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Prescribed burning as a potential regeneration technique for reed stands – a pilot study in the reed belt of Lake Neusiedl, Austria

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Abstract

Nature conservation calls for the management of reed in large stands to support the rejuvenation of reed. Traditional reed management tools at Lake Neusiedl are becoming decreasingly suitable due to insufficient freezing in winter. Therefore, prescribed burning of old *Phragmites australis* stands is currently being considered as a regeneration measure to promote reed regrowth and maintain invaluable habitats for specialized species in the reed belt. In January 2024 a pilot study was carried out near the municipality of Jois to gain insights into suitability and consequences of controlled burning of old reed mats in the reed belt. Applied methods include pre- and post-fire biomass and carbon content analyses from vegetation, litter and soil, fire behavior and intensity monitoring, moisture content measurements during and after the fire, and area-wide UAV-LiDAR mapping. Mean fire temperature was approx. 700°C and peaked at 1034°C. 15.57 ha of the 32 ha study area were affected by the fire, and a total of 57.84 tons of carbon were released (3.72 t C/ha). On burnt areas standing vegetation was removed and litter thickness significantly reduced by approx. 30%, while no biomass loss from soil was detected. Fuel moisture content is negatively correlated to distance from the water table and has mitigating effects on fire spread if above 30%, resulting in unaffected deeper layers and numerous unburnt refugia patches within the fire perimeter. Our results indicate that prescribed fire can be a suitable management tool at Lake Neusiedl for the purpose of reed rejuvenation and wetland habitat regeneration.

Kurzfassung

Verjüngungsmaßnahmen sind notwendig, um unter Naturschutz stehende Schilflebensräume erhalten zu können. Die traditionelle Bewirtschaftung als Schilfmanagement eignet sich hierfür aufgrund der zunehmend milden Winter immer schlechter. Da Jungschilfflächen im Schilfgürtel des Neusiedler Sees einen wertvollen Lebensraum für auf Jungschilf spezialisierte Tierarten im Schilfgürtel darstellen, wird mit dem kontrollierten Abbrennen von *Phragmites australis* aktuell eine alternative in Betracht gezogen, um überalterte Bestände zu reduzieren und den Wiederaufwuchs von jungem Schilf zu fördern. Im Jänner 2024 wurde nahe der Gemeinde Jois im Burgenland eine Pilotstudie zur Untersuchung der Auswirkungen des kontrollierten Abbrennens von Altschilfmatten und der ökologischen Eignung durchgeführt. Diese Arbeit analysiert Biomasse und Kohlenstoffgehalt von Vegetation-, Streu- und Bodenschicht sowohl vor als auch nach dem Brand. Das Brandverhalten und die Brandintensität sowie der Feuchtigkeitsgehalt während und nach dem Brand wurden beobachtet. Die Ergebnisse werden von Daten gestützt, die durch UAV-LiDAR-Scans gewonnen wurden. Die mittlere Brandtemperatur betrug ca. 700°C und erreichte einen Höchstwert von 1034°C. Auf der ausgewiesenen Brandfläche von 32 ha waren 15.57 ha betroffen, und es wurden insgesamt 57.84 Tonnen Kohlenstoff freigesetzt (3.72 t C/ha). Die stehende Vegetation wurde durch das Feuer gänzlich entfernt, die Mächtigkeit der Streuschicht bzw. Knickschilfmatte hat sich um ca. 30 % reduziert, was den Wiederaufwuchs von *Phragmites australis* erleichtert, während kein Biomasseverlust aus darunterliegenden Schichten festgestellt wurde. Es liegt eine negative Korrelation zwischen dem Feuchtegehalt des Brandmaterials und der vertikalen Distanz vom Wasserspiegel vor. Feuchtigkeitswerte von > 30% wirken Brandmindernd, führen zu unverbrannten Flächen innerhalb der Brandfläche (Brandrefugien) und begünstigen die Unversehrtheit der tiefergelegenen Bodenschicht. Unsere Ergebnisse deuten darauf hin, dass Brandmanagement im Schilfgürtel des Neusiedler Sees ein geeignetes Managementinstrument für die Verjüngung von Schilfflächen und für die Regeneration von Feuchtgebietslebensräumen sein kann.

Introduction

On January 13th 2024, a fire drill was held involving approx. 400 representatives of the emergency services and authorities, including around 300 firefighters (FF Jois 2024) from the municipalities of Jois, Kaisersteinbruch, Weiden am See and Winden am See (Land Burgenland 2024). All access roads were closed to the public from 7 am to 5 pm (LSZ Burgenland 2024). This endeavor took place in coordination between the province of Burgenland and the Federal Ministry for Climate Protection and Environment. "Abteilung 4 - Agrarwesen, Natur- und Klimaschutz - Hauptreferat Agrar- und Umweltrecht" worked on the granting of the exemptional authorization under nature conservation law, "Abteilung 4 - Agrarwesen, Natur- und Klimaschutz - Hauptreferat Naturschutz, Landschaftspflege und Agrarwesen" authorized the project with the Federal Government of Burgenland, landowners of the Jois agricultural community authorized the fire to be carried out on their land. The exercises carried out by the participating emergency services included the creation of firebreaks, the deployment of the air service in cooperation with the Ministry of the Interior, crew transport and landing with boats, off-road vehicles, etc., as well as drone-based measurements of pollutants and temperatures. In addition to the training of fire service personnel, the main publicly communicated aim of the pilot project was to achieve an amendment to the Federal Air Pollution Control Act in the future, so that controlled burning can be used as a measure against the over-ageing of the reed belt (Land Burgenland 2024).

The environmental-ecological monitoring was coordinated by the Biological Station Illmitz in cooperation with a large number of research institutions. The team included Boku University and the University of Vienna (both sampling and analysis of biomass and carbon), TU Vienna (remote sensing and creation of a biomass model), Geosphere Austria (dispersion calculation and emission modelling of pollutants), DWS Hydro-Ökologie (effects on water ecology), the herpetological society (effects on amphibians), BirdLife (bird monitoring) and WWF (Land Burgenland 2024). The content of this master's thesis was developed within the scope of this scientific monitoring.

The management of an area as large as the reed belt on Lake Neusiedl with potential effects on the entire lake area is understandably also a political issue and is in the public interest. A press conference was held prior to the controlled fire. While Climate Protection and Environment Minister Leonore Gewessler spoke of the last possible resort, representatives of the

Province of Burgenland favored the prospect of an amendment to the Federal Air Pollution Control Act. WWF and BirdLife also recommend burning old reeds for ecological reasons (Nemeth et al. 2022). Numerous media articles and coverage were published prior to and after the fire (Gluschitsch 2024, Kurier 2024, ORF Burgenland 2024). Thomas Zechmeister, head of the Biological Station Illmitz, mentioned that more than half of the reeds in the burn area were older than 20 years. Such areas can no longer serve as a habitat and allow a lot of water to evaporate from the lake. The large-scale burning of old reeds, on the other hand, pollutes the air, kills animals and releases CO2. Environmental ecological monitoring was carried out in order to make a scientifically supported assessment in this regard and for the purpose of a possible change in the law regarding the management of the extensive wetland site.

Globally, wetlands store a disproportionate amount of the earth's total soil carbon (Nahlik et al. 2016), with most of this carbon (Hugelius et al. 2020) being stored in peatlands, while only covering an estimated 3% of the global land area (Xu et al. 2018). Riparian wetlands, which are often dominated by reed stands and have in many instances formed around lakes or rivers, are much less examined but may also store considerable amounts of carbon (Sutfin et al. 2016). Reed management using fire, as a way of biomass reduction, represents a potential conflict between the interests of climate protection and those of nature conservation: Carbon dioxide (CO_2) and other greenhouse gases (Urbanski 2014) which contribute to climate change are being released while the fire can play a decisive role regarding biodiversity (Fuhlendorf et al. 2006) and potentially having adverse effects on ecosystem functioning and habitats through different responses (Clarke et al. 2012, Walesiak et al. 2022).

The reed belt of Lake Neusiedl in eastern Austria is dominated by *Phragmites australis*. It represents the second largest coherent reed area in Europe after the Danube delta and is reported to have increased in size in the last two centuries (Hietz et al. 1992, Buchsteiner et al. 2023). *Phragmites australis* is considered to be a very tolerant and robust grass-like macrophyte (Den Hartog et al. 1989). As a reed bed grows older the layer of broken reed stems above the original ground or water surface becomes thicker, ultimately preventing reed shoots from penetrating through this layer (Csaplovics 2019), and subsequently leading to a thinning of the standing vegetation and causing unfavorable conditions for certain species (Nemeth and Dvorak 2022) by negatively impacting visibility protection, wind protection, food, and nesting material.

The reed belt is up to 5 kilometres wide in places and represents an important and unique habitat. The importance of the landscapes associated with the lake is emphasised by the numerous protection statuses such as UNESCO World Heritage, Ramsar Convention, Natura 2000, National Park etc. Nemeth and Dvorak (2022) came to the conclusion during their bird counts at 111 points, that the already significantly overaged reed beds (more than 65% older than 10 years) in the peripheral area of the 320km² Lake Neusiedl (**Figure 1**) have a clear negative impact on the populations of certain small reed birds and thus pose a threat to biodiversity.

While certain small birds prefer areas with old reed (e.g. *Acrocephalus melanopogon*), some species of high conservation value to the national park, such as *Acrocephalus arundinaceus* and *Emberiza schoeniclus*, require young reed beds for their survival (Nemeth and Dvorak 2022). Valuable young reed habitats, however, are diminishing and the survival of specialized bird species is possibly jeopardized.

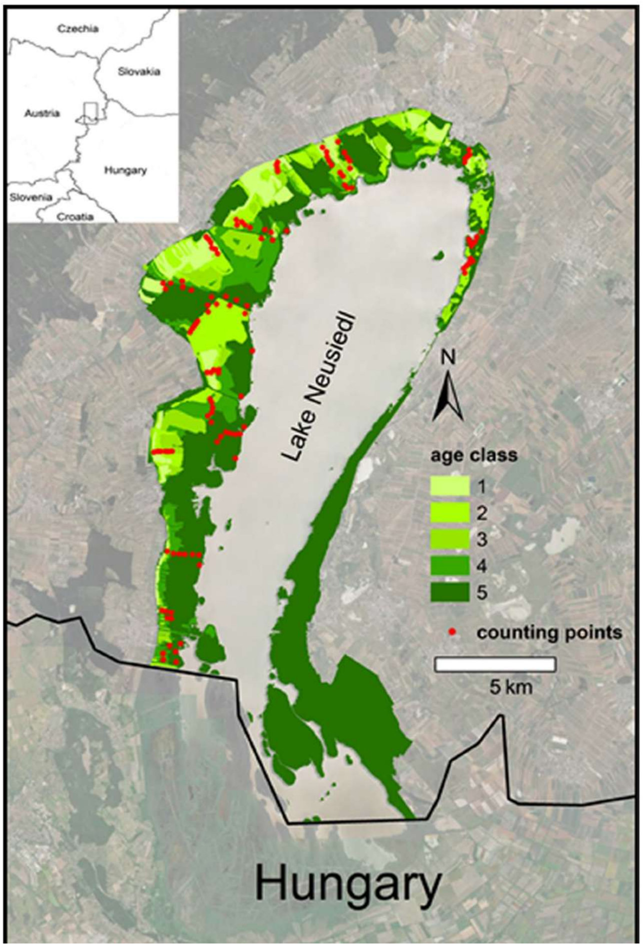

Figure 1*: Age of reed areas in the reed belt visualized in 5 classes: 1 = max. 1 year old, 2 = 2-4 years old, 3 = 5-9 years old, 4 = 10-14 years old, 5 = older than 14 years. (Nemeth & Dvorak 2022)*

Old reed belt areas can accumulate litter mats of up to 1 m when unmanaged (Nemeth and Dvorak 2022), which result in interception of precipitation before water can reach the water body (Muzylo et al. 2009). Reedbeds and especially old stands can facilitate sedimentation of particles brought in from land or the lake water itself, which are caught in the reed stands (Karstens et al. 2016), and can therefore lead to the decline of open water areas on lakes such as Lake Neusiedl. Increased dominance of *Phragmites australis* communities provide ecological benefits due to their growth as floating islands on top of open water areas, subsequently creating new habitat areas for birds, insects, amphibians, and reptiles. These dynamics are of significance due to the often stressed hydrological situation of Lake Neusiedl, as climate change leads to lower mean water levels and less frequent hydrological recovery due to increased evapotranspiration rates from the ecosystem. In addition to its important function as a local recreation area for the public, a large number of stakeholders from the tourism industry, both in Hungary and in Austria, have an evident interest in stable water levels at Lake Neusiedl.

Until 1965, around 50% of the reed belt was used for agricultural purposes by mowing and subsequent processing of *Phragmites australis* (Krail et al. 2013). In addition, old reed stock was commonly removed by controlled burning to enable this agricultural use – a measure which has been prohibited since 1993. Mowing as a reed management method cannot be maintained due to rising temperatures and subsequently insufficient freezing conditions caused by climate change and due to economic reasons. Lake Neusiedl has been subject to decreasing water levels in previous years (Hackl and Ledolter 2023) and management by mowing is becoming more difficult since this measure is only feasible if soil, ground water, or surface water are frozen and extensive damage to the rhizomes can be prevented (Armstrong et al. 1996). Thus, the burning of old reed beds is being considered as a reed regeneration measure in the wetland (Nemeth et al. 2014).

Natural fires in wetlands can promote the dominance of *Phragmites australis* over other, less well adapted species in the area (Norris et al. 2002, Ward 1968). Fire management has had various results in the past and can be beneficial to reed regrowth (Ailes et al. 1992, Link et al. 2024, Thompson and Shay 1985). Reed-dominated landscapes contain high fuel loads and recover rapidly with dense canopy even after an intense fire event (Thompson and Shay 1985). Periodic regeneration measures are desirable for old reed beds, as they can contribute to the preservation of habitats for small reed bird populations and prevent reed die-back mechanisms (Nemeth and Dvorak 2022).

From a nature conservation perspective, it is beneficial to leave the rooting horizon and rhizomes unaffected from fire in order to promote swift *Phragmites australis* regrowth. This may also be accompanied with little to no carbon fluxes taking place from the underlying layers into the atmosphere, which is desirable from a climate protection perspective when employing fire as a management tool (Alcañiz et al. 2018). Carbon dioxide from vegetation fires has the potential to be fully compensated by regrowth (Dixon et al. 2019), especially if rhizomes remain intact. The amount of biomass lost due to the fire can be used for comparison with the aboveground biomass production of 700 to 1700 g/m² typical for *Phragmites australis* in temperate climates (Papchenkov and Čížková 2024).

Prescribed burning is a worldwide accepted and applied technique to meet different land management objectives, including the reduction of wildfire hazard, increasing biodiversity, and managing of vegetation for wildlife and human interests (e.g. Fernández-Guisuraga and Fernandes 2024). Greater fuel loads generally lead to higher fire intensities and hotter burns and therefore more fuel consumption and higher temperatures belowground (Kreye et al. 2013; Zupo et al. 2022). Several studies have shown that prescribed fires under the right weather conditions do not reduce soil C content but may even increase it (e.g. Godwin et al. 2017; Mayor et al. 2016). Prescribed burns in forested areas seem to not negatively influence soil fungal communities (Vázquez-Veloso et al. 2022). In other ecosystems, fire management also has more positive effects than naturally occurring fires (Cheng et al. 2023). Recent studies in longleaf pine savanna ecosystems have shown that prescribed fires have significantly greater proportions of unburnt refugia patches within the fire perimeter than wildfires (Donovan et al. 2024). Unburnt refugia patches being retained throughout the burnt area are also considered advantageous because different ages of vegetation coexisting in the same confined space may result in enhanced biodiversity and leftover unburnt patches of old reed stock can help animal species survive during the fire event as well as regenerate afterwards. Leftover old reed vegetation and standing dead areas can offer small mammals (Puig-Gironès et al. 2018, Shaw et al. 2021), reptiles (Emery et al. 2024) and birds (Reynolds et al. 2022) both potential protection in the landscape during the fire event and a habitat for regeneration after the fire. Factors such as differences in wind speed, wind direction, fuel load, fuel structure, fuel moisture, and topography determine whether such fire refugia patches can remain unaffected from the fire (Leonard et al. 2014).

Aim of the study

Here we analyze fuel properties, fire dynamics and the effects of a prescribed fire, which was carried out on January 13th, 2024, for the purpose of determining the suitability of such measure for the restoration of important habitats in the reed belt of Lake Neusiedl. This study attempts to answer the following research questions using laboratory analyses of fuel loads, aerial image data, and field measurements before and after the burning: (1) How much biomass and carbon was removed from the study area due to the prescribed fire and from which layers? (2) Can expected annual aboveground biomass production compensate for biomass lost due to fire? (3) How does microtopographic variation, specifically groundwater table depth, influence fire severity in reed-dominated wetlands?

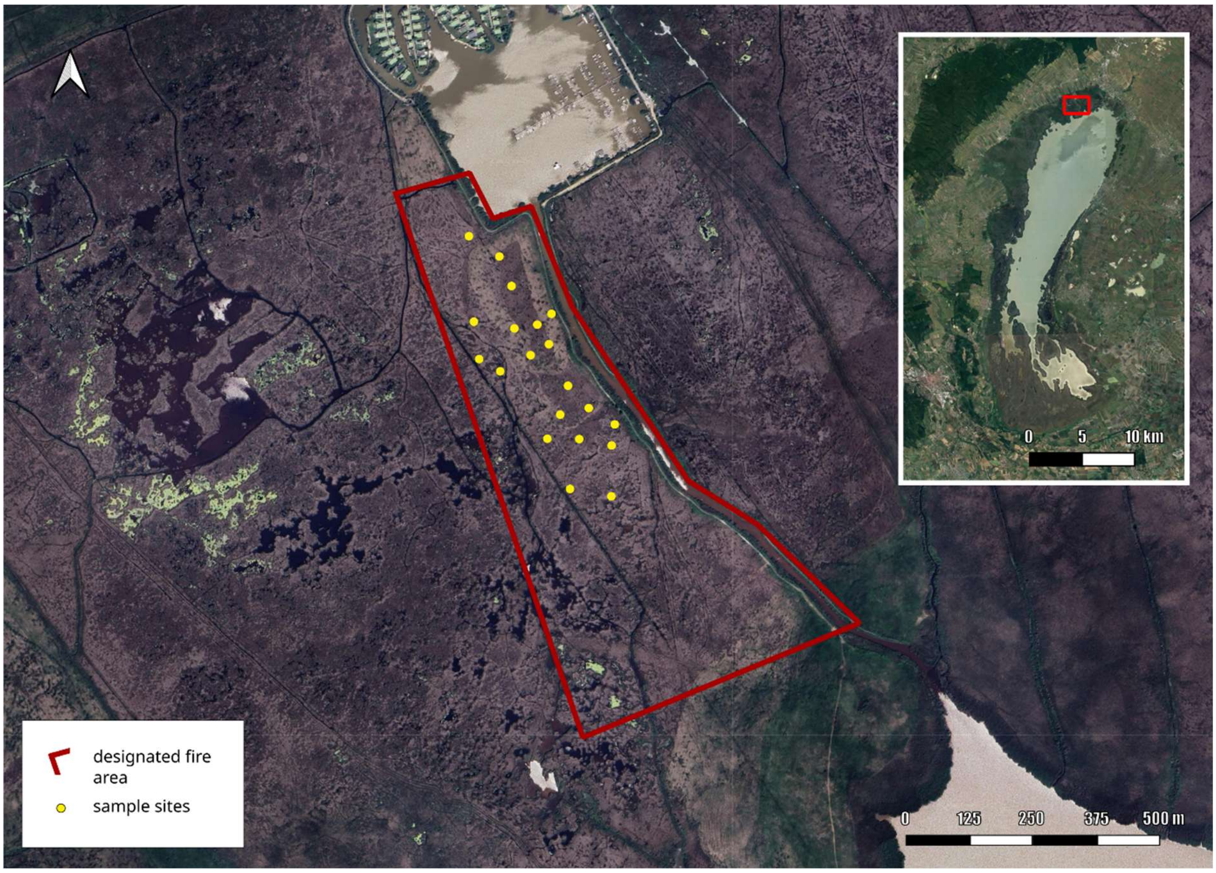

***Figure 2**: Overview map of study area and sampling sites. RGB Google Satellite*

Methodology

Site description

Lake Neusiedl is located on the Austro-Hungarian border and is, without natural drainage, the westernmost steppe lake in Europe. More than half (approximately 181 km²) of the subsaline shallow lake is covered by *Phragmites australis* (Csaplovics 2019), which makes it the second largest contiguous reed ecosystem on the continent. Young reed vegetation patches form a dynamically changing mosaic in conjunction with open water areas and sediment patches (Buchsteiner et al. 2023). The composition of the surface is subject to significant changes over the course of the year, as a sharp decline in open water areas correlates with the increasing growth of reed beds. In our study area, however, *Phragmites australis* and subsequently all present above ground vegetation appears to have formed as a floating mat on top of the former lake surface.

The average air temperature in the region from 1993 - 2022 is 11.8°C, showing a significant annual increase of 0.06°C in the same period, while the average annual precipitation of 548 mm has not changed significantly (-0.25 mm; Cruz-Alonso et al. 2023). 79% of the total water input into the lake comes from precipitation, the remaining inflow is based on a few small streams that flow into the lake. 90% of water losses are due to evapotranspiration (Soja et al. 2013). Due to winter conditions in January all standing reed can be considered standing dead.

On January 13th , 2024, a pilot project was carried out in Jois, Burgenland, Austria, in which a designated area of 32 ha (**Figure 2**) was subject to controlled burning in cooperation with the regional firefighting department. The aim of the project was to reduce the amount of standing dead and litter significantly, to train firefighting personnel, and to determine the suitability of the management measure.

Surface water levels at the time of the fire were low at 115.3 meters above sea level (daily mean value) measured at a nearby stations in Neusiedl am See and Breitenbrunn (HD Burgenland 2024a, HD Burgenland 2024b). Groundwater table measurements were carried out pre-fire and resulted in an estimated water depth of 80 cm on site, and accordingly 114.5 meters above sea level for the lake bottom.

Field inspection and biomass sampling

In January 2024, 20 sampling points were established in the reed belt of Lake Neusiedl (**Figure 2**). The northernmost sample point was located at 47°56'14"N, 16°47'41"E, the southernmost at 47°55'56"N, 16°47'54"E. The sampling points were placed along transects at intervals of around 50 m, considering accessibility, and selected in such a way that the reed was as homogeneous as possible within at least 1 m² of the sampling point. GPS data was recorded, and the points were marked with steel rods to ensure that they could be found again for the subsequent post-fire sampling two days later.

A square measuring 25 x 25 cm was first laid out on each sample area at a distance of approximately 20 cm from the steel rod. Within this square, samples of the three horizons 'standing reed' (S), 'litter layer' (A) and 'soil' (B) were then taken (**Figure 3**).

Standing (S) reed vegetation forms the layer of upright and not yet bent reed stems. It also considers dry reed up to an angle of 45°. When measuring standing reed, all standing reed stems above the horizontally broken reed/bent layer (A layer) within the 25x25 cm square were counted and their average height was measured. These were then cut along the A-layer and placed in a bag. At the time of sampling in winter, all standing reed was dead.

The standing reed was fully combusted on burnt sites (S assumed to be 0) and thus was not analyzed after the fire.

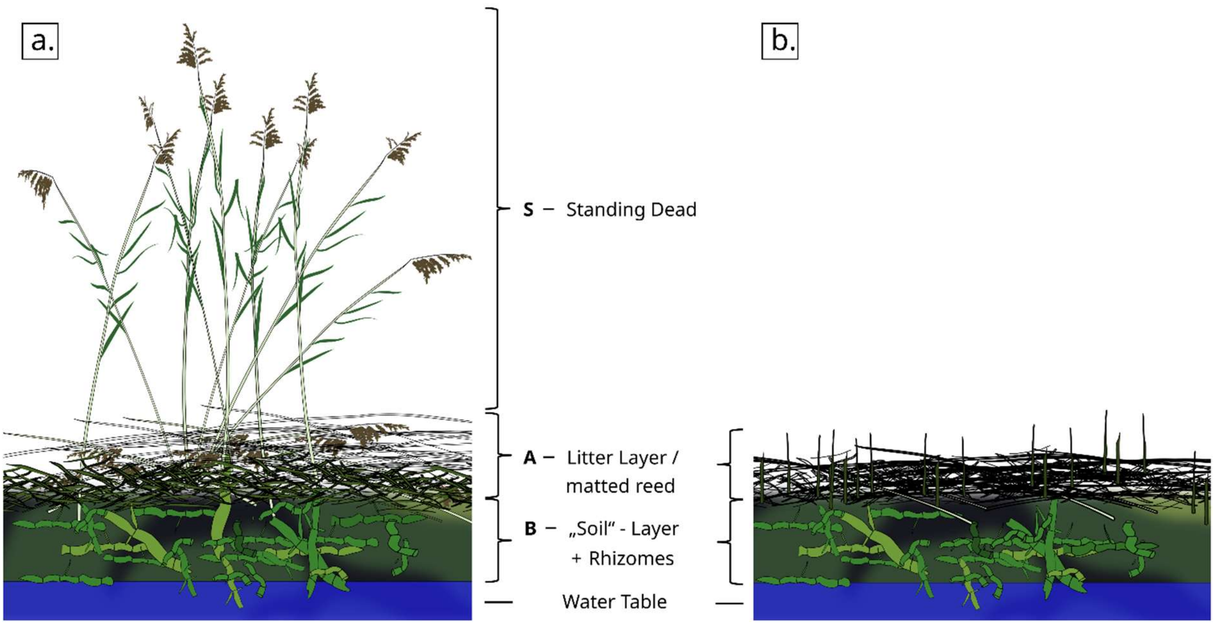

***Figure 3**: Intact Phragmites australis stock (**a**.) and Phragmites australis affected by fire (**b**.). Any material below the water table was not considered to be potentially affected by the fire and was therefore not sampled*

The *A-layer* is the horizontal reed layer (henceforth also called “litter”), which lies loosely above the soil layer or water surface. The litter consists of bent and broken reeds and is inclined at an angle of more than 45° and can form thick horizontal reed mats (matted reed) when left unmanaged. The sample of the litter layer was plumbed vertically along the edges of the measured quadrat area of 25x25 cm down to the bottom-forming sediment (beginning of the B-layer), cut off and placed in a bag. The vertical thickness was measured. The distinction between the two layers A and B was always made based on structure and appearance of the material on site.

Samples of the *B-layer* (also 25x25 cm) were then taken below the litter layer. This layer represents a decomposed layer of organic material. It will also be called soil layer in the context of this research paper, although it differs from the general understanding of the term. Rhizomes were found to be present in the soil layer on several sites, indicating rooting horizons near or above the water level. The soil layer below the water level could not be determined with the available measuring devices due to the cold weather pre-fire (ice cover). Therefore, post-fire sampling also was done until reaching the then liquid ground water level. The volume of the samples taken subsequently depended on the thickness of the layers above the water table. This soil layer consists of the partially decomposed, crushed former litter layer. The intact roots and rhizomes were separated from the soil samples for subsequent measurements. The thickness of the soil layer was also measured, and the biomass was collected with a spade and placed in a bag. Due to solidly frozen open water surfaces not at every sampling point a soil sample could be taken, especially before the fire. In those cases, only samples of the S and A layers were taken. The frozen water table, however, was not present at the time of the post-fire sampling, thus soil samples were taken from all burnt sampling points.

Fire monitoring and fuel moisture measurements

Before the start of the fire monitoring, 19 measuring panels were installed at 10 m intervals along the edge of the planned reed fire area to determine the rate of spread of the fire front. During burning, the time it took to reach the individual measuring points was documented and these measurements were correlated with the average wind speed - measured at a height of 2 m using a Kestrel 5500FW Fire Weather Meter Pro - in order to determine the effective rate of spread.

During the prescribed burn, the absolute (highest) fire temperature was determined using calibrated infrared thermometers (VOLTCRAFT IR 1201-50D, sensitivity up to 1200°C). The maximum temperature of the burning reeds was determined at around 20 measuring points on the fire front during the fire and the fire location and measurements were documented photographically. The measurements via infrared thermometers required immediate proximity - less than 10 m away - to the flame front.

To better understand the moisture content of the reeds and thus the fire behavior and fire intensity, measurements of the moisture content (MC) of the reeds were carried out during and after the fire under different weather conditions following the prescribed burn. Measurements were carried out using a mobile measuring device (Wiltronics Fine Fuel Moisture Meter, ME2000). The ME2000 indicates the moisture or water content in percent by weight of the dry mass.

During the burn, only individual measurements of the MC of the reeds outside the fire area could be carried out. For the follow-up measurements some days after the fire, a vertical moisture profile was created in the reeds. For the matted reed / litter layer (A) we measured at the surface (A-0), at a depth of 5 cm (A-5), 10 cm (A-10) and 20 cm (A-20) whereas the first (uppermost) predominantly homogeneous layer of horizontally bent reed stems was assumed to be the surface. For the standing reeds (S) three measurements were taken per site and compartment at the level of the base of the standing reeds (S-0), at a height of 10 cm (S-10) and 50 cm (S-50). The soil layer (B) was not sampled as it was saturated with water. The data was collected at seven representative sites. In some cases, it was not possible to take moisture measurements at greater depths due to the low thickness of the matted reed horizon (reaching the reed rhizomes, soil and/or water). On both survey days, the Kestrel 5500FW Fire Weather Meter Pro was set up before the start of the measurements to obtain continuous meteorological data from the survey areas.

Laboratory analysis

Firstly, the fresh masses of the standing reed, litter and soil layer samples were determined using a high-precision balance. The reed rhizomes of > 2 mm equivalent diameter in the B-layer were sorted out, weighed, and stored separately. The dry mass was then determined by oven drying. For this purpose, the samples were first dried at 80°C for 48 hours, then weighed and dried at 80°C for a further 24 hours and weighed again to ensure that weight constancy was achieved. The samples of both layers (A; B without rhizomes) were subsequently crushed and pulverized using a vibrating mill (Retsch MM 400) and thus prepared for subsequent CN analysis. This way, approximately 2 ml of representative preparation was produced from each post-fire sample taken. This was then transferred to Eppendorff Safe-Lock tubes. A carbon/nitrogen (C/N) analysis to determine the carbon content and nitrogen content as a percentage of the mass was carried out on all samples of all layers. The C/N analyses were carried out with a LECO Truspec CN. The carbon content in g C/m² can be calculated from these analyses. The results from the litter layer and the underlying soil layer are subjected to a paired T-test for the statistical analysis. As only paired values can be used for this, it should be noted that the sample number of the soil layer is only 8.

Remote sensing and processing

The study was surveyed with two UAV-LiDAR flights and one RGB flight. The aerial surveys were carried out by the company Skyability GmbH using a VUX SYS 1 UAV LiDAR scanner on 11.01. and 26.01.2024. The RGB flight took place on 11.01. using a DJI Zenmuse P1 camera. For the two UAV-LiDAR flights the flight altitude was 120 m above ground, the flight speed was 8 m/s, the scan angle 80 degrees and the scan frequency 550 kHz. The UAV-LiDAR data was pre-processed and georeferenced and was available as laz-files. The UAV-LiDAR point clouds have an average laser shot density >400 transmitted laser shots per m².

Based on the georeferenced UAV-LiDAR point clouds digital terrain models (DTMs) were generated based on the last echoes. A hierarchical, iterative calculation approach was used. Starting with a cell size of 3 m, an initial terrain model was calculated from the lowest points per cell. In the next two iteration steps, the cell size was continuously reduced and only points in the vicinity of the previously calculated terrain model were used. Any gaps due to missing data were closed by triangulation. The final DTMs have a raster resolution of 0.25 m.

For the calculation of the digital surface models (DSMs) the first echoes were used, whereas the land cover-dependent calculation approach of Hollaus et al. (2010) and a quantile-based approach was applied. The land cover-dependent approach follows a combined calculation approach, which, depending on the roughness of the surface of the DSM, is composed of the highest point per grid cell and locally fitted moving planes in the point cloud. The "moving planes" interpolation is applied to a thinned data set (highest points within a cell with half the resolution of the final DSM) to ensure that the interpolated model best describes the surface of the reed. This calculation method leads to an improved description of the reed surface as well as the gaps in the reed, especially in areas covered with reeds, compared to a pure "moving planes" interpolation. Furthermore, this approach has the advantage, especially in areas with a lower point density, that height information can be estimated for image elements in which there are no points by means of the "moving planes" interpolation using the neighboring points. The DSMs were calculated with a grid size of 0.5 and 1.0 m.

For the quantile-based approach a grid size of 1 m was selected and the 95% quantile of all points within each cell was used for the calculation of the DSM. It has been shown that the derived DSMs are less influenced by wind than the land cover dependent DSMs.

The normalized digital surface model (nDSM) was calculated by subtracting the DTM from the DSM. As the grid sizes of the DTM and the DSMs differ, bilinear resampling of the DTM was applied.

The digital water surface model (DWOM) is calculated based on selected points of the open water surface. The selection of the water surface patches was done based on manual inspection of the DSM and the orthophoto. The same water surface elevation of 159.31 m was applied for the aerial surveys on 11.01. and 26.01.2024. The DWOM is calculated with a grid size of 10 m. There is a difference of 44.00 m between all survey data and the local geodetic datum.

In addition to the DWOM, difference-models between DTM and DWOM were calculated. These models have a grid size of 0.25 m. These difference models are therefore very suitable for detecting open water areas or reed areas where the DTM is very close to the water surface.

The detection of the burnt area is based on the difference-model of the two quantile-based UAV-LiDAR DSMs. It was assumed that a height reduction of >0.15 m must be present for the pixel to be identified as a potential burnt area pixel. This threshold was determined based on visual inspection of the DSM changes in burnt and unburnt areas. The final burnt area was derived by applying morphological filters on the previously detected burnt area pixels.

The final burnt area map was used for further spatial statistical analyses such as describing the patchiness or identifying the non-burnt areas within the burnt reed. Further statistics were calculated such as the mean DTM height above the water level for burnt and non-burnt areas.

Results

Fire spread and thermal characteristics

The measurements of the propagation speed during the prescribed burn showed an average propagation of 0.5 m/s or 1.8 km/h of the fire front (**Figure 4**). Even if the spread varied over short periods of time due to alternating stronger and weaker gusts, the average fire spread corresponded to 10% of the average wind speed measured at a height of 2 m.

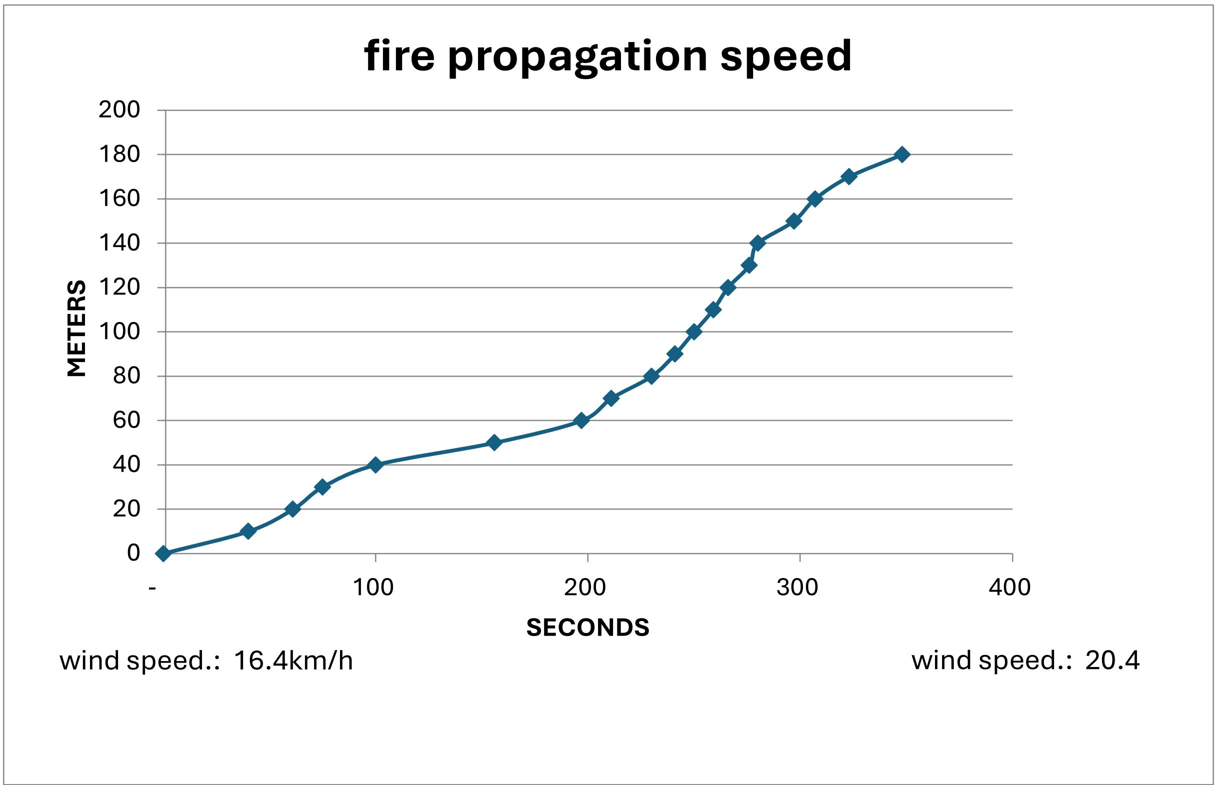

***Figure 4**: Spread speed of the fire front as a function of time and distance. Each line point indicates a distance of 10m. The wind speeds shown are mean values and were recorded at the beginning and end of the propagation measurement at a height of 2m*

The highest recorded fire temperature was 1034°C. The average temperature was 726°C. The results were evenly distributed over the measurement period. The highest fire temperatures were reached at a flame height of more than 2 m (see appendix Table A1).

Fuel moisture patterns

The measurements of MC during the prescribed burn were taken between 10:00 and 11:00 local time and yielded values of 20% to 62%, with an average value of 31%, whereby the standing reed measured had an average MC of around 10% lower than the matted reed (see appendix Table A2). Regarding the matted reed, the uppermost horizon was sampled. During the study period, the relative humidity measured at a height of 2 m was constantly around 67%.

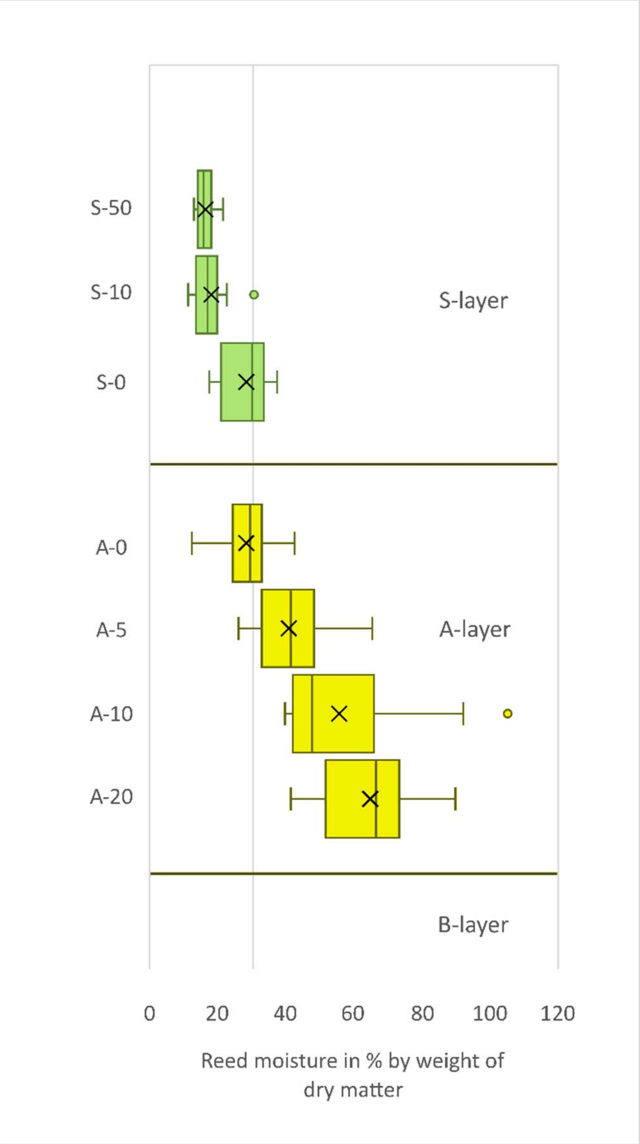

***Figure 5**: Results of the reed moisture measurements after the fire event based on compartments. Standing reed MC measured at respective heights descending from S-50 to S-0, litter layer from A-0 to A-20. Fire-retardant moisture content of 30% marked with vertical line. The colored box corresponds to the middle 50% of the data bounded by the upper and lower quartiles. Median value represented by vertical line within the box, mean value represented by the black cross*

On 24.01, moist conditions prevailed due to a previous rain event, and there was also little wind. On this day the focus was on moisture measurements on the different compartments of the matted reed, the standing reed was not sampled. The second day (29.01) was consistently dry and windier. With increasing daytime temperatures and decreasing relative humidity, the MC of the standing reed decreased significantly and that of the matted reed near the surface slightly (see appendix Table A3). The lowest MC results, around 15%, were recorded in the early afternoon in the standing reed, the highest with up to 90% in the deeper layers of the matted reed. On 29.01, lower moisture tended to be recorded on the surface of the matted reed than on 24.01, which is probably related to the weather conditions.

The measurements gave a clear picture of the distribution of reed MC by compartment (**Figure 5**). At a relative humidity of around 60% and more than 48 hours without precipitation, which corresponds to slightly more favorable fire conditions than on the day of the prescribed burn, less than 20% water content was measured in the standing reeds (S-10, S-50), around 30% in the matted reed close to the ground (S-0, A-0) and more than 40% in the deeper matted reed layers (A-5, A-10, A-20).

Biomass reduction and carbon dynamics

The fire did not completely cover the designated area. On burnt sites (n = 11) the pre-fire standing vegetation (S) was completely removed from the surface. Visually the A-layer was seemingly only marginally affected by the fire. Signs of fire activity were noticeable in the form of charred pieces of stems, but right underneath surface level the mat was very much intact with a minimum of 6 cm (mean = 11.6 cm +/- 5.4) of thickness (Table 1) remaining above the underlying partially decomposed B-layer. Also patches of intact standing dead were spontaneously left, seemingly unaffected by the fire.

The average height of the reed vegetation pre-fire was 154.8 cm (highest: 350; lowest: 110). Taken reed stems amount to 189 stems per square meter on average. The thickness of the litter layer of old reed stems from previous years was 16.6 (+/- 8.6; min = 1; max = 35) cm and had been reduced by approx. 30% to an average of 11.6 (+/-5.4, min = 6, max = 20) cm by the fire. The fire affected the uppermost layer of the litter layer and did not reach the soil layer B below.

Table 1*: Results of layer thickness, biomass, carbon content, carbon change by fire (carbon flux). Mean values (bold) and standard deviations (±) pre- and post-fire. Pre-fire affected by fire in brackets (n=11).*

	Layer Thickness (cm)		**Biomass (g/m^2)**		**Carbon (%)**		Carbon flux (t/ha)
Layer	Pre	Post	Pre (n=11)	Post	Pre	Post	
S	**154.8** ± 52.0	0 0	**482** (450) ± 339 (306)	0 0	**51.1** ± 1.6	0 0	**-2.46**
A	**16.6** ± 8.6	**11.6** ± 5.4	**1851** (1737) ± 1132 (916)	**1554** ± 502	**49.2** ± 4.3	**51.3** ± 1.0	**-1.14**
B	**13.5** ± 9.7	**16.9** ± 3.5	**5196** (5176) ± 4267 (4124)	**5029** ± 2397	**37.2** ± 11.1	**38.2** ± 9.9	**-0.12**

The dry biomass of standing reed averaged 482 (+/-339) g/m² before the fire and was completely lost due to the fire on the 11 burnt sites. The mass of the litter layer was 1851 (+/-1132) g/m² before the fire and was reduced to 1554 (+/-502) g/m² after the fire. The dry mass data from the soil layer was more variable than the other horizons, as evident from standard deviations. Before the burning event the mean dry mass of the soil layer was 5196 (+/-4267) g/m² and after the fire it was 5029 (+/-2397) g/m². Additionally, rhizomes taken from the soil samples on average accounted for 412 (+/- 357) g/m² before fire and 627 (+/- 587) g/m² post fire respectively. Results are noticeably heterogenous in terms of layer thickness as well as bulk density. The standing reed vegetation had a C content of 51.1%. The litter layer had an average of 49.2% C before the fire (after the fire: 51.3%), while the soil layer had 37.2% (after the fire: 38.2%).

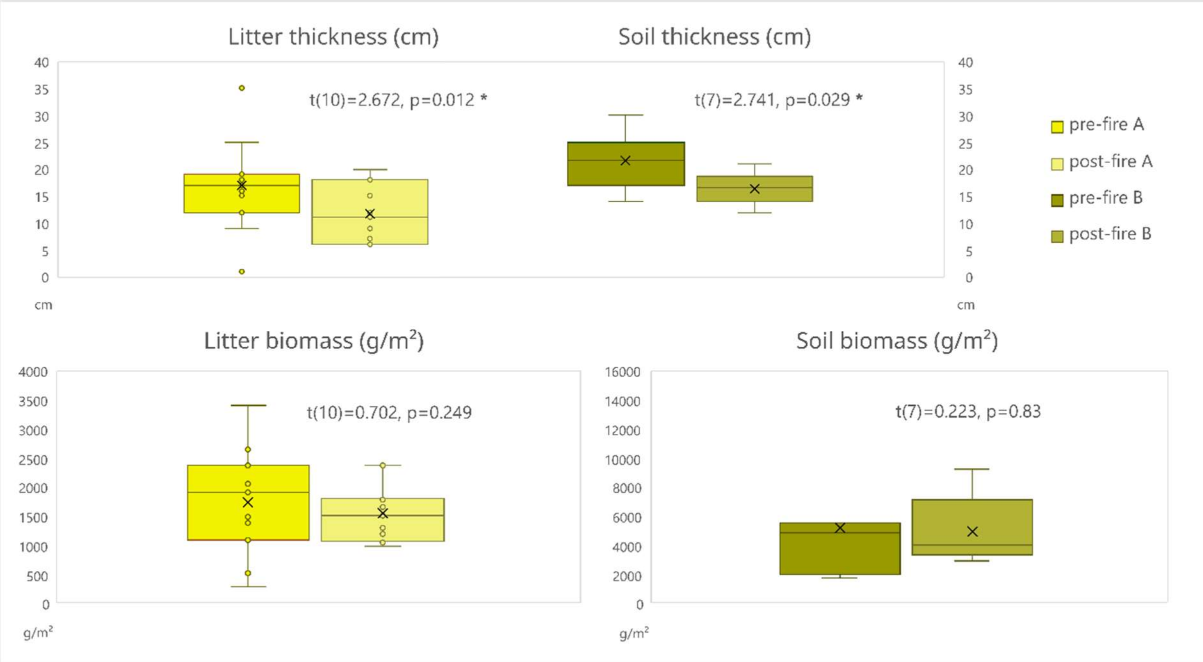

***Figure 6**: Statistical comparison of pre-and post-fire thickness of affected layers (top). Pre- and post-fire biomass comparison of affected layers (bottom). The colored box corresponds to the middle 50% of the data bounded by the upper and lower quartiles. Median value is vertical line within the box. Mean value is represented by the black cross*

The decrease in thickness (**Figure 6**) of the litter layer is significant (one-sided) at p=0.012, but a significant decrease is also given for the soil layer, where no changes in thickness were expected as a result of the fire. Although the mean values of the biomass (dry mass) results show a slight decrease compared to the pre-fire samples of the A-layer, this difference is not statistically significant due to the fluctuation or standard deviation in the paired T-test.

The fire also resulted in a noticeable reduction of 19.1% of the pre-fire biomass in the litter layer compared to the pre-fire results from all 20 sampling points. The standing vegetation on the burnt areas had been completely removed by the fire. Regarding the soil layer, there was only a small deviation between pre- and post-fire samples of <1% of the biomass. Thus, it can be concluded that the biomass of the decomposed layer has not been affected by the fire management.

Aerial survey

The differences between the two UAV-LiDAR derived quantile-based DSMs provide an area-wide overview of the reed changes due to the burning. For **Figure 7** the respective values of the DTM were subtracted from the DSMs. Transparent visualization represents results smaller than or equal to 0. The additional transparent area in the right image (**Figure 7b**) represents the area, which lost standing reed and parts of the litter layer as a result of the fire. The burnt area amounts to 15.57 ha. According to this the total carbon stock lost due to the fire is 57.84 t C (3.72 t/ha), with an estimated 38.30 t C (2.46 t/ha) originating from standing vegetation and 17.74 t C (1.14 t/ha) from the litter layer.

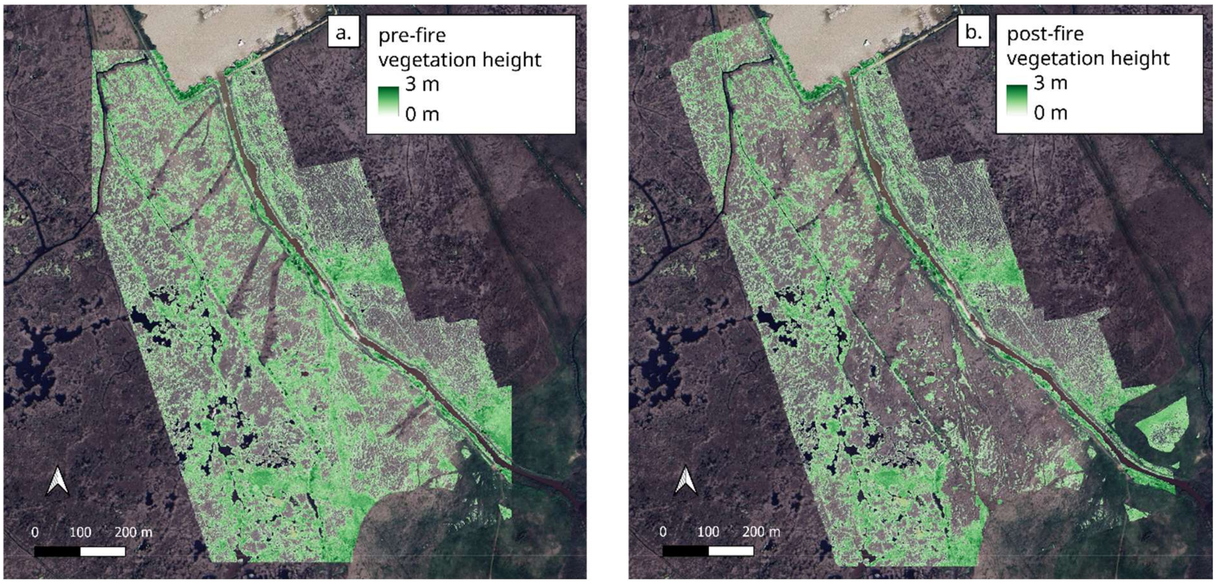

***Figure 7**: Normalized Digital Surface Models before the fire (**a**.) and after the fire (**b**.). Present standing vegetation in green. Transparent values represent DSM ≤ DTM values. RGB Google Satellite*

Figure 8a shows the detected burnt area. For deriving the final burnt area map a majority filter with a 5x5 kernel was applied. The pixel size is 1x1 m, the total burnt area within the AOI is 15.57 ha. As can be seen in **Figure 8** (a.) several patches within the fire perimeter remain un-burnt. From the approx. 20% of remaining unburnt areas approx. 3% belong to open water surfaces where the difference between the pre-fire DTM and the water surface is ≤ 0.05 m. The right image (b.) in **Figure 8** shows the difference map between the DTM before the burning and the water surface (DTM-DWOM). DTM areas near the water surface are highlighted in blue.

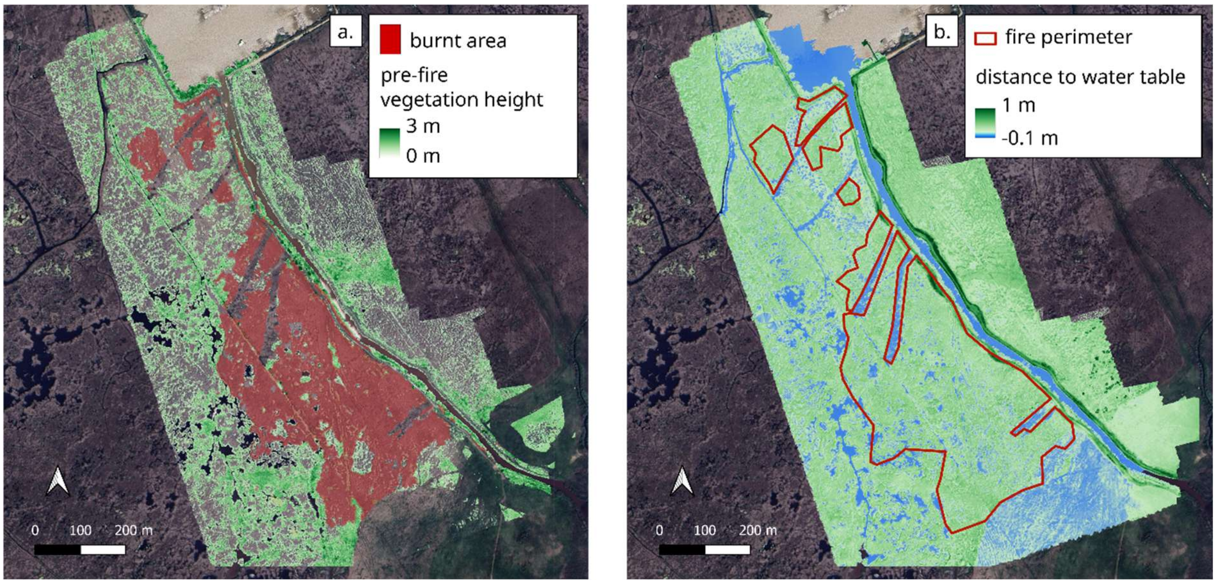

Figure 8: ***a***: *Pre-fire nDSM overlaid with burnt area in red.* ***b***: *Pre-fire DTM height relative to the pre-fire water level (DTM-DWOM). Areas where the difference between the DTM and the water level is less than 0.10 m are highlighted in blue. The fire perimeter is visualized as red polygons. Firebreaks are excluded from the fire perimeter. RGB Google Satellite*

Further analyses of the burnt versus unburnt areas show that the pre-fire median of the DTM height above the water level is 0.33 m for burnt areas and 0.19 m for unburnt areas within the fire perimeter. Statistical details are given in the histogram shown on **Figure 9**.

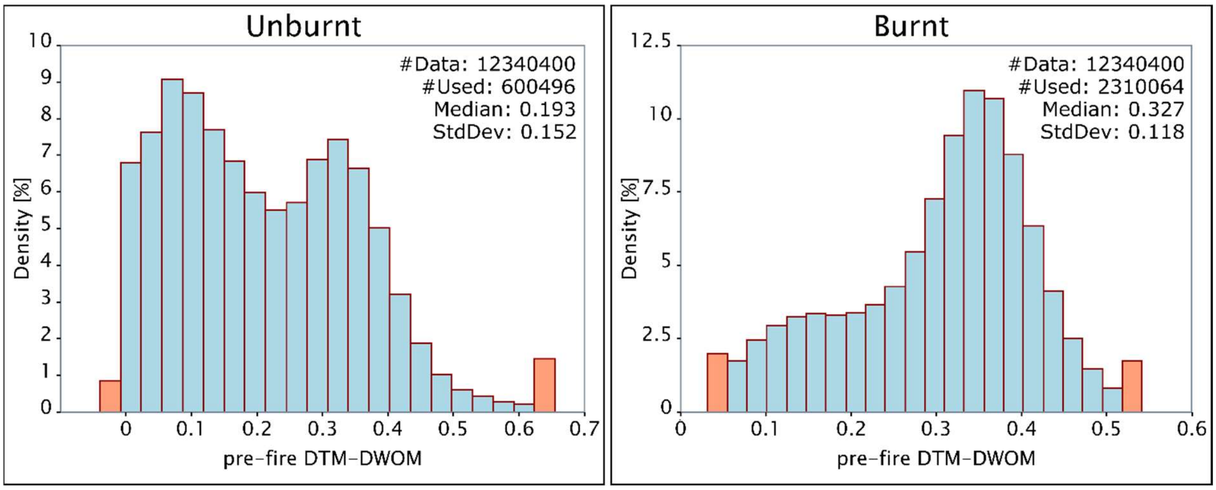

Figure 9: *Histogram of the DTM heights above the water level before the fire event for later unburnt areas (**a**.) and burnt areas (**b**.)*

In **Figure 10** the detailed histograms of the pre-fire DSM heights for burnt areas are shown. Median changes at burnt and unburnt areas as well as visualized underlying data are provided in appendix Figure A1. Due to the burning the median reduction of the DSM for the burnt areas is 0.51 m, whereas the median change for the unburnt areas is 0.08 m. Changes of unburnt areas primarily reflect the influence of the wind during LiDAR data acquisitions and can be seen as data related uncertainty.

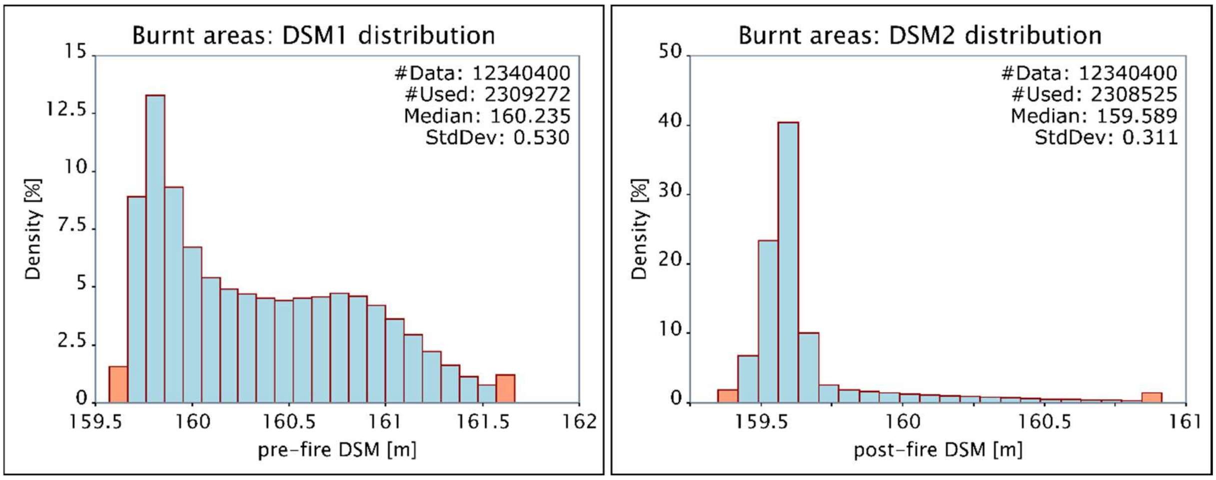

***Figure 10**: Histogram of the burnt area DSMs pre-fire and post-fire*

Discussion

Fire characteristics

The measured fire temperatures of around 1000°C appear high but have been confirmed by other studies: The maximum temperature of uncontrolled vegetation fires is usually 800-1200°C (Bova and Dickinson 2008; Wotton et al. 2012). The highest temperature of crown fires in the forest can exceed 1300°C (Butler et al. 2004). The highest temperatures during the prescribed burn in the reed belt of Lake Neusiedl were detected in connection with a high fuel load and greater flame length, which is consistent with findings from fire research. The results of the measurements (**Figure 4**) during the prescribed burn in the reed belt also show that the 10% rule can be used to make a good estimate of the spread of a reed fire (Cruz et al. 2020).

Reed moisture and combustion behavior

The measurements of reed MC clearly show the influence of wind, precipitation and air humidity. Shortly after a rain event (measurements on 24.01.), the MC of the reeds near the ground was more than 30%. With such a high moisture content, no or only partial combustion is to be expected (Wade 2021a). With more than 48 hours of dryness and a humidity of around 60% (second day of measurement and slightly below the humidity on the burning day), the MC in the standing reeds was below 20%, which means that independent maintenance of combustion is likely, especially under the influence of wind. The compartments close to the ground (S-0, A-0) had an average moisture content of just under 30%, suggesting partial combustion. Due to the high moisture content, no combustion is to be expected under these conditions for deeper lying matted reeds.

In general, the MC of the burnt material should be below 30%, otherwise it can be assumed that hardly any burning takes place (Wade, 2021a). In addition, the possibility of using backfire techniques in reed under favorable conditions (low wind, low humidity, positive temperatures) should be examined. These lead to a higher fuel consumption due to the lower propagation speed and longer holding time of the fire. Only around 1/3 of the emissions of a headfire can be expected under the same fire conditions (Wade, 2021b).

Biomass recovery and carbon stocks

According to recent findings *Phragmites australis* produces aboveground biomass within the range of approximately 700 to 1700 g/m² per year in temperate climates (Papchenkov and

Čížková 2024). However, our data suggests that standing biomass of this older reed vegetation plot is about 482 g/m² (4.82 t/ha). This is expected, due to wintertime as well as young reed shoots having difficulties penetrating through the accumulating layer of old matted reed. We also conclude that annual *Phragmites australis* aboveground biomass production may exceed the amount of biomass lost to the fire within the following year, as the combined biomass loss from layers S and A (mean values) of 779 g/m² is only marginally higher than the expected minimum regrowth value. Additional growth-promoting conditions such as improved nutrient availability due to ash residue (Alcañiz et al. 2018) and more space available for young shoots can be assumed.

Our study site shows similar amounts of accumulated biomass and subsequently carbon stock compared to other study areas at Lake Neusiedl. Examinations by Baur et al. (2024) show a mean carbon amount of about 37.7 t C/ha on the study area, 14.40 t C/ha (± 6.60 t C/ha) of which was from litter and standing vegetation combined and the belowground biomass was sampled up to a depth of 30 cm. Our data reveal a mean total stock of 30.90 t C/ha on the study area, 11.57 t C/ha of which are from standing and litter combined. However, our average belowground sampling depth was only about 13.5 cm pre fire. Since our sampling was limited by the water table it can be assumed that large amounts of biomass were also present below.

The effects of the fire can explain changes in the carbon pools: While all of the carbon was removed from the layer of standing reed by the fire, this does not mean that all of this carbon was released into the atmosphere. It can be assumed that partially burnt pieces of reed and ash residues have come to rest in the surrounding area and on the post-fire litter layer A exposed by the measure, thus leading to higher proportions of carbon post management (Certini et al. 2005, Cheng et al. 2023). Same could be argued for the B-layer below, which showed an estimated carbon content increase from 37.2% to 38.2% (Table 1). Total carbon in this horizon is likely to increase over time due to translocation of partially burnt particles and ash. Further investigation is needed, as the short sampling interval and lack of precipitation limited particle movement into deeper layers.

Unburnt patches and habitat diversification

While rejuvenation measures support habitat preservation, retaining patches of old vegetation is also beneficial. Not all standing vegetation and litter are likely to be removed during controlled burns, allowing reed structures of varying ages to coexist under similar conditions as present during this pilot management project. As our results show a reduction in the thickness of the litter layer, an improvement in the habitat quality for protected or endangered animal species who prefer young reed habitats can be expected, while the loss of animal life could be minimized by the framework conditions, in particular by the implementation of the pilot project in winter. Disregarding the presence of plenty of available old reed stock zones in the area of Lake Neusiedl, the deterioration of the habitat for species that favor old reed beds could be reduced both by the non-extensive burning of the entire reed bed and remaining refugia patches, as well as by the incomplete burning of the litter layer itself.

The aerial surveys made it possible to establish a correlation between calculated water table depth and the flammability of the fuel in the landscape. The Lidar flights show the fire spread and, together with data from the biomass surveys, the burnt reed mass. The analyses have shown that the median difference between the pre-fire DTM and the water table is 0.19 m for unburnt areas compared to 0.33 m for burnt areas. It can be assumed that if parts did not burn without firefighting measures (e.g., firebreaks, see **Figure 8a**) being carried out, properties of the material led to a reduction of fire spread. If the calculated water level is close to the DTM before the fire, it can be expected that these areas have a high moisture content and therefore burn poorly, as shown in (**Figure 8b**). Thus, shallow water table depth serves as a reliable indicator of reduced fire propagation in areas with higher moisture content.

According to the lower post-fire standard deviations, heterogeneity appears to have decreased as a result of the fire. However, the small number of samples needs to be taken into consideration. In our opinion, such an investigation is valuable regarding the data obtained by remote sensing on surface elevation differences as well as layer thicknesses determined on site before and after the fire. Reliable comprehensive comparative biomass analysis can be carried out if a sufficiently large sample size can be obtained.

Prescribed fire effectiveness and dynamics across other ecosystems (Williams-Jara et al. 2022, York and Russell 2025) as well as habitat feedback of ecosystems dominated by *Phragmites australis* following management by fire (Brooks et al. 2024, Geurts et al. 2020, Ward et al. 2025) have been subject to research in recent years. The investigation of such measure and subsequent consequences in the national park of Lake Neusiedl is a novelty and could ultimately be utilized to promote an amendment to the legislation. Understanding implications due to the fire is essential for future management of the wetland site. Nevertheless, it is important to also recognize possible negative implications of prescribed fires such as unintended damage to non-targeted species or wildlife, possible soil degradation (Alcañiz et al. 2018), smoke emissions and pollutants, and risk of unintended wildfire. Future research in the study area may help to clarify the full extent of fire management success, particularly regarding *Phragmites australis* regrowth performance, effective biodiversity retention, carbon stability, among other ecological indicators.

Biomass and thickness of the samples from the A-layer and the B-layer vary significantly, which can be attributed to microtopographic characteristics in the stratification of these old reed stands. The stratification is in-situ spatially heterogenous and could have led to the fluctuations in the sample quantities taken from the A-layer and B-layer. This subsequently also evidently influences the total amount of carbon present for each sample point. Therefore, in order to provide reliable results regarding reed biomass and statements related to pre-fire - post-fire comparisons, a sufficiently large sample size is necessary in the light of apparent microtopographical variations on areas dominated by reed.

Matted reed landscapes prove to be particularly heterogeneous not only in terms of surface area but also vertically. Possible explanations for the strong fluctuations of the extracted biomass and the pronounced standard deviations (Table 1) include distance to water level, old rootstocks, voids in the bedding, previous mowing practice etc. This heterogeneity can only be estimated to a limited extent in advance, for example using aerial photographs or by estimation from current standing vegetation on site.

Conclusions and Outlook

The prescribed burn on 13.01.2024 showed that burning of the reed belt at Lake Neusiedl is possible even under adverse conditions (high humidity, low temperatures). Our research regarding the consequences indicates that various positive effects such as habitat rejuvenation and fuel load reduction could be achieved while simultaneously providing refugia patches and avoiding C loss from deeper, partially decomposed layers. In order to minimize the risk and under the premise of also burning deeper matted reed areas, beneficial meteorological conditions in the winter months include no precipitation for at least 48 hours (preferably longer), relative humidity below 60% but above 30%, average wind speed below 30 km/h, and temperature above 0°C.

Possible preparations for the procedure on site include measurements of reed moisture in different compartments in the early afternoon of the day before the prescribed burn (comparative values for the following day) and immediately before the start of the burn. If the aim is to reduce matted reed biomass, this layer should preferably have a water content of around or below 30%. Prescribed burning in winter should ideally begin around midday when the humidity is typically lower. The weather has a fire-retardant effect from late afternoon onwards due to rising humidity and decreasing air temperature.

It is not foreseeable whether similar studies can take place at other locations in the reed belt in the near future. The amendment of the current Federal Air Pollution Control Act is currently uncertain. The research site is therefore unique in Austria for the time being and should be thoroughly investigated. Further measurements of reed MC, especially of the litter layer, under drier conditions in winter should be considered in order to record the variability of conditions for the burning of deeper layers. Follow-up aerial surveys should also be considered for the next years in order to document and correctly estimate regrowth performance at the study site in Jois after the prescribed fire, since it is uncommon to have pre-fire values for comparison in the reed belt of Lake Neusiedl. Additionally, comparisons should be conducted between GHG emissions (methane, CO2) occurring on the burnt area and those of undisturbed sites. Additionally, pathways and fluctuations of greenhouse gas emissions as a consequence of the post-fire condition of the reed bed should be studied.

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Appendix A

Table A1: Measurements of the fire temperature during the prescribed burn.

No.	**Maxtemp (°C)**	**Fire description**	**Local time**
1	663	Flame height >2m	10:56
2	607	Flame height 1m	11:02
3	520	Flame height <1m	11:12
4	601	Flame height <1m	11:12
5	1009	Flame height >2m	11:25
6	933	Flame height 2m	11:25
7	780	Flame height 1,5m	11:28
8	862	Glowing embers	11:31
9	848	Burning matted reed	11:31
10	700	Glowing embers	11:33
11	684	Glowing embers	11:34
12	925	Burning matted reed	11:35
13	889	Flame height 1,5m	11:42
14	448	Smoldering matted reed	11:49
15	628	Glowing embers	11:51
16	770	Flame height 1,5m	11:55
17	1034	Flame height >2m	12:15
18	169	Glowing embers	12:29
Mean	**726**		

Table A2: Measurements of reed MC during the prescribed burn.

Local time	**Reed moisture [%]**	**Compartment**	**RH 2m [%]**
10:27	23.4	matted reed	67.7
10:32	62.3	matted reed	65.8
10:36	27.1	standing reed	66.5

10:39	24.6	standing reed	66.1
10:42	30.4	matted reed	66.1
10:42	27.9	matted reed	66.1
10:42	29.8	matted reed	66.1
10:49	38.1	matted reed	65.6
10:49	33.1	matted reed	65.6
10:49	33.8	matted reed	65.6
10:53	24.9	standing reed	66.1
10:53	20.9	standing reed	66.1
10:53	21.4	standing reed	66.1

Table A3: Measurements of reed MC after the prescribed burn (average of three measurements).

No.	Plot	Local time	Compartment	Mean MC [%]	RH 2m [%]	Date
1	1	10:24	A-0	31.23	71.3	24.01.2024
2	1	10:39	A-5	43.30	72.1	24.01.2024
3	1	10:55	A-10	94.77	76.6	24.01.2024
4	1	11:10	A-20	76.77	72.8	24.01.2024
5	2	12:58	A-0	31.53	68.4	24.01.2024
6	2	12:47	A-5	33.67	65.9	24.01.2024
7	2	12:34	A-10	45.53	64.3	24.01.2024
8	2	12:23	A-20	69.80	63.5	24.01.2024
9	3	13:12	A-0	35.70	65.9	24.01.2024
10	3	13:24	A-5	48.83	66.9	24.01.2024
11	3	13:33	A-10	40.83	67.3	24.01.2024
12	3	13:49	A-20	74.83	70.9	24.01.2024
13	4	09:32	A-0	28.20	76.9	29.01.2024
14	4	09:43	A-5	43.50	74.4	29.01.2024
15	4	09:55	A-10	48.57	76	29.01.2024
16	4	10:12	S-0	33.17	77.2	29.01.2024
17	4	10:26	S-10	23.97	72	29.01.2024

18	4	10:38	S-50	18.63	72.8	29.01.2024
19	5	10:48	A-0	24.27	71.5	29.01.2024
20	5	11:00	A-5	27.67	71	29.01.2024
21	5	11:08	A-10	47.43	69.7	29.01.2024
22	5	11:16	A-20	48.30	70.6	29.01.2024
23	5	11:25	S-0	29.67	67.5	29.01.2024
24	5	11:42	S-10	17.20	63.9	29.01.2024
25	5	11:54	S-50	15.80	65.4	29.01.2024
26	6	12:57	A-0	29.93	59.9	29.01.2024
27	6	13:06	A-5	43.13	59.7	29.01.2024
28	6	13:15	A-10	67.73	59.1	29.01.2024
29	6	13:24	A-20	65.33	60.4	29.01.2024
30	6	13:38	S-0	27.83	57.9	29.01.2024
31	6	13:49	S-10	15.10	56.1	29.01.2024
32	6	13:58	S-50	14.53	58.1	29.01.2024
33	7	14:09	A-0	18.37	57.8	29.01.2024
34	7	14:17	A-5	47.27	56.5	29.01.2024
35	7	14:27	A-10	44.67	57.2	29.01.2024
36	7	14:40	A-20	54.53	59	29.01.2024
37	7	14:49	S-0	22.07	57.9	29.01.2024
38	7	14:56	S-10	15.43	58.1	29.01.2024
39	7	15:03	S-50	16.80	60	29.01.2024

Appendix B

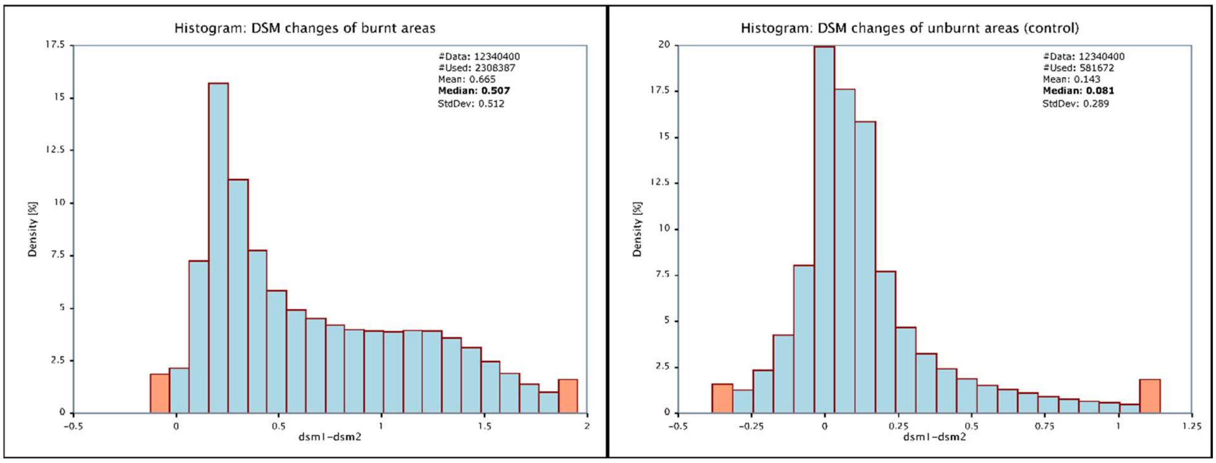

Figure A1: Histogram changes of burnt and unburnt areas within the fire perimeter.