (Ebel, 2019). Post-fire soil water repellency is usually related to soil temperature, with higher temperatures corresponding to higher repellency (Cawson et al., 2016; DeBano, 2000). Because of the low-intensity fire with a relatively short burning time, the installed thermometers only recorded a 4 °C

temperature rise at 10 cm below the surface, and the soils used in the presented study exhibited no soil water repellency. The maximum Ks value was observed on day 83 with a high spatial variation (Fig. 3). Meanwhile, the soil cover and dead biomass also reached high levels (Fig 2), implying that the Ks variation and increase could be linked to vegetation growth. Therefore, the variation in Ks could be associated with the variation in biological activity (e.g. roots growth; earthworms). Besides, the recovery of the Ks can be observed in an average of 5 years since the fire (Ebel and Martin, 2017). As a result, trends in Ks may be observed in a timespan exceeding the current study. The trend in Ks was reproduced with the tension infiltration suggesting that the increase in Ks over time cannot be attributed only to the large cracks or macropores formation but also to structural changes in pores with an equivalent pore diameter of 1 mm.

The leading causes of changes in root zone soil water storage are precipitation, direct evaporation from the soil surface, and plant transpiration (Hillel, 2004). Swift Jr. et al. (1993) stated that fire could enhance soil water storage by reducing evapotranspiration when vegetation is removed by burning. In this study, the burned vegetation resulted in lower transpiration rates, especially in late spring 2022. As a result, the soil water storage was generally higher at the fire plot due to a reduction in transpiration, which corresponds to severe burning (Atchley et al., 2018). Besides, Scharenbroch et al., (2012) indicated that increases in soil organic matter with fire might also result in an increase in soil moisture.

Silva et al. (2006) found a more substantial decrease in SWC in the reference plot during the drying season than in the burned plot owing to the water extraction by vegetation, which is consistent with the findings of this study. Besides, Silva et al. (2006) claimed that differences between different depths were more important than plot differences, which also agrees with this study (Table A.1). The root residues at the fire plot did not form macropores, or the macropores were inaccessible to water, as evidenced by the less flashy nature of SWC during rainfall events, even in deeper soil layers. Furthermore, Silva et al. (2006) noted that a high SWC could lead to rapid plant recovery during the post-fire period, which corresponds with this study (Fig 2). Besides, the scale of the study area also matters. At the catchment scale, which includes both burned and unburned areas, the abundance of soil water in burned areas (due to reduced transpiration) could supply vegetation at adjacent unburned and increase evapotranspiration in unburned areas (Maina and Siirila-Woodburn, 2020). Because the current study is on a small field scale, the climate and groundwater conditions for both the reference and fire plots were assumed to be the same. Thus, the complex interaction between soil water and groundwater is beyond the scope of this study.

CONCLUSION

In this study, we investigated the effects of fire by conducting a small-scale straw-burning experiment. The hypothesis was that the control and fire plots' soil conditions were comparable before the burning. Even though fire and hot ash reached temperatures of up to 700 °C immediately after the burning, the installed thermometers recorded only a 4 °C temperature rise at 10 cm below the surface. This slight temperature increase suggests that rapid burning has a limited effect on soil organisms. However, there was a slight decrease in bulk density and porosity right after the burning, revealing that ash and char infiltration may occur and occupy the micropore space, further reducing porosity. Furthermore, the burned straw acted as a mulching layer, improving the hydraulic properties of the topsoil. Also, the infiltration capacity

on the fire plot has increased, and soil water content was higher than on the control plot throughout the year, which provided suitable habitat for colonizing vegetation. One year after the fire, the number of plant species is significantly lower. Annual plants were no longer found, and perennial grasses took over completely. As a result, we contend that small-scale controlled burning of biomass, such as dried grass, poses no significant risk to the soil ecosystem. It may even improve the hydraulic properties of the upper soil layer, though the effect is probably temporary. However, because many chemical/toxicological effects have not yet been investigated in this study, we are not encouraging small straw burning. Future research should concentrate more on the chemical/toxicologic effects on the soil and long-term monitoring of soil water storage changes.

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APPENDIX

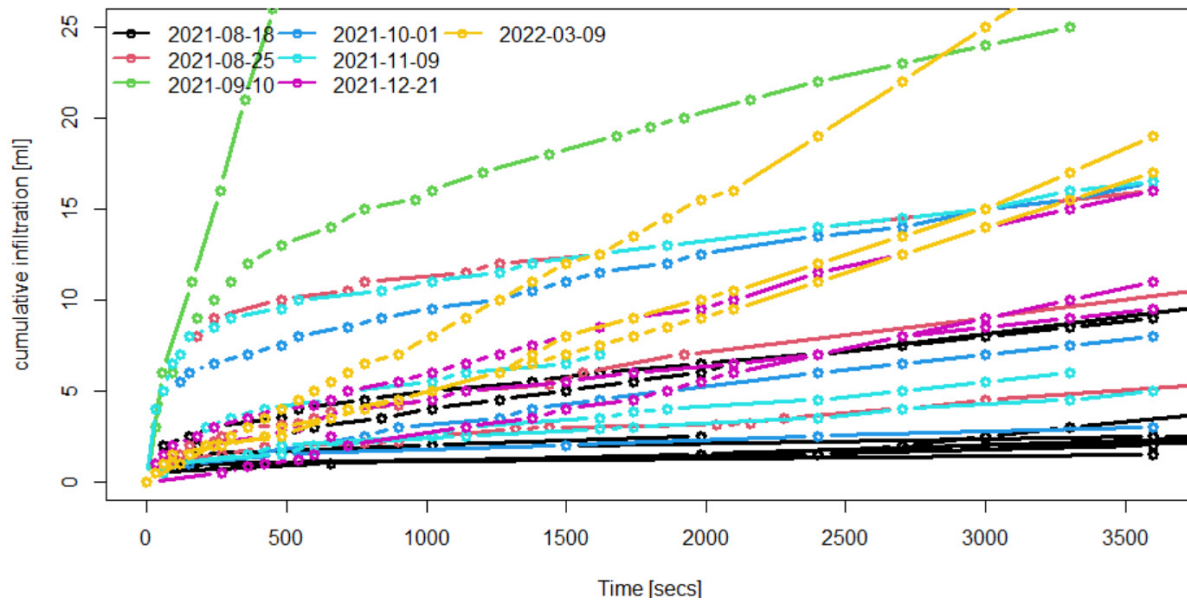


Fig. A.1. Cumulative tension infiltration measured under -3 cm pressure at multiple locations and times after the fire experiment.

Table A.1. Monthly mean and standard deviation of soil water storage and soil water content in both plots (in "swc_xx", xx stands for the depth (cm)). The different letters indicate that the variance between two datasets differed significantly, and the same letter represents that there was no significant variance between two datasets.

Month	Plot	SWS mean	SWS std	swc_10 mean	swc_10 std	swc_20 mean	swc_20 std	swc_30 mean	swc_30 std
Aug-21	Fire	49.12a	2.41	15.50a	0.76	15.98a	0.52	22.95a	0.32
	Ref	45.54b	5.95	12.33b	2.12	16.57b	2.75	20.93a	0.28
Sep-21	Fire	46.03a	3.00	13.89a	1.34	15.08a	1.01	22.90a	0.42
	Ref	38.76b	4.77	11.23b	1.44	12.01b	2.42	19.81b	0.60
Oct-21	Fire	40.74a	0.36	11.88a	0.12	13.17a	0.12	21.36a	0.28
	Ref	34.22b	1.27	10.02b	0.37	9.91b	0.79	18.56b	0.08
Nov-21	Fire	64.05a	5.90	18.53a	1.98	21.51a	2.45	26.52a	1.26
	Ref	68.17b	7.15	21.52b	2.60	22.47a	2.43	26.82b	1.96
Dec-21	Fire	78.21a	7.91	25.18a	3.66	26.54a	2.89	28.60a	1.73
	Ref	77.86b	5.81	24.40b	2.64	26.45b	1.21	29.63a	1.74
Jan-22	Fire	92.57a	1.76	30.10a	0.89	31.95a	0.51	33.05a	0.30
	Ref	86.37b	2.25	28.01b	1.05	28.30b	0.55	32.11b	0.41
Feb-22	Fire	94.19a	1.25	30.43a	0.67	33.05a	0.21	33.57a	0.10
	Ref	86.43b	2.33	27.86b	1.09	28.50b	0.57	32.31b	0.38
Mar-22	Fire	84.91a	3.73	25.84a	2.44	31.69a	1.09	33.14a	0.25
	Ref	74.54b	7.80	21.61b	4.78	26.45a	0.99	31.36b	0.33
Apr-22	Fire	82.43a	3.74	24.60a	2.47	28.49a	0.42	32.14a	0.17
	Ref	81.98b	5.64	26.54b	2.39	26.37b	1.83	31.59b	0.75
May-22	Fire	52.54a	12.04	15.85a	3.16	18.57a	4.69	26.00a	4.12
	Ref	40.75a	13.10	10.22b	4.48	13.56b	4.07	23.74b	4.93
Jun-22	Fire	43.54a	11.69	14.00a	4.05	14.88a	3.70	20.63a	1.74
	Ref	32.04b	14.44	8.69b	6.56	10.38a	4.33	17.27a	1.14