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# Mid to late Holocene storminess and fire history on the Baltic coast of Latvia

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Coastal peatlands are sensitive archives of past environmental change, preserving evidence of both atmospheric and surface disturbances. Here, we reconstruct Mid- to Late Holocene storminess and fire dynamics from a 330-cm peat sequence recovered from Bog Bažu in northwestern Latvia, located ~3 km inland from the Baltic Sea coast. A multi-proxy approach combining macroscopic charcoal, sand grain counts, quartz grain surface characteristics, and plant macrofossils was used to assess how storms and fires influenced peatland development over the past ~5400 years. The charcoal record reveals 30 fire episodes with a mean return interval of ~170 years, with highest fire frequencies between 4500–3900 and 3000–800 cal yr BP. Sand influx analysis identifies 46 episodes of enhanced storminess, characterized by a dominance of cracked quartz grains indicative of high-energy transport. Sixteen intervals show partial temporal overlap between fire and storm peaks, suggesting that thunderstorms may have occasionally linked the two disturbance regimes, particularly during relatively dry phases when fire susceptibility was enhanced. In contrast, wetter periods are associated with weaker coupling between storminess and fire activity. Plant macrofossil evidence indicates a gradual transition from fen to ombrotrophic bog around 4200 cal yr BP, followed by a shift from pine-dominated vegetation to dwarf-shrub communities, likely increasing landscape-fire susceptibility. Despite chronological uncertainties, this study provides the first integrated reconstruction of storminess and fire history from a Baltic Sea coastal peatland and highlights the role of recurrent natural disturbances in shaping long-term peatland development, ecological stability, and recovery capacity under varying hydroclimatic conditions.

### KEYWORDS

Baltic sea, Holocene, Latvia, charcoal, plant macrofossils, sand, peatland

## 1 Introduction

Significant climate changes are projected to intensify in the coming decades (Naumann et al., 2021; Xi et al., 2021; Calafat et al., 2022). The Baltic Sea region, and particularly its coastline, is highly sensitive to climate-related impacts such as sea-level rise, shoreline erosion, and sediment redistribution (BACC II Author Team, 2015; Barcikowska et al., 2018;

Martewicz et al., 2022; Weisse et al., 2021). The southeastern Baltic coast hosts a mosaic of ecosystems, including dunes, forests, peatlands, and lakes, which are shaped by complex interactions between climate, geomorphology, and sea-level change. Coastal peatlands in this region are relatively young landforms that developed in depressions isolated by dune accumulation and influenced by glacio-isostatic uplift and successive stages of Baltic Sea evolution (Kalińska et al., 2022; Kreuzburg et al., 2018; Rosentau et al., 2023). Their formation and persistence depend on interacting factors such as vegetation composition, hydrology, surface oxygen exposure, climate variability, fire, and human activity. These ecosystems develop where water supply exceeds evapotranspiration, promoting waterlogged conditions that favor organic matter accumulation. As raised bog peat can consist almost entirely of organic matter, any input of minerogenic matter or compositional variation may indicate environmental disturbances, including storm events or fires during peat accumulation (Mooney and Tinner, 2011; Vandel et al., 2019; Suursaar et al., 2015).

Fire activity is commonly reconstructed from particulate charcoal produced during incomplete combustion and preserved in peat and lake sediments (Harrison et al., 2022; Sim et al., 2023). In the Baltic region, however, peatland fire regimes remain relatively poorly studied, despite evidence from recent centuries demonstrating the ecological significance of large wildfires (Kitenberga et al., 2019). Understanding long-term fire dynamics in coastal peatlands is therefore essential for placing modern fire activity into a broader environmental context.

Wind-blown sand grains preserved within peat provide an independent proxy for reconstructing past storminess. A “storm” is generally defined as a wind event exceeding a critical velocity capable of causing damage or sediment transport, whereas “storminess” refers to the frequency or intensity of such events over longer timescales (Leszczyńska et al., 2024). In palaeoenvironmental archives, storminess is not resolved at the scale of individual storms but instead inferred from intervals of enhanced storm activity. Studies from Sweden, Estonia, and Scotland demonstrate that aeolian sand influx (ASI) recorded in peat reflects phases of stronger or more frequent storms (De Jong et al., 2006; Orme et al., 2016; Vandel et al., 2019). Grain-size distributions provide information on storm energy (e.g., >180 μm associated with stronger winds), while microscale surface features such as fresh fractures and angular grain morphologies offer additional evidence of high-energy transport processes (Costa et al., 2012).

Because coastal peatlands can archive both organic combustion products and minerogenic inputs, they are uniquely suited to investigating the interactions between multiple climate-driven disturbance regimes. In particular, peat records allow the co-evaluation of fire activity, inferred from charcoal accumulation, and storminess, inferred from aeolian sand influx and grain surface characteristics.

Storms and fires are both climate-driven disturbances that may occur independently, yet thunderstorms represent a potential link between them. Lightning provides a natural ignition source for fires, while strong storm winds mobilize sand and enhance aeolian transport. Consequently, periods of increased storminess and fire

activity may occasionally co-occur under atmospheric and hydroclimatic conditions, especially during relatively dry phases (Aakala et al., 2018; Kylander et al., 2020).

Holocene climate variability in the Baltic Sea region has been shaped by changes in large-scale atmospheric circulation, regional moisture balance, and land-sea interactions driven by ongoing glacio-isostatic uplift. Palaeoclimate reconstructions suggest that the Middle Holocene was characterized by relatively warm conditions and variable moisture availability, whereas the Late Holocene experienced increasing climatic variability, including shifts in storm frequency and hydroclimatic extremes (BACC II Author Team, 2015; Seppa et al., 2009; Warden et al., 2017).

Past fire activity in the Baltic region has primarily been reconstructed from charcoal records in lakes and peatlands, revealing strong links to vegetation composition, climate-driven moisture variability, and, during the Late Holocene, increasing human influence (Carcaillet et al., 2001; Feurdean et al., 2017; Kitenberga et al., 2019). In contrast, reconstructions of storminess largely rely on coastal dune systems, lake sediments, and aeolian sand influx preserved in peat deposits, reflecting periods of enhanced wind activity rather than individual storm events (De Jong et al., 2006; Orme et al., 2016; Vandel et al., 2019). Despite these advances, storminess and fire histories are usually examined separately, and integrated reconstructions from coastal peatlands remain rare. Consequently, the extent to which these disturbance regimes are temporally coupled or decoupled, and how they jointly influence development, is still poorly understood in the Baltic Sea region.

The aim of this study is to reconstruct Late Holocene disturbance dynamics in northwestern Latvia using a multi-proxy approach applied to a 330-cm peat sequence from Bog Bažu (hereafter Bog Bazu). Macroscopic charcoal is used to reconstruct fire history, sand grain counts and surface characteristics to infer episodes of enhanced storminess, and plant macrofossil to document local vegetation development and indirectly infer hydrological conditions. By analyzing these proxies together, we assess how storminess and fire activity, occurring both independently and with partial temporal overlap, have shaped peatland development over the past ~5400 years. To our knowledge, no previous peatland study in the Baltic region has explicitly examined storminess and fire histories in combination, underscoring the novelty of this approach. Sand grains preserved in peat are interpreted as indicators of enhanced storm activity, recognizing that not every storm leaves a sedimentary signal and that deposition integrates multiple events over decadal timescales. Our findings contribute to understanding long-term disturbance interactions in coastal peatlands, with implications for ecosystem resilience, natural hazard assessment, and conservation planning.

In palaeoecological research, the concept of an ecological threshold is commonly used to describe non-linear or stepwise ecosystem responses to gradual environmental change or episodic disturbances, rather than abrupt tipping points in a strict theoretical sense. Such thresholds may involve shifts in dominant vegetation types, hydrological regimes, or disturbance sensitivity once certain environmental conditions are exceeded (Willis et al., 2010; Jimenez-Zamora et al., 2024). In peatland systems, these responses are

typically expressed over decades to centuries and integrate multiple drivers, including climate variability, fire, and storm activity. In this study, ecological thresholds are used as a heuristic framework for interpreting major transitions in vegetation composition and disturbance regimes, while explicitly acknowledging the limitations imposed by proxy resolution and chronological uncertainty.

## 2 Materials and methods

### 2.1 Study area

Latvia has a 497-km-long Baltic Sea coastline that provides living space for approximately 0.9 million people, or ~45% of the country's population (Brunina et al., 2011; Lagzdiņa et al., 2017). Bog Bazu is in northwestern Latvia (Figure 1), within the coastal lowland of the Irves Plain. The coastline in this region is characterized by extensive dune fields composed of fine- to medium-grained sand, typical of much of the Latvian coast (e.g., Martewicz et al., 2022). Bog Bazu developed in inter-dune depressions isolated by coastal sand accumulation. Glacio-isostatic land uplift and alongshore sediment transport from south to north promoted the formation of successive dune ridges, leading to poorly drained conditions and elevated groundwater levels favorable for peat initiation. The underlying and surrounding Quaternary deposits consist mainly of marine and aeolian sands. The western margin of the bog is bordered by an ancient coastal barrier ridge, several kilometers long, up to 50 m wide, and 2–3 m high, oriented parallel to the former shoreline. Following marine regression and the formation of younger dune ridges, depressions between dunes became paludified and gradually infilled with peat. As peat accumulation progressed, the bog expanded laterally across adjacent depressions. Consequently, the elevation difference between the bog surface and surrounding dune crests reaches up to ~20 m, while peat thickness varies considerably, from 0.5 to 4 m over short distances (Pakalne and Kalnina, 2005). Bog Bazu is currently located within the Slitere National Park, a Natura 2000 protected area. Poor soil nutrient status and complex topography

limited historical agricultural use, and available records suggest that slash-and-burn practices were not widespread in this coastal landscape (Doniņa-Kalniņa et al., 2024).

Climatically, the area is influenced by prevailing westerly winds that transport moist maritime air masses from the Baltic Sea and the North Atlantic. Storm-force easterly winds can occur when cyclones pass through the Danish straits and southern Sweden, reaching the Latvia coast. The dominant wind direction is southwest-west to northeast-east (Dravniece, 2003). The mean annual temperature is +6.4 °C (−2.8 °C in February; +16.5 °C in July), and mean annual precipitation is 606 mm.

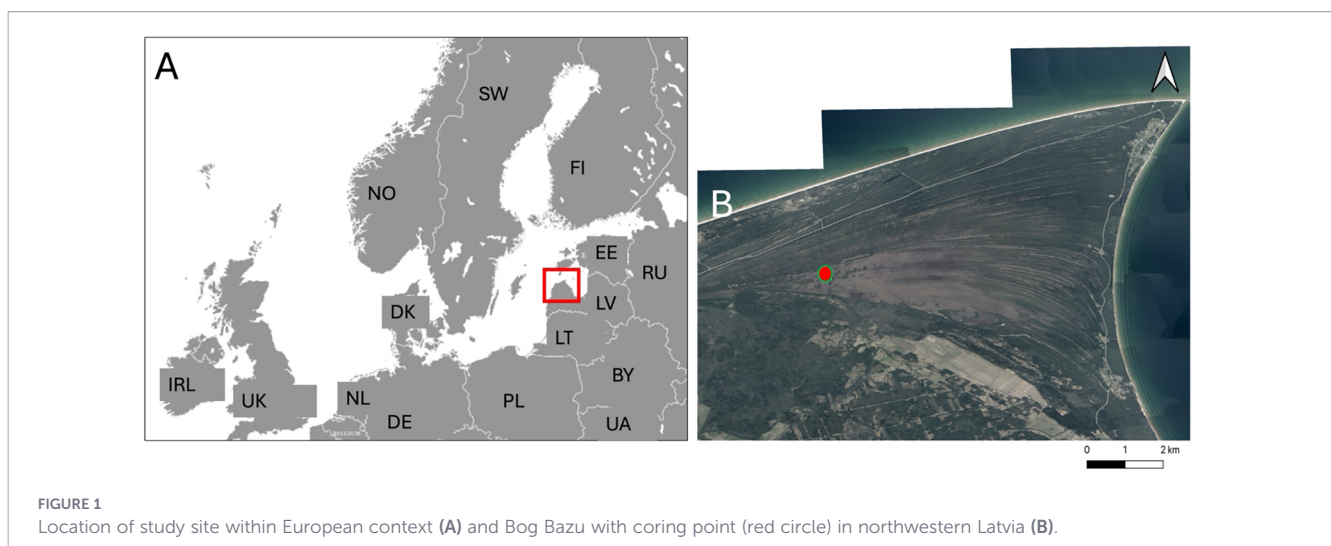
### 2.2 Fieldwork

Fieldwork was conducted in August 2019 in the western part of Bog Bazu (57°41'39.7"N 22°26'38.9"E), approximately 3 km inland from the Baltic Sea (Figure 1). Vegetation at the coring site was dominated by *Sphagnum* sp., *Calluna vulgaris*, *Vaccinium myrtillus*, *Vaccinium vitis-idaea*, *Empetrum nigrum*, *Pinus sylvestris*.

A 330-cm long peat sequence was recovered using a peat corer with a diameter of 7.5 cm. The uppermost 30 cm were carefully cut with a knife to preserve peat structure and density. The core was extracted in overlapping drives to ensure continuous sediment recovery. Stratigraphy was described in the field, photographed, wrapped, and subsequently stored horizontally in cold storage (5 °C) at the University of Latvia.

### 2.3 Chronology

The chronology of the peat sequence is based on six AMS <sup>14</sup>C dates measured at the Poznań Radiocarbon Laboratory (Poland). Only terrestrial plant macrofossils were selected for dating to minimize potential hard-water or old-carbon effects. Sampling and preparation followed established protocols for AMS radiocarbon dating of terrestrial plant macrofossils (Birks and Lotter, 2020). An age-depth model was constructed using the *rbacon* package (Blaauw and Christen, 2011) in R and calibrated with the IntCal20 calibration curve (Reimer et al., 2020). Peat accumulation rates were derived from the model output and used in subsequent analyses.



## 2.4 Plant macroscopic remains

Plant macrofossils were analyzed at contiguous 1-cm intervals throughout the sequence. Each 1 cm<sup>3</sup> subsample was washed and wet-sieved through a 0.25-mm mesh under warm water, and the retained material was examined under a stereomicroscope. Taxonomic identification followed standard reference works (Birks, 2007) and regional identification keys (Cappers et al., 2006; Katz et al., 1965, 1977; Mauquoy and van Geel, 2007). The resulting data provide information on local-scale vegetation composition and associated hydrological reconstructions.

Indicative mean annual precipitation ranges for selected taxa are presented in [Supplementary Table 1](#) to provide ecological context. However, it is emphasized that peatland plant distributions primarily reflect local hydrological conditions, particularly water-table depth, rather than regional precipitation alone.

## 2.5 Loss-on-ignition

Loss-on-ignition (LOI) analysis was conducted at 1-cm intervals throughout the peat sequence (n = 330). Subsamples of 1 cm<sup>3</sup> were dried at 105 °C for 12 h to determine moisture content, defined here as mass loss due to the removal of pore water prior to combustion. The dried samples were then combusted at 550 °C for 4 h to estimate organic matter content following standard procedures (Dean, 1974). Mineral content was calculated as the inorganic residue remaining after combustion and is assumed to be dominated by silicate material. Although oxidation of sulphur compounds can contribute to mass loss at intermediate temperatures, the analyzed sequence consists of low ash, ombrotrophic peat in which sulphur concentrations are typically low. Any contribution of sulphur oxidation to total mass loss is therefore considered negligible relative to organic matter combustion.

## 2.6 Fire-event reconstructions

Macroscopic charcoal (>160 µm) was analyzed at contiguous 1-cm resolution throughout the peat sequence. Subsamples (1 cm<sup>3</sup>) were treated with dilute NaOCl to bleach the peat and disaggregate organic matter prior to wet sieving through a 160 µm mesh (Constantine and Mooney, 2021). The retained residues were transferred to Petri dishes and counted under a stereomicroscope. Charcoal morphotypes were identified to infer fuel type and fire characteristics following established classification schemes (Courtney-Mustaphi and Pisaric, 2014; Feurdean, 2021; Feurdean et al., 2017). Individual charcoal particles were assigned to morphotype subcategories according to Courtney-Mustaphi and Pisaric (2014): A1 – A6: polygonal charcoal (fuel: wood, herbaceous material, leaves), B1 – B4: orthoangular polygons and polyhedral (blocky shaped) (fuel: wood, Poaceae leaves, grass), C3, C4 and C7: long and complex (fuel: conifer needles, twigs, roots, leaf stems and veins), D1 – D3: long and simple (fuel: leaves, wood), E1: spheroidal (fuel: seeds, sap, resin), F1: irregular (fuel: root masses), G1: glassy (fuel: resin, phytoliths).

Charcoal peak detection followed the approach of Higuera et al. (2009, 2010) using the CharAnalysis software. Charcoal counts were interpolated to the median temporal resolution (~15 years), smoothed with a 500-year LOWESS smoother, and decomposed into background and peak components. Noise thresholds were determined using a Gaussian mixture model, and peaks exceeding the 95<sup>th</sup> percentile were interpreted as fire episodes. Signal-to-noise index (SNI) values were calculated to assess the robustness of the charcoal record (Kelly et al., 2011). Fire frequencies were smoothed using a 1000-year moving window. To complement the sedimentary charcoal record, published fire-scar data from *Pinus sylvestris* at Bog Bazu was incorporated for the last few centuries (Kitenberga et al., 2019).

## 2.7 Storminess reconstruction

Sand grain content was analyzed from contiguous 1 cm<sup>3</sup> subsamples. Samples were combusted as part of the LOI pre-treatment, wet-sieved at a 160-µm mesh, and retained sand grains were counted under a stereomicroscope. This mesh size was selected as a compromise between excluding fine mineral contaminants and retaining grains relevant for high-energy aeolian transport (cf. Orme et al., 2016; Vandel et al., 2019).

Peak detection was performed using the *tapas* package in R (Finsinger and Bonnici, 2023). The sand-count time series were interpolated to ~15-year resolution, smoothed with a 1000-year moving average, and decomposed into background and peak components. A locally adaptive threshold separated background sand deposition from statistically significant peaks, interpreted as episodes of enhanced storminess. While CharAnalysis and *tapas* implement similar principles, *tapas* provide greater flexibility for non-charcoal proxies.

## 2.8 Sand grain surface analysis

To assess potential sand sources and transport energy, quartz grains were examined under a Zeiss Discovery V20 stereomicroscope (100–200x magnification) at Nicolaus Copernicus University, Toruń. Samples with >100 grains (20 samples) and one reference sample from a nearby coastal dune were analyzed. On average, ~100 grains were classified per sample. Grain shape and surface textures were categorized following Cailleux (1942) and Mycielska-Dowgiałło and Woronko (1998) into seven types (Table 1).

# 3 Results

## 3.1 Bog bazu evolution and characteristics

The basal part of the sequence (~330–280 cm) consists of fen peat, followed by a transitional peat layer (280–260 cm). Above this, the sequence is characterized by peat dominated by bog taxa, reflecting the progressive development of ombrotrophic conditions, while the establishment of a fully raised bog morphology likely occurred later in the sequence. Specifically,

TABLE 1 Quartz grain groups, distinguished according to Cailleux (1942) as three types listed in 'Full name' column, and as modified by Mycielska-Dowgiatto and Woronko (1998) in 'Grain description' and 'Environment' columns, while with no additional references.

Abbreviation	Full name (in French after Cailleux, 1942)	Grain description	Environment
NU	<i>non-usés</i>	non-abraded fresh grains with sharp grain edges	abrasion in glacial environment; frost weathering in periglacial environment (Woronko and Pisarska-Jamroz, 2016); damage in energetic subaqueous environment (Gutiérrez-Mas et al., 2003) marking a storm interval (Kalińska-Nartiša et al., 2017)
C	–	cracked grains with a significant degree of fragmentation	high-energy transport (Martewicz et al., 2025); effect of frost weathering (Woronko and Pisarska-Jamroz, 2016), and short-distance transport in non-glacial environment (Rose and Hart, 2008)
RM	<i>ronds-mats propres</i>	well-rounded grains with entirely matte surface	long-lasting abrasion in aeolian environment
EM/RM	–	partially-rounded grains with matte surface only on most convex parts	short abrasion in aeolian environment
EL	<i>émoussés-luisants</i>	well-rounded grains with entirely shiny surface	abrasion and solution in fluvial or beach environment, long sediment transportation
EM/EL	–	partially-rounded with shiny surface	abrasion and solution in fluvial or beach environment, short sediment transportation
O	–	others with silica precipitation or solution	solution and precipitation in periglacial environment or hot deserts

peat accumulation begins at a depth of 326 cm, marking the onset of peatland development at the site. No sharp lithological boundaries were observed, although variability in peat type and degree of decomposition suggests changing moisture conditions through time. A full description of lithology is available from Stivrins et al. (2025a).

The age-depth model (Figure 2), based on six AMS <sup>14</sup>C dates (Table 2), indicates continuous accumulation without hiatuses. The basal radiocarbon date was obtained from the lowermost peat layer. The basal age of the sequence is 5265–5530 cal yr BP, corresponding to peat initiation at ~5400 cal yr BP. The upper 3000 years are constrained by only two <sup>14</sup>C dates, resulting in greater chronological uncertainty in the upper profile. Mean peat accumulation rate was 0.06 cm yr<sup>-1</sup> (0.6 mm yr<sup>-1</sup>).

### 3.2 Plant macrofossils

Plant macrofossil assemblages (Figure 3) reflect a progressive transition from fen-dominated conditions to ombrotrophic bog development. Between 5400 and 4200 cal yr BP, aquatic and fen taxa (*Chara* sp., *Alisma plantago aquatica*, *Myriophyllum* sp., and *Phragmites australis*) dominate, indicating persistently high water-table conditions. After ~4200 cal yr BP, typical bog taxa appear, including *Sphagnum* sp., *Eriophorum vaginatum*, *Scheuchzeria palustris*, *Juncus* sp., *Andromeda polifolia*, *Vaccinium oxycoccus*, *Empetrum nigrum*, *Calluna vulgaris*, *Ledum palustre* and other Ericaceae, reflecting the development of ombrotrophic conditions. Tree macrofossils are present through much of the sequence but vary markedly in abundance and taxonomic composition. *Pinus sylvestris* ramins are most abundant between 5400 and 3500 cal yr BP, *Alnus glutinosa* occurs mainly between 4300 and 4000 cal yr BP, while *Betula* sp. is recorded between 4550–4000 and again between 3500–2750 cal yr BP. After ~2750 cal yr BP, tree macrofossils become rare, indicating reduced local tree presence near the coring site.

Loss-on-ignition (LOI) values indicate that organic matter content is generally high throughout the sequence, ranging from 93 to 100%. Markedly lower values (<50%) were recorded in six isolated single-sample intervals at approximately 5000, 4000, 3250,

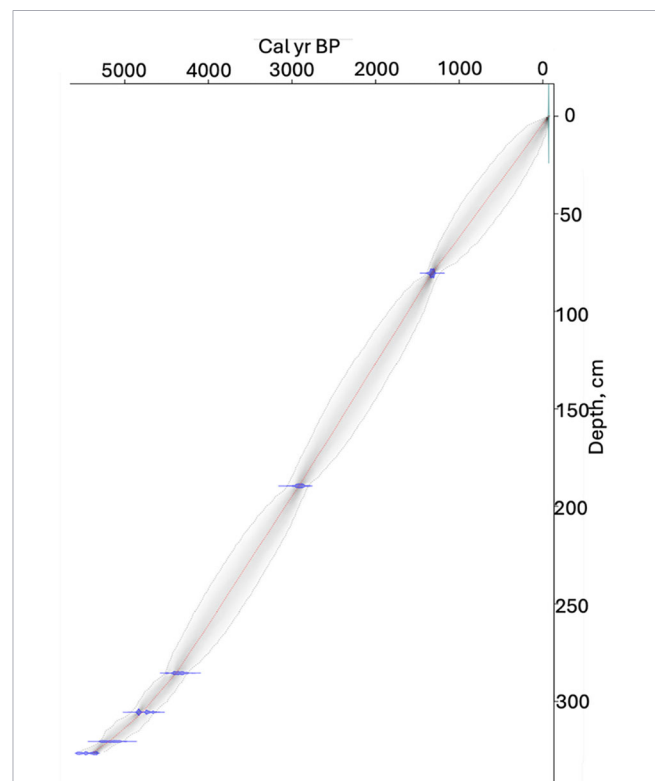
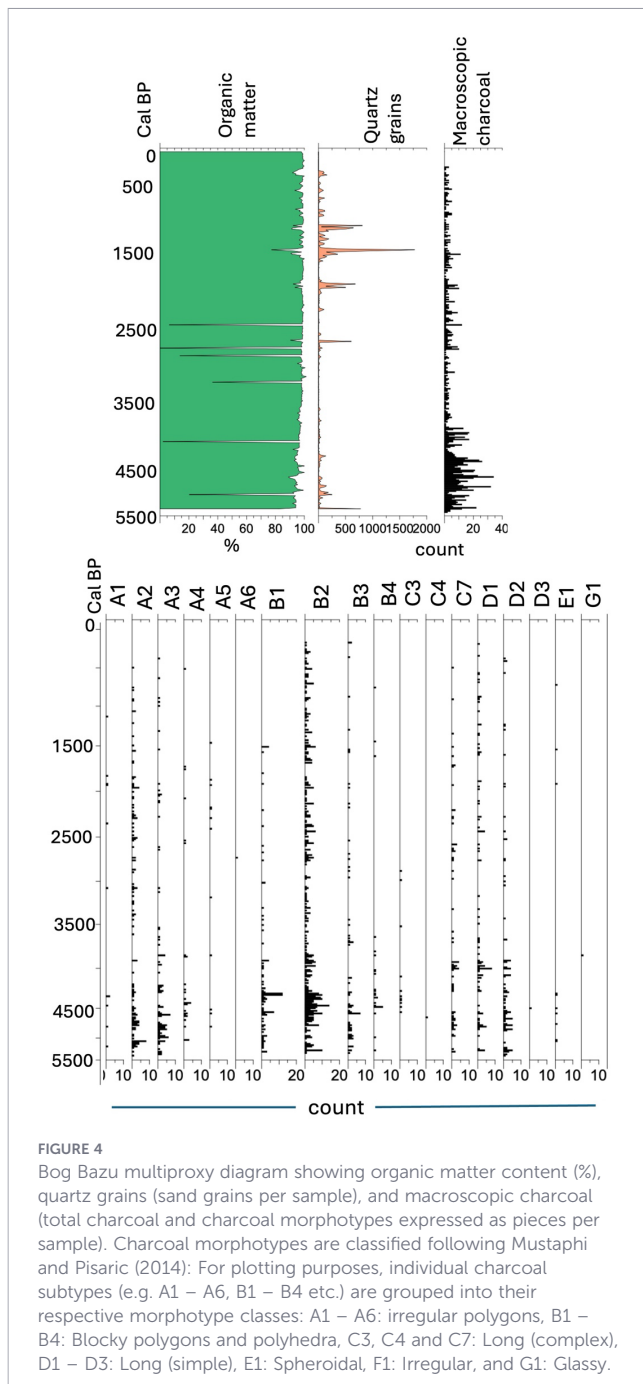


FIGURE 2 Age-depth model of Bog Bazu, showing calibrated ages, accumulation rates, and uncertainty envelopes. The age-depth model is based on <sup>14</sup>C AMS (blue) dates. Finely dotted red line shows the weighted mean ages for all depths, and greyscale show uncertainties (darker grey indicates more certain section). X axis (top) represents calibrated years (cal yr BP). Y axis (right) represents sediment depth expressed in cm.





30 statistically significant fire peaks were detected (Figure 5). The mean fire return interval (FRI) was 170 years, ranging from 129 to 230 years. Higher fire frequencies (6–8 fires per 1000 years) occurred between 4500–3900 and 3000–800 cal yr BP. Lower frequencies (2–4 fires per 1000 years) occurred between 5400–4500 cal yr BP. The SNI values were consistently above the recommended threshold (SNI 3) for most of the sequence, indicating that the charcoal peak record is statistically robust. For intervals where the SNI approached or fell below this threshold, we noted this and interpret fire episodes from these sections with caution. Charcoal morphotype analysis indicates that blocky types (B2, B3), associated with woody fuels, were dominant, while morphotypes A and D were also sporadically present (Figure 6).

The dendrochronological reconstruction spanning AD 1558–2014 identified 62 individual fire years with a mean point-scale fire return interval of 46 years (Kitenberga et al., 2019). The shortest observed interval was six years, while the fire cycle length varied between 45 and 80 years depending on the period. Fire activity was higher between 1750 and 1950, coinciding with widespread use of slash-and-burn agriculture, and declined markedly after 1960, reflecting changes in land use and fire suppression policies. Despite this decline, a major fire in 1992 burned more than 3000 ha, including over 1000 ha of forest. The fire-scar data thus confirm the recurrent nature of fires in the coastal dune-bog landscape and provide a higher resolution context for the peat-based charcoal record.

### 3.4 Episodes of enhanced storminess reconstruction

Sand grains were identified throughout the peat profile, with marked variability in concentrations. In total, 47 statistically significant peaks of sand influx were detected, corresponding to episodes of enhanced storminess (Figure 6). The mean return interval was 145 years, ranging from 30 to 345 years. Distinct peaks occurred around 5000–4700, 2665, 1950, at 1500–1110 and 310 cal yr BP. Between 1500 and 310 cal yr BP, sand deposition was consistently high, with frequent peaks.

Quartz grain surface analysis shows that cracked grains (C-type) were dominant during periods of elevated sand input, reaching up to 82% of the assemblage at ~5300, 5000–4600, 1110, and 310 cal yr BP. Slightly lower values (72–78%) occurred at ~4700–4600 cal yr BP and at multiple intervals during the past two millennia (~1900, 1500, 1300, 330, 290 cal yr BP). Periods of increased sand input were also characterized by a higher proportion of aeolian grains (EM/RM, up to 25%) and fluvial grains (EM/EL, up to 27%). The dune reference sample contained 57% cracked grains and ~40% fluvial grains, with no aeolian types.

## 4 Discussion

### 4.1 Storms, fires, and their potential interactions

Understanding interactions between storminess and fire in peatland ecosystems is challenging because both disturbances can operate independently or occasionally co-occur under shared atmospheric drivers (Senf and Seidl, 2021; Ibanez et al., 2022). Our results indicate that over the past ~5400 years, northwestern Latvia experienced at least 47 episodes of enhanced storminess and 30 fire episodes (Figure 6). Sixteen instances of partial temporal overlap between storminess and fire peaks were identified at approximately 5370, 4750, 4600, 4300, 2960, 2770, 2580, 1960, 1510, 1315, 1150, 1110, 950, 730, 550 and 330 cal BP. Such overlaps are consistent with thunderstorms producing both lightning, which can act as an ignition source for fires, and strong winds capable of mobilizing sand, as observed in modern boreal and temperate regions (Krawchuk et al., 2009; Veraverbeke et al., 2017; Dowdy, 2020).

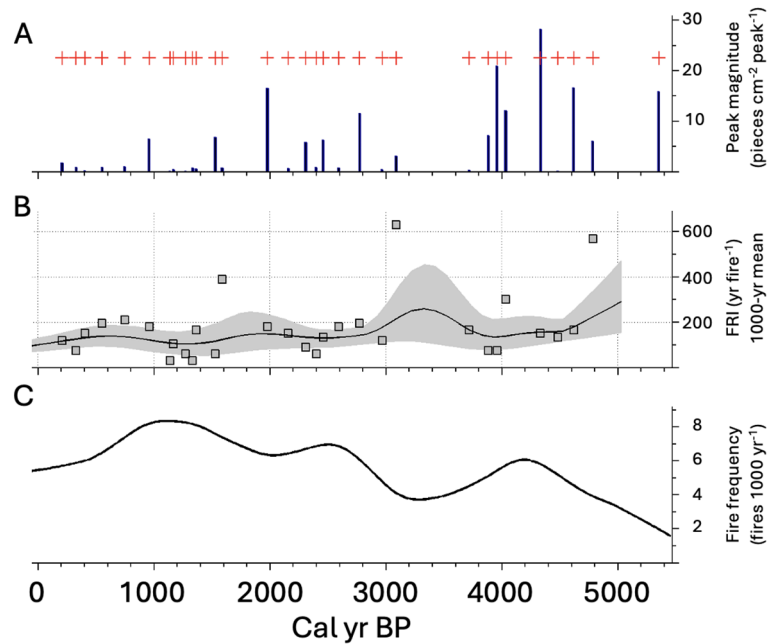


FIGURE 5

Fire event reconstruction results from Bog Bazu based on macroscopic charcoal analysis. From the top: (A) fire peak magnitude (solid bars) and significant fire events (red crosses), (B) fire return interval (FRI) expressed as moving average per 1000-year windows, and (C) fire frequency (expressed as moving average per 1000-year windows).

However, limitations in temporal resolution and age-depth uncertainty restrict our ability to resolve short-lived storm and fire events and to assess their precise synchrony, even though all proxies derive from the same sedimentary archive. These overlaps should therefore be interpreted as indicative rather than definitive, in line with previous palaeoecological studies that emphasize the difficulty of distinguishing between lightning- and human-ignited fires in sediment records (Carcaillet et al., 2002; Power et al., 2008).

The geomorphological setting of Bog Bazu likely plays an important role in facilitating such apparent overlaps. The bog is situated close to the Baltic Sea coast and adjacent dune systems, making it particularly exposed to strong winds during storm events. Under relatively dry conditions, this exposure may enhance surface drying of peat, increase fire susceptibility, while simultaneously promote aeolian sand transport onto the bog surface. In this context, episodes of enhanced storminess and fire activity may co-occur not because storms directly cause fires in all cases, but because local geomorphology and hydroclimatic conditions favor the preservation of both signals within the peat archive.

## 4.2 Storminess reconstruction and its limitations

In this study, sand grain influx was used as a proxy for episodes of enhanced storminess, following approaches applied in Sweden, Estonia, and Scotland (De Jong et al., 2006; Orme et al., 2016; Vandel et al., 2019). Comparable methods have been applied in Newfoundland and other North Atlantic coastal settings, where mineral grain influx reflects periods of stronger or more frequent storm activity (Pleskot et al., 2023). The statistically significant peaks identified here represent intervals of unusually high sand

input rather than individual storm events. We do not assume that every storm resulted in detectable deposition, nor that sand accumulation scales linearly with storm frequency or intensity.

Transport of sand grains  $>160\ \mu\text{m}$  from coastal dunes to the Bog Bazu site ( $\sim 3\ \text{km}$  inland) would have required strong winds, likely exceeding Beaufort force 8 ( $>62\ \text{km h}^{-1}$ ) based on modern transport thresholds (Liu et al., 2023; Sherman and Li, 2012). The predominance of cracked quartz grains (C-type) exceeding 80% during major peaks, supports deposition under high-energy transport conditions (Costa et al., 2012). Lower proportions of cracked grains likely reflect weaker storm phases. Alternative explanations must nevertheless be considered. Niveo-aeolian processes may transport sand during winter without direct association with storm winds (Woronko and Pisarska-Jamroz, 2016). In addition, even limited human activity could have locally increased sediment availability, particularly during the last two millennia when sand influx remained elevated. These factors underline the need for cautious interpretation, as emphasized in other coastal storm reconstructions (Dawson et al., 2004; Hansom and Hall, 2009).

Chronological uncertainty further limits interpretation. With only two  $^{14}\text{C}$  dates constraining the last  $\sim 3000$  years, correlations with other regional storm records should be treated cautiously. Although broad agreement exists with storm phases identified in Estonia (Vaasma et al., 2025), southern Sweden (Björck and Clemmensen, 2004; Kylander et al., 2023), and Poland (Leszczyńska et al., 2022, 2024), precise event-level synchrony cannot be demonstrated. This limitation is common to palaeostorm records and highlights the importance of improved chronological control in future studies (Sorrel et al., 2012).

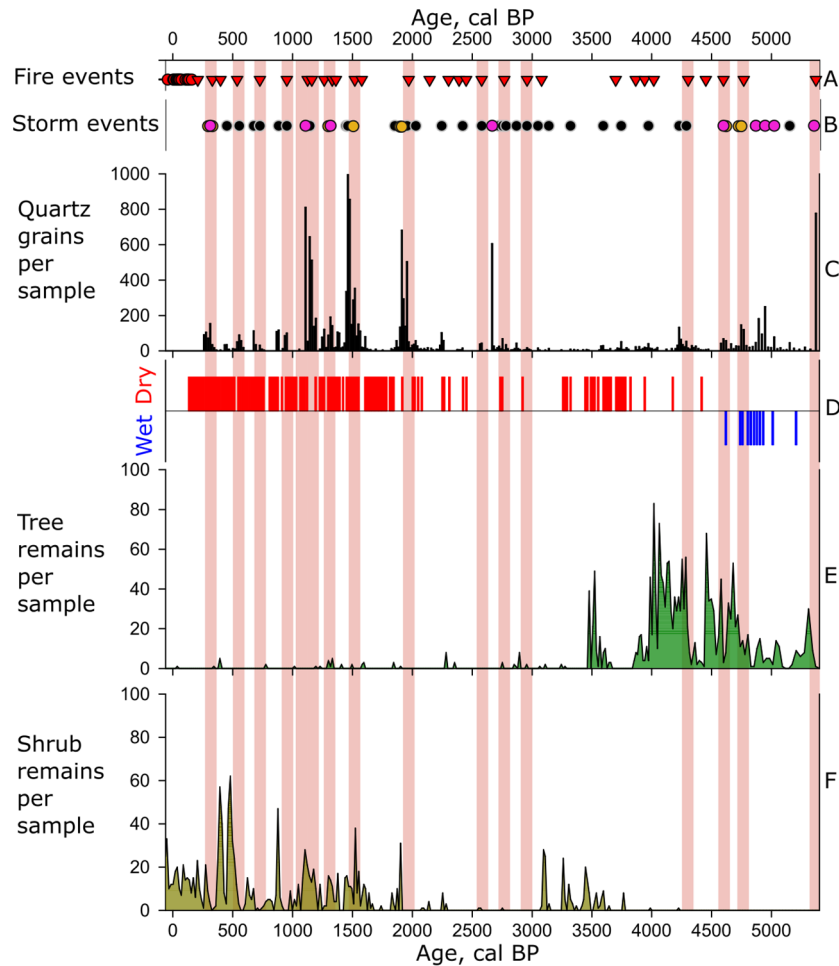


FIGURE 6

Selection of variables studies in current study from Bog Bazu (from the top): A – Fire events (based on 160  $\mu\text{m}$  macroscopic charcoal and tree fire-scar data), B episodes of enhanced storminess (based on quartz grain data; pink – strong, orange – average, black – undefined strength), C – Quartz grains per sample, D – dry/wet conditions (based on plant macrofossil data), E – tree (*Pinus sylvestris*) and F – shrub (*Vaccinium oxycoccus*, *Empetrum nigrum*, *Calluna vulgaris*, *Ledum palustre* and *Ericaceae*) remains per sample.

### 4.3 Regional patterns

The Bog Bazu record indicates stormier phases around 5300, 5020–4600, 2665, 1950, 1320, and 1100 cal yr BP, broadly corresponding to phases S4, S8 and S10a identified in Estonian records (Vaasma et al., 2025). A distinct storminess episode around 5280 cal yr BP may be coeval with sand layers dated to 5315–5085 cal yr BP in Scottish coastal peats (Kylander et al., 2020). Periods of weaker storm activity (e.g. ~4750, 1900, 290 cal yr BP) were less consistently recorded in neighboring archives, except for a weaker storm event at around 1440 yr BP in the Gulf of Riga (Kalińska et al., 2024) corresponding to period of around 1500 cal yr BP. This variability likely reflects spatial heterogeneity in storm impacts across the eastern Baltic region, driven by shifts in cyclone trajectories and changes in North Atlantic atmospheric circulation (Sepp et al., 2018; Wolski and Wisniewski, 2021; Kautz et al., 2022). At longer timescales, stormier phases at Bog Bazu coincide with broader North Atlantic circulation changes linked to declining summer insolation and enhanced moisture transport during the Late Holocene (Seppä et al., 2005; Muschitiello et al., 2013).

Agreement with regional records supports the interpretation that Bog Bazu peat preserves a robust signal of Baltic coastal storminess.

### 4.4 Hydroclimatic controls on fire activity

Bog Bazu initiated around 5400 cal yr BP, consistent with the timing of peatland development at other coastal sites around the Gulf of Riga (Stivrins et al., 2025b). Although lower temperatures and reduced evapotranspiration during the Late Holocene likely favored peat accumulation, yet our plant macrofossil data indicate persistently dry surface conditions (Figure 6). Mean peat accumulation rates of 0.6–0.7  $\text{mm yr}^{-1}$  are consistent with relatively dry ombrotrophic bog conditions. It should be noted that plant macrofossil assemblages integrate environmental conditions over longer timescales and may mute short-term hydrological variability (Valiranta et al., 2012). Testate amoebae-based water-table reconstructions would provide more sensitive insights into hydrological dynamics (Booth, 2010; Marcisz et al., 2014). Combined proxy approaches would yield a more comprehensive understanding of peatland hydrology at Bog Bazu.

Charcoal evidence indicates recurrent fire activity throughout the sequence, with highest charcoal influx between 5400 and 3800 cal yr BP, coinciding with pine-dominated vegetation (Figure 3). In total, 30 fire peaks were identified, yielding a mean fire return interval (FRI) of ~170 years. Fire frequency was highest between 4500–3900 and 3000–800 cal yr BP (6–8 fires per 1000 years) and lowest between 5400–4500 cal yr BP (2–4 fires per 1000 years). Dominance of woody charcoal morphotypes (B2, B3) indicates burning of trees and shrubs, while morphotypes A and D reflect contributions from finer fuels (Figure 3).

Vegetation change appears to have influenced fire regimes. Around 3500 cal yr BP, *Pinus sylvestris* declined locally while shrubs (*Calluna vulgaris*, *Empetrum nigrum*, *Ledum palustre*) expanded. These shrubs provide fine, volatile-rich fuels that burn readily under dry conditions, with *Calluna* stands supporting rapid fire spread and high fire intensity (Davies et al., 2009; Grau-Andres et al., 2018). This shift likely lowered fuel-moisture thresholds for sustained surface fires and increased the likelihood of frequent, fast-moving burns. Fire-scar data from *Pinus sylvestris* at Bog Bazu (Kitenberga et al., 2019) indicate shorter fire intervals during the historical period, reflecting vegetation-fire feedback and potentially increased human-induced ignition. Modern meteorological observations confirm frequent thunderstorms activity in the region (Rutka, 2010), supporting the plausibility of natural lightning ignitions.

Human activity provides additional context for interpreting Middle and Late Holocene disturbance regimes. Archaeological and palaeoecological evidence suggests low population densities and limited land use during much of the Middle Holocene, implying predominantly climate-driven fire activity. From the Late Holocene onward, increasing human presence, forest clearance, and land-use practices may have locally influenced vegetation structure and fire occurrence during dry phases. However, at Bog Bazu, the absence of strong anthropogenic indicators and the dominance of climate- and storm-related proxies suggest that natural drivers remained the primary controls on disturbance dynamics, with human influence likely secondary and spatially limited (Kitenberga et al., 2019; Feurdean et al., 2017).

#### 4.5 Limitations and implications

Several limitations must be acknowledged. Chronological control is limited by only six  $^{14}\text{C}$  dates, with the last three millennia constrained by just two ages, increasing uncertainty in the upper part of the age-depth model. This particularly affects interpretation of sedimentary charcoal records, as the absence or scarcity of macroscopic charcoal does not necessarily indicate an absence of fire activity. Charcoal production, transport, and preservation depend on fire intensity, fuel type, and post-depositional processes, and near-surface layers are prone to oxidation and taphonomic loss. Tree-ring fire-scar records provide an important complementary archive by capturing low-intensity fires that are often underrepresented in sedimentary records (e.g., Whitlock and Larsen, 2001).

Second, the temporal resolution of the peat record is insufficient to resolve individual storms or fires, meaning that apparent overlaps between storminess and fire peaks may reflect coincidence rather

than true synchrony. Higher-resolution archives, such as varved lake sediments or annually resolved tree-ring records, would be required to rigorously test storm–fire linkages.

Third, interpretation of sand influx as a storminess proxy requires a caution. Peaks most likely represent intervals of enhanced storm activity rather than individual events, and additional processes, including niveo-aeolian transport or limited anthropogenic disturbance, may have contributed to sand deposition. Vegetation-based proxies are unlikely to resolve short-lived storm–fire interactions, as macrofossil assemblages integrate long-term ecological change.

Despite these limitations, the Bog Bazu sequence provides the first integrated reconstruction of storminess and fire history from a Latvian coastal peatland. By combining charcoal, sand-grain evidence, and plant macrofossils, this study offers new insights into long-term disturbance regimes and highlights the value of multi-proxy approaches for understanding coastal peatland resilience and natural hazard dynamic under changing climatic conditions.

## 5 Conclusion

This study presents the first multi-proxy reconstruction of Late Holocene disturbance history from a coastal peatland in northwestern Latvia. By analyzing macroscopic charcoal, sand grains, quartz grain surface features, and plant macrofossils from Bog Bazu, we reconstructed long-term fire regimes, episodes of enhanced storminess, and local hydrological conditions over the last ~5400 years. Bog Bazu initiated as a fen around 5400 cal yr BP and subsequently transitioned to an ombrotrophic raised bog. Peat accumulation rates were relatively low, and plant macrofossil evidence indicates persistently dry surface conditions despite generally cool and moist regional climate trends. These conditions favored recurrent fire activity, reflected by 30 significant charcoal peaks a mean fire return interval of ~170 years. Fire activity was particularly pronounced during periods dominated by *Pinus sylvestris* and, later, by flammable Ericaceous shrub communities. Sand grain analyses reveal 47 statistically significant influx peaks interpreted as episodes of enhanced storminess. The dominance of cracked quartz grains during major peaks indicates deposition under high-energy conditions. Although storminess and fire peaks occasionally overlap, chronological uncertainty and sampling resolution limit our ability to determine whether these overlaps represent true synchronous events or broader periods of increased disturbance activity. The Bog Bazu record demonstrates that recurrent storms and fires have played an important role in shaping peatland development and resilience over millennial timescales. This integrated perspective highlights the value of coastal peatlands as archives of interacting disturbance regimes and provides a long-term context for assessing ecosystem responses to future hydroclimatic variability.

## Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession

number(s) can be found below: <https://data.mendeley.com/datasets/s2mkc6k2y8/1>.

## Author contributions

NS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft. AC: Investigation, Methodology, Resources, Writing – review & editing. MK: Formal analysis, Methodology, Resources, Validation, Writing – review & editing, Funding acquisition. EK: Formal analysis, Investigation, Methodology, Writing – review & editing. AM: Formal analysis, Investigation, Resources, Writing – review & editing. AF: Formal analysis, Investigation, Writing – review & editing. SV: Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Writing – original draft.

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## Supplementary material

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