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Key Points:

- Temporal shifts in environmental stressors cause spatially explicit system feedbacks that define ecosystem resilience to change
- Layers of peatland ecosystem complexity reduce thermal hot spot intensity
- Novel application of Fiber-Optic Distributed Temperature Sensing gives soil-surface temperatures at unprecedented spatiotemporal resolution

Supporting Information:

- Supporting Information S1
- Movie S1
- Movie S2
- Movie S3

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Disturbance Impacts on Thermal Hot Spots and Hot Moments at the Peatland-Atmosphere Interface

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Abstract Soil-surface temperature acts as a master variable driving nonlinear terrestrial ecohydrological, biogeochemical, and micrometeorological processes, inducing short-lived or spatially isolated extremes across heterogeneous landscape surfaces. However, subcanopy soil-surface temperatures have been, to date, characterized through isolated, spatially discrete measurements. Using spatially complex forested northern peatlands as an exemplar ecosystem, we explore the high-resolution spatiotemporal thermal behavior of this critical interface and its response to disturbances by using Fiber-Optic Distributed Temperature Sensing. Soil-surface thermal patterning was identified from 1.9 million temperature measurements under *undisturbed*, *trees removed* and *vascular subcanopy removed* conditions. Removing layers of the structurally diverse vegetation canopy not only increased mean temperatures but it shifted the spatial and temporal distribution, range, and longevity of thermal hot spots and hot moments. We argue that linking hot spots and/or hot moments with spatially variable ecosystem processes and feedbacks is key for predicting ecosystem function and resilience.

Plain Language Summary Peatlands cover 3% of the Earth's surface but hold more carbon than the world's forests. Surface temperatures are a key control over many important peatland processes such as carbon storage and release. While peatland function and their response to disturbances has traditionally been examined as uniform, spatially isolated systems, peatland processes occur in a spatially complex and interconnected manner. New technology enables us to explore these fine-scale behaviors, examining near-surface temperatures spatially across a peatland. Temperatures were measured high spatial and temporal resolution in an undisturbed ecosystem, and subsequently repeated after the trees canopy was removed, and after the shrubs and grasses were cut and removed. We effectively removed layers of the ecosystem, reducing the complexity of the system. Results showed that average temperatures increased with removal of vegetation layers as expected. However, importantly, this temperature increase was uneven across the peatland surface and did not reflect predisturbance temperature patterns. We relate this system response to ecosystem layers and system complexity. As more layers are removed (e.g., shrub layer, and tree layer), the intensity of thermal hot spots increases. This has important implications for understanding ecosystem resilience and for predicting carbon storage ability of soils.

1. Introduction

Soil-surface temperature acts as a “biocontroller” (Buchan, 2011) of terrestrial ecohydrological, biogeochemical (Jiménez et al., 2007) and micrometeorological (Johnson-Maynard et al., 2001) processes, regulating carbon storage and release (Kirschbaum, 1995; Taggart et al., 2011), water use efficiency (Stout, 1992), metabolic processes (Dijkstra et al., 2011), and species competition (Brand, 1990). Temperatures at the pedosphere-atmosphere interface control ecosystem functioning, determining the rate and direction of energy and mass exchange with the atmosphere (e.g., carbon and water fluxes), and act as the driving force of subsurface thermal dynamics (Kettridge et al., 2013; Wullschlegel et al., 1991) and associated biogeochemical processes. Despite this, there remains a critical gap in our understanding of how thermally driven processes vary both spatially and temporally across complex, heterogeneous or self-organized landscapes. This constrains our ability to accurately characterize the system function, resilience, and service provisions of complex ecosystems and project their response to disturbance.

Accurate, spatially explicit characterization of spatiotemporal thermal dynamics at the soil-atmosphere interface will likely yield important new process understanding (Hrachowitz et al., 2013; Krause et al., 2015). Moreover, it will also allow the determination of how a landscape disturbance, such as canopy removal, produces nonuniform amplification or dampening of local-scale thermal variability, and redistribution of thermal patterning in both space and time. The detection of thermal hot spots and hot moments (i.e., hot spots that do not fully persist though time) will provide insight into the location, frequency, and duration of areas where shifts in ecohydrological, biogeochemical (Jiménez et al., 2007), and micrometeorological (Johnson-Maynard et al., 2001) processes occur. These hot spots/hot moments may not only stress a system but may result in tipping points in ecosystem processes. That is, moments when critical thresholds are reached or surpassed irregularly across spatially diverse thermal landscapes may influence ecosystem resilience to perturbations. Examples of such critical thresholds and nonlinearity are numerous, from crops, where yield declines for corn, soybeans, and cotton past a defined threshold are greater than the yield increase approaching that temperature (Schlenker & Roberts, 2009), to changes in biogeochemical cycles as a result of shifts in soil bacterial populations (Biederbeck & Campbell, 1973; Zogg et al., 1997) (e.g., soil NO_3^- -N concentration, gross mineralization, and nitrification rates rapidly increase when soil temperatures increase from 2, 5 or 10°C to 15°C (Cookson et al., 2002)).

Applying high spatiotemporal resolution soil-temperature surveys to understand the temperature complexities at the interface have been limited by technological constraints until recently. Soil-temperature measurements within vegetated ecosystems have been restricted to small sample numbers (Morecroft et al., 1998) as a result of cost and logistical constraints (Krause et al., 2011; Webb et al., 2008) such as data storage (Kang et al., 2000), power, and time limitations. However, technological advances in the form of Fiber-Optic Distributed Temperature Sensing (FO-DTS) now enables extensive, high frequency and resolution, thermal measurements at the decimeter scale (Tyler et al., 2009), allowing exploration of interface thermal processes within vegetated ecosystems at unprecedented spatiotemporal scales and resolutions. This offers the opportunity to advance our understanding of dynamic interface processes that are vital for understanding how ecosystems function as a whole, and how those functions change in response to disturbance stresses (Krause et al., 2015; Scheffer et al., 2001).

This study pioneers the application of high-resolution FO-DTS monitoring for characterizing thermal patterns at the pedosphere-atmosphere interface of one of the most important and complex ecosystem interface types: carbon-rich northern peatlands (Belyea & Baird, 2006; Belyea & Clymo, 2001). The high-resolution data acquisition that may be acquired by the FO-DTS allows identification of thermal hot spots and hot moments and, for the first time, allows assessment of their response to vegetation removal at an appropriate scale and resolution. Peatland soil temperatures provide a strong control on the pedosphere-atmosphere interface and ecosystem functions, regulating the cycling of carbon (Dunfield et al., 1993) and hydrological fluxes (Blok et al., 2011; Kettridge & Waddington, 2014). These peatland systems have distinctively complex surfaces, characterized by a mosaic of hummock and hollow features (spatial scale of $\sim 10^1$ – 10^2 m²; Belyea & Clymo, 2001). This visible structural heterogeneity reflects the spatial heterogeneity observed in surface processes. For example, methane fluxes, for which temperature is a key driver, are more variable across a few meters than between peatland systems or regions (Moore et al., 1998) and respiration may vary significantly between microsites (Juszczak et al., 2013). Despite being long-term carbon stores, holding 25% of the world's soil carbon (Turunen et al., 2002), peatland ecosystems are greatly affected by multiple disturbances (Harden et al., 2000), which likely exert a strong influence on surface temperature and associated processes. For example, tree-canopy removal for linear seismic lines (Timoney & Lee, 2001), for thinning, and from insect infestations (Aukema et al., 2008), will influence surface temperatures because forest canopies induce variability in the transmission of incoming solar radiation to the ground due to variations in structure, height, and density across spatial scales (Hardy et al., 2004). The spatial patterns in thermal shielding by vegetation also interact with other controls on ground temperatures, such as climate and small-scale distributions in geomorphological, hydrological, thermal and aerodynamic properties (Al-Kayssi, 2002; Folwell et al., 2015; Peters-Lidard et al., 1998).

By utilizing FO-DTS technology to measure soil-surface temperatures at high spatiotemporal resolution in a highly patterned, forested peatland, we determine (i) the spatiotemporal variability in peat-surface temperatures and the magnitude and persistence of associated thermal hot spots and (ii) the thermal response to

tree-canopy removal and lower vascular vegetation removal how such changes are spatially and temporally distributed and whether the distribution, intensity, and duration of thermal hot spots and hot moments changes in response to disturbance.

2. Materials and Methods

2.1. Study Site

The study was conducted in a poor fen peatland in central Alberta, Canada (55.8°N, 115.1°W). The site was last burned in ~1935 and has a tree cover of black spruce (*Picea mariana*) with a basal area of 11 m² ha⁻¹ and mean height of 2.3 m (Kettridge et al., 2012), characteristic of boreal peatland ecosystems (Wieder et al., 2009). The site is characterized by a surface microtopography of *Sphagnum fuscum* hummocks and *S. angustifolium* hollows. In addition, there are considerable areas, primarily under areas of dense black spruce tree cover, where the surface is composed of feather mosses (e.g., *Pleurozium schreberi*) and bare peat surfaces. Subcanopy vascular vegetation consists of *Rhododendron groenlandicum*, *Rubus chamaemorus*, *Chamaedaphne calyculata*, *Maianthemum trifolium*, and *Vaccinium* spp.

2.2. FO-DTS Monitoring and Field Manipulations

Temperatures at the pedosphere-atmosphere interface were measured using a Silixa Ltd. XT Fiber-Optic Distributed Temperature Sensing (FO-DTS) system. FO-DTS determines the temperature along a fiber-optic cable by analyzing the Raman backscatter (inelastic collisions, and the thermal excitation of electrons) of a laser pulse propagating through a glass fiber. Raman backscatter causes a shift in the return energy level below (Stokes band) or above (anti-Stokes band) the Rayleigh scatter band (the return of backscatter at the original laser pulse frequency). The resultant Stokes/anti-Stokes output ratio is used to determine temperature. For a detailed overview of the FO-DTS, measurement approach, its capabilities, limitations, and methodological challenges, the reader is directed to a number of recent reviews including Krause et al. (2012), Krause and Blume (2013), Selker et al. (2006), and Tyler et al. (2009).

A gel-coated fiber-optic (FO) cable was installed at 0.02 m depth below the surface at the study site in May 2015. This depth of 0.02 m allowed measurements of peat/moss temperature in close proximity of the peat surface whilst avoiding solar radiation directly heating of the cable. The cable was installed carefully at a depth of 0.02 m by cutting the peat/moss with scissors and enabling the moss to expand back around the cable. While the impact of this installation approach is considered minimal (see photos of cable installation in supporting information Figures S4–S6), limited disturbance to the peat structure should be borne in mind. The maximum likely range in temperature as a result of variations in burial depth of ± 0.015 m is predicted to be between ± 3.2 and 5.9°C (Table S1). A full uncertainty analysis on the impact of a 0.015 m deviation in burial depth is presented in section S1 in the supporting information (Kettridge & Baird, 2007, 2008).

The experimental setup comprised a sequence of eleven 10 m long rows spaced 1 m apart (Figure S3). Two additional control rows were deployed to extend the measurement array 10 m to the north and 10 m to the west of the primary measurement plot. Due to the undulating surface (up to 0.41 m topographic variation), the actual cable length varied from the 10 m plan view length, resulting in a total of 121 m of cable being buried in the main plot and 22.8 m in the control rows. FO-DTS surveys were conducted in alternate single-ended monitoring mode, with calibration carried out using temperature matching to thermally controlled water baths at both ends of the monitoring cable (Krause & Blume, 2013; Tyler et al., 2009). Within these control baths, sections of FO cable (> 20 times the sampling interval) were maintained at a constant temperature throughout the experiment. FO-DTS temperatures were calibrated to thermistor measurements of the bath temperature to account for potential drift caused by differential loss along the cable length.

Measurements were obtained at a 0.25 m interval along the length of the FO cable, averaged over 1 min intervals. Surveys were run for 4 days under premanipulation conditions on 21, 22, 24, and 26 May 2015. All trees in the plot and within a 10 m buffer around the plot were cut and removed on 27 May 2015, and FO-DTS monitoring was repeated on 30 May 2015 (felled: trees removed). Trees were not disturbed around the two extended sections of cable to the north and west, thus providing a reference (control) for temperatures measured within the primary plot. All remaining vascular vegetation was removed from the primary plot on 31 May 2015 and FO-DTS measurements of surface temperatures taken subsequently on 3 June 2015 (cleared: tree and vascular vegetation removed). For all treatments, FO-DTS monitoring was carried

out between 06:30 and 20:30 local standard time. Weather conditions during the experiment periods were characterized by hot, dry, largely cloud-free conditions, with maximum air temperatures ranging from 25 to 28°C (Table S1). No rain fell during the experimental period, except on 31 May and 1 June, between the felled and cleared treatment periods, a small rain event of 13 mm was recorded. Rain-free periods and high surface temperatures subsequently resumed prior to the cleared temperature measurements.

Due to undulations in the peat surface and shallow tree roots, small sections of the buried FO cable became exposed by the end of the overall experiment period. Exposed sections were reburied and temperature differences preburial and postburial used to assess the length of affected measurements beyond the physically exposed section. A mean affected cable length of 0.58 m (± 0.22 m standard deviation) either side of the exposure was established for exposures greater than 0.15 m in length, (i.e., 1.16 m of buried cable was affected in addition to the physically exposed length). Exposures less than 0.15 m in length did not influence measured temperatures. Data from exposed sections and the 0.58 m either side were removed from every exposed section greater than 0.15 m during the postprocessing. At a sampling interval of 0.25 m, this resulted in 305 sampling points within the primary plot, 1,024,800 temperature measurements under premanipulation conditions and 256,200 temperature measurements under each of the felled and cleared treatments. Control rows with 79 sampling points produced a total of 66,360 temperature measurements over the whole measurement period.

2.3. Data Analysis

A Wilcoxon rank sum test (significance threshold of 0.05) was used to determine any significant differences in mean temperatures between the primary plot and control rows for each measurement day under each treatment (premanipulation, felled, and cleared). Hot spots were identified by subtracting the daily mean temperature of the control rows from the daily mean temperature at each spatial location within the plot (ΔT °C).

Empirical orthogonal functions (EOFs) were used to decompose space-time patterns in the soil temperature data (i.e., a space-time principal component analysis). EOFs illustrate patterns in the space-time data that explain most of the observed variability, with each EOF representing a mode of variation. The approach has been successfully applied previously to decompose patterns of soil moisture (Perry & Niemann, 2007) and has been used in atmospheric science for many decades (Hannachi et al., 2007; Lorenz, 1956). The time series principal components (also called expansion coefficients) indicate the importance of a particular EOF in time.

Due to the time and effort required for FO-DTS cable installation, only one plot and two 10 m control sections were instrumented with FO-DTS cable. We are aware of the pseudoreplication (Hurlbert, 1984) this causes. We therefore undertake extensive additional data analysis (included in the supporting information) and note that the results of significance tests agree with existing literature.

3. Results

3.1. Effects of Vascular Vegetation Removal on Surface Temperatures

Wilcoxon rank sum tests showed that vascular vegetation removal significantly increased mean temperatures. Premanipulation, temperatures did not differ significantly between the primary plot ($n = 305$) and control rows ($n = 79$: 21 May: $p = 0.61$, 22 May: $p = 0.94$, 24 May: $p = 0.39$, 26 May: $p = 0.56$) (Figure 1a). Significant differences were found between the primary plot and control rows once felled ($p < 0.001$) and when cleared ($p < 0.001$). Peat-surface temperatures show substantial variability in both space and time (Figure 1b). Sixty minute mean temperatures range from 0 to 25°C, with the temperature range across the 10 m \times 10 m plot regularly exceeding 25°C during the day. See also supporting information (section S2, Figures S9–S11 for spatially interpolated hourly mean data for each treatment, and Movies S1–S3 for a movie of spatially interpolated 10 min mean data).

3.2. Hot Moments and Hot Spots in Surface Temperature Patterns

Increases in mean temperatures with each successive treatment were not homogenous across the peat surface in either space or time. The hot spot intensity (ΔT) increased from 6.7°C under premanipulation conditions to 11.4°C after felling and was more than double the premanipulation intensity when cleared, at 13.7°C.

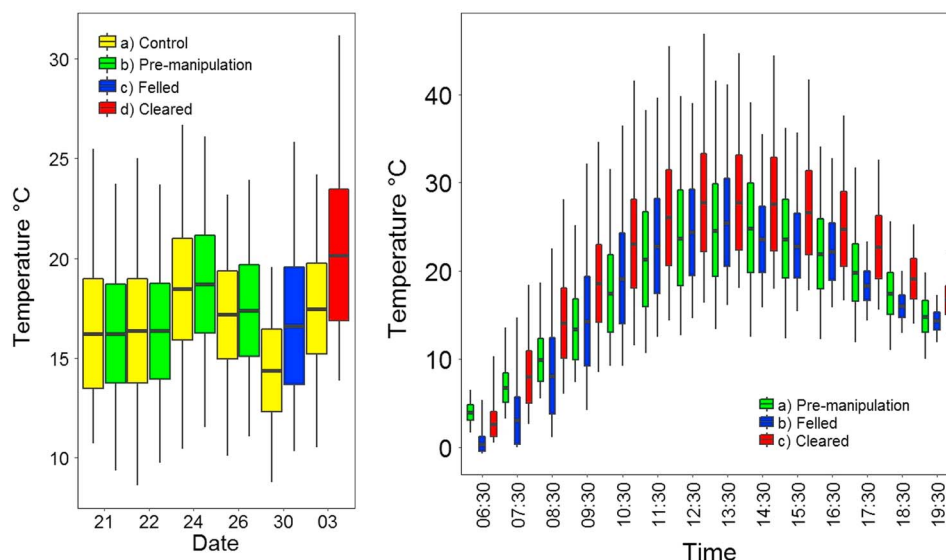


Figure 1. Box plots representing the mean, \pm SE, and range of (a) daily mean plot temperature data presented for control ($n = 79$), premanipulation ($n = 305$), felled (trees removed; $n = 305$), and cleared (all vascular vegetation removed treatments; $n = 305$) and (b) hourly mean plot temperature data presented for premanipulation, trees removed (felled), and all vascular vegetation removed (cleared) treatments ($n = 305$).

The first three EOFs explain 57.7%, 21.1% and 9.1% of the variation observed under premanipulation conditions (Figure 3). Greater variance was explained by the first EOF after felling (80.1%) and clearing (77%) compared to premanipulation conditions (57.7%). EOFs 2 and 3 for felled (15.4 and 3.3% respectively) and cleared (18.1% and 3.2%, respectively) explain less variance than their corresponding EOFs under premanipulation conditions.

There is very little change in EOF patterns among premanipulation days (Spearman's rank correlation coefficient; $r = 0.95$ – 0.97), but with felling and clearing, the spatial patterns change substantially ($r = 0.39$ – 0.67 and $r = 0.38$ – 0.59 , respectively). The importance of the first three EOFs during the measurement period (PC's) also vary between premanipulation and postmanipulation conditions. Notably, principal components 1 and 2 of the first two EOFs are consistent between the felled and cleared conditions but show the inverse pattern of principal component 1 and 2 under premanipulation conditions (Figure S12). Further assessment of the heterogeneous nature of the shifts in spatial temporal temperature signatures is presented in section S2 (Vachaud et al., 1985).

4. Discussion

4.1. Vegetation Controls on Spatial Patterns and Temporal Dynamics of Peatland Surface Temperatures

Significant surface temperature increases observed with both felling and clearing (also reported by Scull, 2007) were not uniform across the peatland surface. Canopy disturbance induces shifts in the distribution, intensity (Figure 2, also supported by section S2 and Figure S7), and longevity (Figure 3, also supported by section S2 and Figures S8–S12) of high surface temperatures, with felling and clearing decreasing the spatial variability of incoming solar radiation in both space and time.

We consider that the intensity and longevity of such surface thermal hot spots is linked to peatland ecosystem heterogeneity, as shown in the conceptual model of Figure 4. Independent spatial patterns in surface processes, driven by high levels of peatland ecosystem heterogeneity, induce uniformity, because the summation of these processes induces short-lived low-intensity white noise (Figure 4, point a). Removing such layers and limiting the complexity of the pedosphere-atmosphere interface increases the potential for long-lived positive effects to align, and to align for sustained periods. The most extreme spatial diversity thus results when the system is driven by a single process (Figure 4, point b). When the system is completely homogenous then inputs, such as solar radiation, are also spatially and temporally homogenous and hot

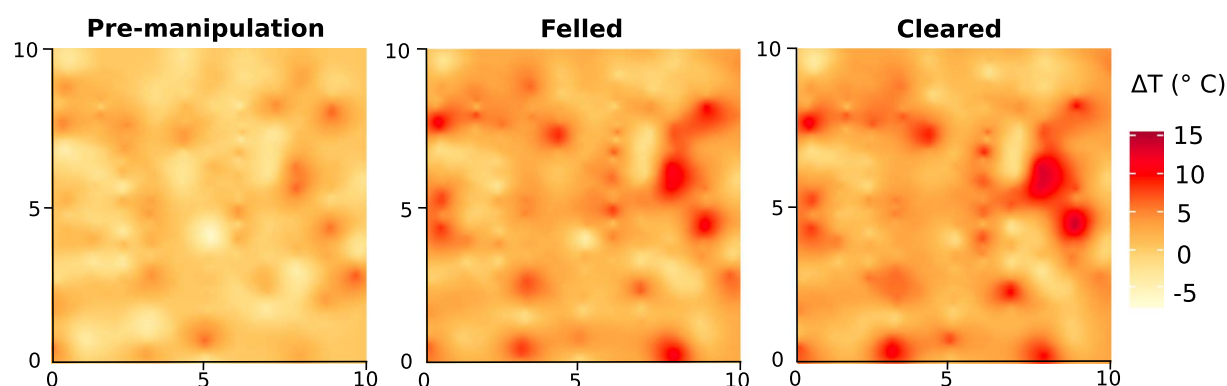


Figure 2. Mean daily hotspot intensity (ΔT °C) under premanipulation, cleared, and felled conditions. Hot spot intensity (ΔT °C) was identified by subtracting the daily mean temperature of the control rows from the daily mean temperature at each spatial location within the plot.

spots and hot moments are not observed (Figure 4, point c). Within peatlands systems, ecological, hydrological, and geomorphological heterogeneity drives variability in surface temperatures in addition to canopy complexity. These controls likely show strong codependence, maximizing hot spot intensity in peat surface temperatures. Canopy removal means such complexity is not further fragmented in space and time, and hot spot intensity is increased (Figure 4, moving the system from point d to e).

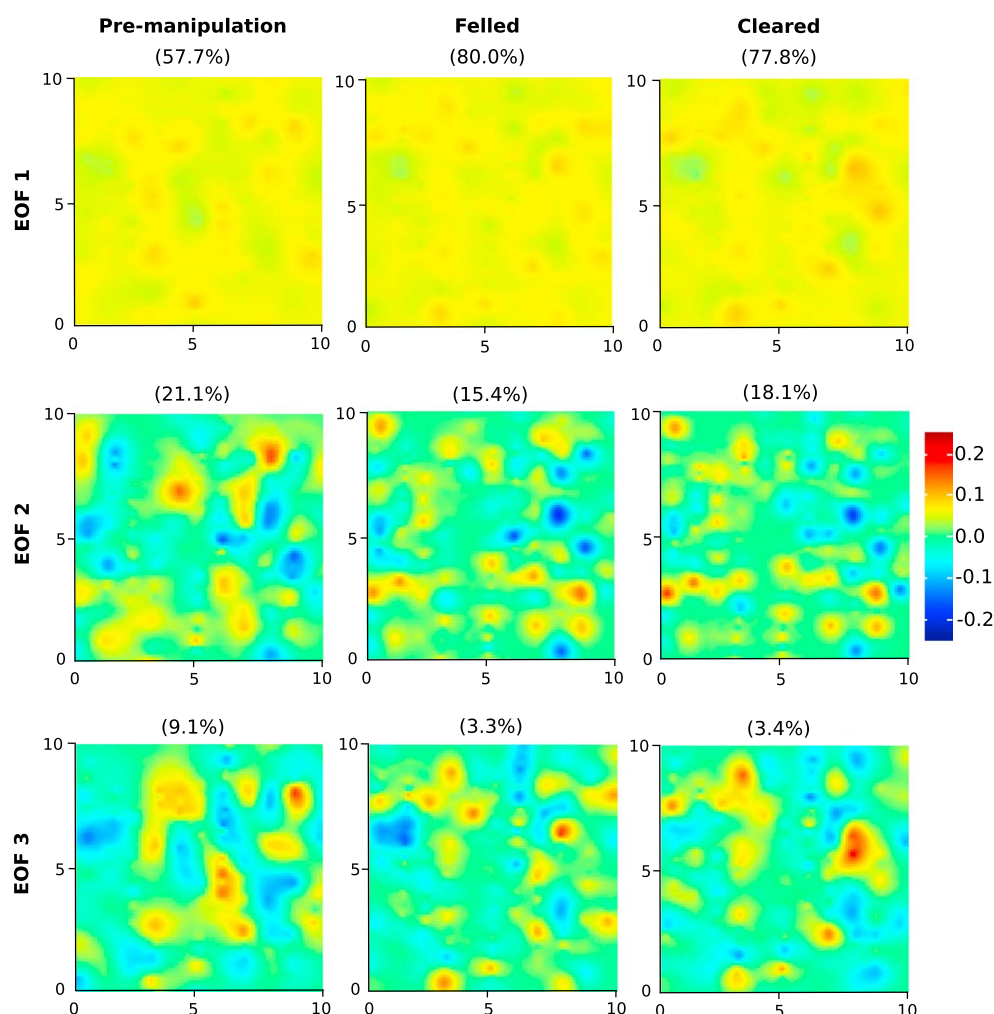


Figure 3. First three EOFs (dimensionless) for each treatment, derived from hourly mean temperature, with associated variance explained provided in parentheses.

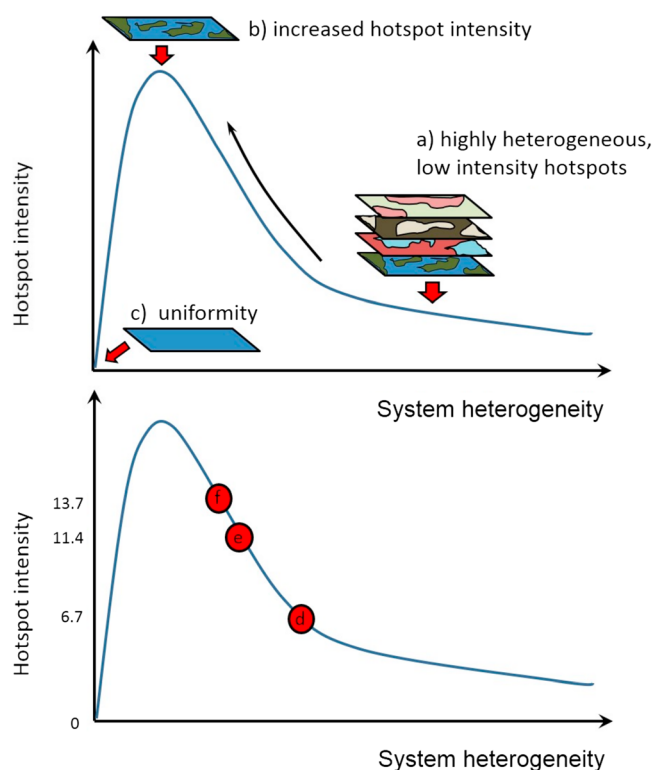


Figure 4. Conceptual dependence of peatland hotspot intensity on system heterogeneity. (top) A multilayered heterogeneous peatland system (point a) induces highly heterogeneous, low-intensity outputs. Reducing peatland complexity to a single spatially disturbed parameter/processes (point b) increases the intensity of associated hot spots. Uniformity with reduced system complexity is obtained only by limiting peatland heterogeneity to a minimum (point c). (bottom) Points d–f represent positions of the observed peatland on the conceptual model under premanipulated, felled, and cleared treatments, respectively. The y axis values on the lower panel represent the hot spot maxima observed (see Figure 2).

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The removal of subcanopy vascular vegetation had only a limited impact on the heterogeneity of surface temperatures in space and time (Figure 3, also supported by section S2 and Figures S7e and S7f, S8, and S12). This will be because (i) the vegetation is distributed comparatively uniformly in nature; (ii) it has limited impact on soil temperatures or (iii) is strongly codependent with other drivers of system complexity function.

4.2. Implications for Ecosystem Functioning and Resilience

Observed shifts in the location, longevity, and intensity of thermal hot spots and hot moments after vegetation removal shows that the peatland system is now under discrete heterogeneous stress. Average transitions in system forcing in response to the disturbance resulted in part from intense concentrated changes within spatially isolated locations across the peatland. Spatial and temporal changes in process rates such as productivity, species competition, decomposition, and evapotranspiration will thus occur within a spatially irregular and locally extreme manner. The shift in hot spot locations also means such extremes do not map onto previous predisturbance hot spots in which the landscape has potential inherent resilience to mitigate the impact of such conditions. Heterogeneous stresses may therefore breach process thresholds and tipping points and thus promote or dampen the strength of key system feedbacks (Waddington et al., 2015; Belyea, 2009; Rietkerk & van de Koppel, 2008).

The spatial dynamics and strengths of these competing feedbacks are integral to the spatial patterning and resilience of peatlands and wider ecosystems (Barbier et al., 2006; Guichard et al., 2003; Kéfi et al., 2007; Rietkerk et al., 2004). Intense, heterogeneous stresses may therefore change not only the ecosystem functioning but also induce catastrophic shifts. For instance, the quick reduction in treed areas has been simulated in wind-disturbed forests associated with small increases in gap fraction (Kizaki & Katori, 1999). Yet models used to predict changes to ecosystem functioning and resilience rarely consider the heterogeneous nature of applied stresses. Understanding the interconnected nature of feedbacks and heterogeneous stresses is an important consideration for assessing ecosystem dynamics, function, and resilience (Schneider & Kéfi, 2016).

Longer-term studies that directly relate heterogeneous shifts in stresses to spatially and temporally varying system feedback mechanisms will advance our understanding of system responses to disturbances. Linking these poses a key research frontier for evaluating and predicting shifts in ecosystem function and assessing system resilience.

5. Conclusion

High spatiotemporal resolution surface temperature data significantly improves our understanding of the complex thermal and radiative interactions at the peatland pedosphere-atmosphere interface and how these interactions change with vegetation removal. Vegetation removal increases mean temperatures as expected, but the high-resolution data and EOF analysis showed that the increase is not uniform in space or time across the peatland surface. The removal of these layers from the ecosystem decreases ecosystem complexity but increases thermal diversity of the surface. The nonuniform response of thermal dynamics at the surface highlights the need to consider and link spatially explicit ecosystem functioning mechanisms (e.g., soil-plant feedbacks) with the heterogeneous stresses placed on systems to fully assess their functioning and resilience.

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