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Key Points:
- Peatland restoration led to reduction of air temperature relative to surrounding agricultural land
- Air temperature significantly decreased by 1.2 K over 18-year period compared to surrounding landscape
- For 5 km^2 of the peatland the relative decrease in air temperature was 2 K

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The Impact of Peatland Restoration on Local Climate: Restoration of a Cool Humid Island

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Abstract Land use, land use change, and forestry (LULUCF) have been directly altering climate, and it has been proposed that such changes could mitigate anthropogenic climate warming brought about by increases in greenhouse gas emissions to the atmosphere. Changes due to LULUCF alter the Bowen ratio, surface roughness, and albedo and so directly change air temperatures. Previous studies have focused on changes in the area of forestry and have used space-for-time substitutions to assess the impact of LULUCF. This study considered 18 years of daytime land surface temperature over an area of actual land use change in comparison to its surrounding landscape and considered the restoration of a lowland peat bog: satellite land surface temperature data across 49, 1-km^2 grid squares with 20 on peatland and 29 on surrounding agricultural land on mineral soils from 2000 to 2017. The peatland squares were, until 2004, dug for horticultural peat and after 2004 were restored with revegetation of bare soil and restoration of natural water tables. Over the 18 years, the average annual daytime land surface temperature significantly decreased for six grid squares, five of which were on the restored peatland where land surface temperature decreased by 2 K. In 2000, before restoration, the peatland was 0.7 K warmer than the surrounding agricultural land on mineral soils but by 2016 was 0.5 K cooler. This study has shown that anthropogenic land use change could cool a landscape and that functioning peatlands could act as cool, humid islands within a landscape.

1. Introduction

Peatlands have long been thought of altering climate via their potential to sequester and store atmospheric carbon. Although peatlands cover approximately 3% of the Earth's terrestrial surface (Rydin & Jeglum, 2013), they are known to store as much carbon (500 ± 100 Gt; Gorham, 1991; Yu et al., 2014; Loisel et al., 2014) as the entire terrestrial biosphere (Intergovernmental Panel on Climate Change, 2013). Unlike many other terrestrial environments, the potential continuing growth of peat soils means that they can act as ongoing sinks of atmospheric carbon (Gorham, 1991) and so help moderate ongoing anthropogenic climate change. Therefore, there has been considerable attention to measure the carbon budgets of peatlands (e.g., Billett et al., 2004; Nilsson et al., 2008; Roulet et al., 2007; Worrall et al., 2003) and, more specifically, the greenhouse gas budgets of peatlands (Worrall et al., 2012). The potential for additional greenhouse gas drawdown from the atmosphere means that research has also focused upon the potential to enhance or restore peatlands to ensure that they will act as greenhouse gas sinks (e.g., Clay et al., 2010; Herbst et al., 2013; Rowson et al., 2010). Through their role as greenhouse gas sinks, peatlands have been seen as offering the key ecosystem service of climate mitigation (Reed et al., 2013). However, rather than just contributing to climate mitigation through acting as greenhouse gas sinks, peatlands could also modify the climate we experience at the Earth's surface. By modifying the way in which the surface energy budget is partitioned, the peatland could change the local climate and we would hypothesize that, compared to many ecosystems, peatlands are cool humid islands. Feddema et al. (2005) have suggested that land use and land cover changes could induce temperature changes greater in magnitude, and potentially of opposite sign, to those due to greenhouse gas forcing. Indeed, Betts et al. (2007) have modeled the impact of land use change in the industrial period (deforestation since 1750) and showed that northern midlatitudes are 1–2 °C cooler in winter and spring compared to their preindustrial state solely due to the land use change.

Bonan (2008) proposed that land cover influences surface climate through radiative (i.e., albedo) and nonradiative (i.e., surface roughness and Bowen ratio) biophysical surface properties, although these properties are not necessarily independent of each other (Rigden & Li, 2017). The energy budget of an ecosystem can be considered as

$$R_n = H + G + \lambda E + P + e \tag{1}$$

where R_n is net radiation (W/m^2), H is sensible heat flux (W/m^2), G is soil heat flux (W/m^2), λE is latent, or evaporative, heat flux (W/m^2) where λ is the heat of vaporization (2,260 kJ/kg), P is primary production (W/m^2), and e is residual error. The term due to primary production (P) is generally not considered, and even for peatlands with their net organic matter accumulation is negligible when compared to the other surface energy flux terms (Worrall et al., 2015). The balance between evaporation and sensible heat fluxes is commonly expressed as the Bowen ratio (B) or the evaporative fraction (EF)

$$B = \frac{H}{\lambda E} \tag{2}$$

$$EF = \frac{\lambda E}{\lambda E + H} = \frac{1}{1 + B} \tag{3}$$

Change in albedo (as the balance of short wave reflectivity) represents a change in the net radiation and alters the net solar radiation, here defined as the fraction of the solar radiation reflected by the surface (Allen et al., 1998). The available energy at the surface, which is equivalent to the net solar radiation, can be partitioned in several ways; the balance of these means that in some environments the net radiation will result in a greater proportion of sensible heat flux compared to the other fluxes and in turn that will lead to greater warming of the air in that environment. The partitioning of energy between H, G, and λE is strongly influenced by the nature of the ecosystem, for example, wetness such as a water table close to the surface or vegetation type controlling rooting depth and surface roughness.

The overwhelming majority of research that has been conducted on the impact of land use on biogeophysical properties, as impacting surface temperature, has considered the impact of forests compared to open land (typically thought of as arable or grassland; Muñoz et al., 2010, Rautiainen et al., 2011, Chen & Dirmeyer, 2016) and few studies of peatland (see review in Luyssaert et al., 2014). Nonforested land tends to have a higher albedo than forested land (Betts & Ball, 1997) but lower surface roughness (Rotenberg & Yakir, 2010). The deeper rooting structures of trees mean a greater availability of water and a greater consumption of incoming energy as latent heat flux (i.e., higher Bowen ratio; Juang et al., 2007). The balance of processes that alter the air temperature can be different between different latitudes (Lee et al., 2011) even for the same ecosystem; for example, Shultz et al. (2016) have shown that deforestation in the Tropics leads to strong daytime warming because of the dominance of the evaporative cooling effect and a change in Bowen ratio, while in the Boreal region deforestation leads to a cooling effect as changes in albedo dominate. Some studies have considered land use change other than forestry (e.g., Georgescu et al., 2011). There has been less consideration of land management as opposed to land use and land use change; the exception has been studies of irrigated cropland which can increase the Bowen ratio and cool surface temperatures over open land compared to forests (Adegoke et al., 2003; Kueppers et al., 2007). Luyssaert et al. (2014) have suggested that the impacts of land management could be equal to those due to land cover change; however, none of these studies cited were for peatlands. Hemes et al. (2018) have considered energy budgets between wetlands and drained agricultural land on the Sacramento delta in California and showed that air temperatures on the wetlands were lower than on the drained agricultural land.

Peatlands are by their nature wetter than many other landscapes, and so the availability of water is higher. It might therefore be expected that peatlands would be able to partition energy into a latent heat flux in greater proportion than for most other environments. For a New Zealand peat bog, Campbell and Williamson (1997) measured Bowen ratios over a 6-month period at a 20-min frequency of between 2 and 5 and so dominated by sensible heat flux. Conversely, Admiral et al. (2006) measured Bowen ratios over an Ontario bog and found that values were typically below 1 and therefore dominated by evaporation (λE), similar to a Swedish Sphagnum mire (Kellner, 2001). Worrall et al. (2015) examined a 19-yearlong data set for a U.K. blanket bog and found that the median Bowen ratio was 0.11 with an interquartile range of −0.74 to 1.27. The seasonal cycle in the Bowen ratio peaked in May and June with median values of the Bowen ratio greater than 1 showing dominance of sensible heat flux. For November through to March, the median monthly Bowen ratio was negative representing the times of sensible heat sink often observed for snow or frozen ground (e.g., Yao et al., 2011). Ruhli et al. (2004) found that the Bowen ratio of Lake Erie was typically between 0.15 and 0.3 although negative values could be measured; the open lake was dominated by evaporative losses and even acted as a sensible heat sink. Conversely, for an arid grassland of the Chinese loess, Ping et al. (2018) found an annual mean value of 1.32. Therefore, we would propose that a functioning peatland, with its relatively shallow water tables, would have a relatively low Bowen ratio compared to other land uses and that a low Bowen ratio means that comparatively less energy is partitioned to sensible heat and so leading to lower air temperatures. Therefore, we propose that a functioning peatland will produce cooler air than many other ecosystems, including croplands. Here, we consider a functioning peatland to be one in which there is sufficient vegetation and the water table sufficiently high to enable ongoing organic matter accumulation.

Many peatlands are managed, or indeed damaged, and the management of the peatlands (e.g., drainage; Rowson et al., 2010) can lead to reduction in the magnitude of the carbon sink (e.g., Tiemeyer et al., 2016) or lead to the peatland becoming a net source of carbon to the atmosphere (e.g., Clay et al., 2010). Management provides an opportunity as its means that there is a human intervention that could be altered. A change in management could enhance the storage of greenhouse gases even if the intervention may not lead to the peatland reverting to a net greenhouse gas sink. The potential is that not only could intervention lead to benefits for climate mitigation through changes in greenhouse gas flux but also by changing energy partitioning. Worrall et al. (2015) found that for an upland blanket peatland in the United Kingdom, the sensible heat flux rose with deeper water tables and decreased as the air temperature rose while the latent heat flux increased with shallower water tables and as air temperature rose. Therefore, restoration of water tables may lead to a change in partitioning of energy leading to a lower sensible heat flux and to cooler air temperatures. Luyssaert et al. (2014) reviewed 30 studies of the biogeophysical effects due to land management changes; all but one did not consider the entire energy budget and four considered peatlands, only one of which considered change in air temperature, but even that particular study (Venalainen et al., 1999) did not actually measure change but rather performed a modelling study.

Therefore, we propose that peatlands, by virtue of their high-standing water tables, will be relatively cool "islands" in a landscape and that, therefore, restoration of a peatland would bring about a local cooling of air temperatures. Further, we propose that peatland restoration not only provides for the ecosystem service of climate mitigation but also acts directly to modify the local climate.

2. Approach and Methodology

The study considered the change in land surface temperature (LST) across England's largest lowland peat complex: Thorne and Hatfield Moors (NB.; by local tradition the sites are referred to in the plural; Figure 1) in comparison to the LSTs of the surrounding farmland on mineral soils. Thorne and Hatfield Moors were chosen not only because they are the largest area of lowland peat in England but also because they are in an area of flat land where topographic effects on temperature will be minimized. The approach used LSTs as derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) TERRA satellite over the period before and after restoration of the Moors.

2.1. Study Site

Thorne and Hatfield Moors are a 33-km^2 peatland which formed as a raised bog, but the original areal extent was greatly diminished by successive phases of drainage after 1630. Bronze Age wooden artifacts at the base of the peat have been dated to 3580 ± 108 Calendar years BP (Shotton and Williams, 1973). Parsons (1878) recorded peat depths up to 6.1 m on Thorne Moors, implying that the long-term accumulation rate would be of the order of 1.7 mm/year. However, the discovery of a Neolithic trackway on Hatfield Moor dated to 4500 to 4900 Calendar years BP (Chapman & Gearey, 2013) would imply an earlier onset of peat formation and a slower average accumulation rate. Since the 1870s, the remaining bog area has been exploited, largely for horticultural uses, until 2004 when the area in its then condition came under *Natural England*'s control—the U.K. government's nature conservation agency in England—and restoration started. At the time of the purchase, peat depths across the site were generally thought to be 0.5 m although some areas remained deeper. Two peat cores of 1 m from Thorne Moor were characterized and included in the study of Clay and Worrall (2015).

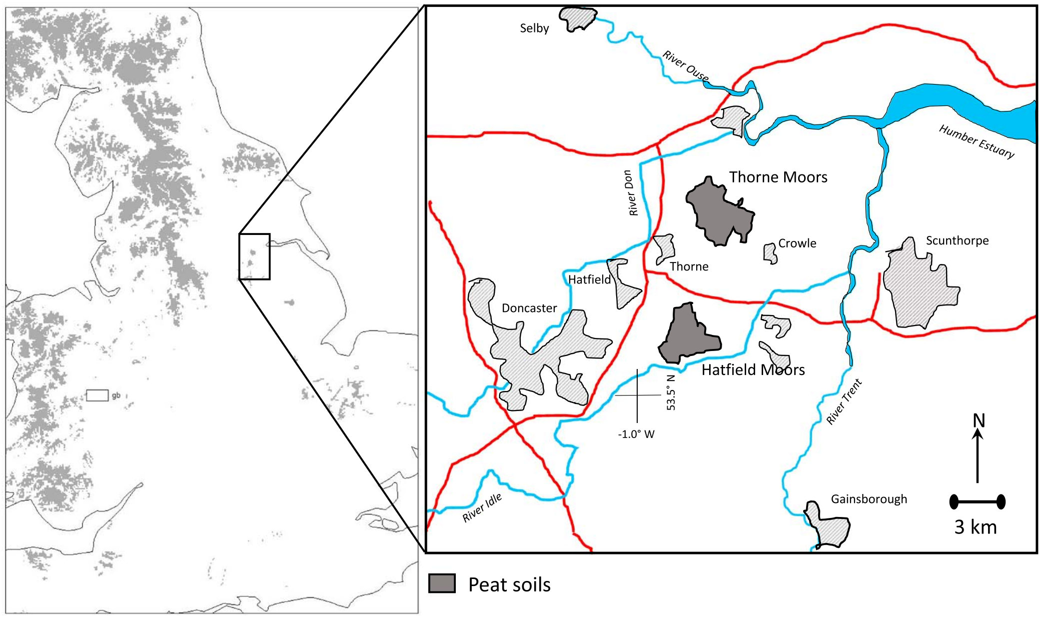

Figure 1. The location of the Thorne and Hatfield Moors. The point of −1.0°W and 53.5°N has been included.

Restoration of the area began in 2004 with the blocking of the drains and the raising of the water tables. A second phase of restoration started in 2013, which particularly focused upon scrub removal.

2.2. LST

This study uses the MODIS product TERRA LST 8-day average Global 1-km Grid data (MOD11-C2). Full technical details are available online and so will not be covered here (NASA Land Processes Distributed Active Archive Center, 2009). MODIS satellite measures infrared emission bands with a pixel size of 1 km^2, and for ambient LSTs the wavelengths used are in the region 10–12 μm (bands 31 and 32; Petitcolin & Vermote, 2002). Radiative temperature of the Earth surface must be corrected for atmospheric effects, and the emissivity of that surface within this study as land use changes occurs with peatland restoration then emissivity of the surface could be expected to change and any change in the MODIS LST product uses split window algorithms and techniques (Wan & Dozier, 1996) that correct for atmospheric effects (including absorption and emission) and surface emissivity (inferred from MODIS land cover calculations) by utilizing the other bands from the 36 available on the MODIS sensor. The MODIS LST split window algorithm has been tested using a range of the available infrared bands (Coll et al., 2005, 2009; Petitcolin & Vermote, 2002; Wan, 2014; Wan et al., 2002, 2004) and also found to be linearly related to actual air temperatures experienced at land surface (e.g., Bosilovich, 2006; Tomlinson et al., 2012; Xu et al., 2011). The daily measurements, to reduce issues of missing data due to cloudy days, are summarized over 8-day periods. The use of 8-day periods means that consistent records between years are achieved, and it is this record of 8-day averages that was used in this study.

2.3. Albedo (α)

To aid in the understanding of the change in the energy balance at the surface over the study area, albedo data from the MODIS data set were examined. No direct albedo product exists from the MODIS satellite. The visible band reflectance MCD43A3 product was used and extracted for each of the MODIS grid squares used in the study. Only the data for the first complete year and last complete years of the data were chosen as means of directly comparing a before and after restoration. Many studies have considered the calibration of albedo and MODIS products (e.g., Liang et al., 2002; Wang et al., 2014); no direct calibration was available for this type of land use or data. Therefore, to understand the change in reflectance (taken as a measure of albedo), the relative change between the peat and arable grid squares was considered.

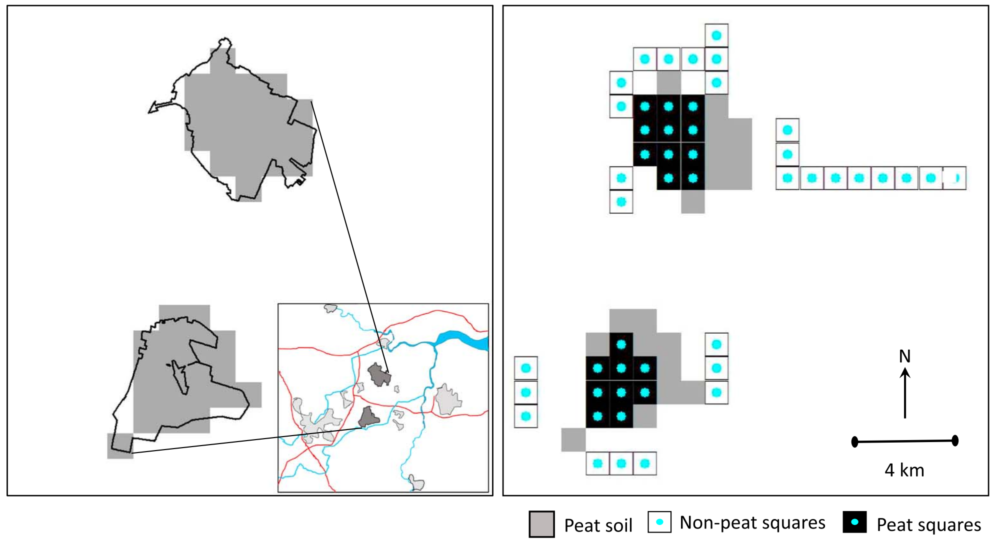

Figure 2. The location of grid squares used within this study with respect to the Thorne and Hatfield Moors with respect to Host classification of peat soils and the boundary of the current national nature reserve of the Thorne and Hatfield Moors.

2.4. Experimental Design

In total, forty-nine 1-km^2 grid squares were selected within the experimental design (Figure 2). Of the 49 grid squares, 20 were within the area of the Moors and selected so that the entire 1 km^2 of the grid was on peat soil and within the boundary of the either Thorne or Hatfield Moors—these are henceforward referred to as peat squares. Peat soil was defined from the HOST classification of soils (Boorman et al., 1995). The remaining grid squares being considered were chosen to be within the arable farmland around the Moors and are henceforward referred to as nonpeat squares. The nonpeat squares outside the Moors were chosen to be entirely separate from either Thorne or Hatfield Moors and this meant they were all at least 1 km from the edge of the Moors. Nonpeat squares were chosen on the north, south, east and west sides of both Thorne and Hatfield Moors with the caveat that the nonpeat squares did not contain the surrounding villages (most notably the villages of Thorne and Moorends) or the higher ground around the village of Crowle where the land rises above 10 m above sea level. On the north side of Hatfield Moors there are no 1-km^2 grid squares of only farmland. To the north and east of Thorne Moors, it was possible to extend the nonpeat squares a further 2 km north and 7 km east of the peat squares; this was done so that it was possible to test whether any effect increased with distance away from the Moors. As noted above, much of the farmland surrounding the Moors may have once been raised bog and was drained for agricultural use; these areas have subsequently been "warped." Warping of soils is a deliberate flooding of land to lay down a layer of alluvium, and in this way the local peat soils, and other low-lying soils, were covered to produce 50 to 60 cm of fine silt soils (Gaunt, 1976). Therefore, the areas outside of the Moors that were once active peat no longer have any of the surface characteristics of peat.

For each of the sampled grid squares the 8-day MODIS LST temperature was examined from 2000 to 2017 and the 8-day data were examined using analysis of variance (ANOVA). The first ANOVA examined four factors and was focused on question of whether there was a change in the LST due to the restoration of the peatlands; this was a four-factor ANOVA. The first factor was the difference between years (henceforward called Year); this factor had 18 levels, one for each calendar year between 2000 and 2017. The second factor was the difference between 8-day periods (henceforward referred to as Day); this factor has 49 levels, one for each 8-day period in a calendar year and by using an 8-day period there is a consistency in recording between calendar years. The third factor was the difference between peat and nonpeat squares (henceforward referred to as Peat) which had two levels between the grid squares within the Moors and those on the surrounding arable farmland on mineral soils. The final factor was the difference between the two moors (Thorne and Hatfield) and is henceforward referred to the Moor factor. The design had sufficient observations such that both two-way and three-way interactions between factors could be estimated. The term of interest in this ANOVA is the interaction between the Peat and Year factors. The interaction can be interpreted as the question of whether the difference between peat and nonpeat squares changes over the course of the study with the progress of restoration.

A second ANOVA was performed to examine the response at each of the squares over the course of the study period. It is again a four-factor ANOVA, but in this case, rather than the Peat factor with two levels (peat and nonpeat squares), a Squares factor was considered which had 49 levels, one for each of the squares for which LST was collected regardless of whether they were peat or nonpeat squares. The other factors were as for the first ANOVA, that is, Day, Year, and Moor. To understand the response on each of the squares, it was the three-way interaction between Square, Moor, and Year factors that needed to be estimated to give the least squares mean for each square over the time of the study.

As a final test of the temperature change for the study sites within the study period, the LSTs were reanalyzed but including an additional factor. The additional factor was restoration status (henceforward referred to as Restoration) with two levels—prerestoration and postrestoration. The prerestoration period was 2000 to 2003 and the post-restoration period 2005 to 2017. The year 2004 was excluded as this was the year of the restoration works. Because there are only certain years in the prerestoration and postrestoration periods, the Year was nested within the restoration factor.

Albedo (α) data were analyzed in the same manner as the LST data with four factors, Year, Peat, and Moor factors as above. In the case of the Year factor there were only two levels—2001 and 2017. The fourth factor is henceforward referred to as Month and is the albedo data summarized to each month of the year—this factor had 12 levels one for each calendar month.

Before any ANOVA was performed, the data were Box-Cox transformed to remove outliers and tested for normality using the Anderson-Darling test (Anderson & Darling, 1952)—it did not prove necessary to transform the data for any of the metrics in this study. The homogeneity of the variance was tested using the Levene test. The magnitude of the effects of each significant factor and interaction was calculated using the generalized ω^2 (Olejnik & Algina, 2003), and values were presented as least squares means (otherwise known as marginal means). Post hoc assessment of factors and interactions was carried out using the Tukey test. Power analysis was used post hoc to estimate the achieved power within the data set. The power analysis was performed using the G*Power 3.1 software (Faul et al., 2007; http://gpower.hhu.de/)—a priori the acceptable power was set at 0.8 (a false negative probability $\beta = 0.2$).

Even using the 8-day MODIS LST data, there are missing values. If it is assumed that the missing data represent the distribution of cloud over the Moors and surrounding area, then it is possible to assess whether this changes over time for the same factors as considered for LST. An initial Chi-square test of the frequency of cloud cover across the chosen grid squares had suggested that an exploration was worthwhile. So we analyzed the proportion of missing data in each year (there should be 46 values in each year for each grid square) using binomial regression with three factors. The factors were the same as for the first ANOVA above except that Date could not be included as it was the proportion of missing data over a year that was used.

2.5. Additional Data

The restoration of the Moors was based upon the restoration of water tables, revegetation of bare soil, and later the removal of scrub; therefore, monitoring of restoration focused upon these aspects of the habitats and characteristics of the Moors. Monitoring of bare soil, open water, and scrub cover took place in 2002, 2013, and 2016. In 2002 and 2016 more detailed vegetation surveys were conducted by ground-truthing aerial images. These more detailed surveys meant that it was possible to assess the area of woodland, bare peat, open water, scrub (here defined as areas of vegetation between 0.5 and 3 m in height), grasses, sedges, heather, bracken, and the area of nonpeat soils.

Water table monitoring was initiated at the outset of restoration, but increase in area of open water meant that initial monitoring points were lost. As part of the second phase of restoration, water table monitoring was reinitiated in 2013. Over the Thorne and Hatfield Moors, 81 dip wells were sited with 48 on Thorne Moors and 33 on Hatfield Moors, and the depth to the water table was measured every month from 2014 to 2017 for 26 dipwells and for 2017 for the remaining dipwells. ANOVA was used to assess the impact of three factors on the depth to the water table: first, the Moor factor as defined above; second, the difference between years (henceforward referred to as the Year factor) with four levels, one for each year between 2014

Table 1
The Results of ANOVA for the Four Factors: Year, Peat, Day, and Moor

Factor (interaction)	P	Proportion of variance explained (ω^2)
Year	0.00	9.7
Peat	0.00	0.2
Day	0.00	64.5
Moor	0.00	1.9
Year*peat	0.00	0.2
Year*moor	0.00	0.2
Peat*day	0.00	0.9
Peat*moor	0.00	0.3
Day*moor	0.00	1.2
Year*peat*moor	0.04	0.1
Residual		19.5

Note. ANOVA = analysis of variance.

and 2017 inclusive; and third, the difference between months of water table measurement with 12 levels and henceforth referred to as the Month factor. Prior to analysis, values beyond three standard deviations of the mean were excluded as outlying values to improve data set distribution. This approach was different to the other ANOVA as Box-Cox transformation cannot be performed on negative values, and for the Moors water tables above and below the surface were recorded. As above, the magnitude of the effects of each significant factor and interaction was calculated using the generalized ω^2 (Olejnik & Algina, 2003), and values are presented as least squares means. Post hoc assessment of factors and interactions was again carried out using the Tukey test.

2.6. Calibration

A limitation of this study is that LST as viewed by the MODIS data is not directly a measure of air temperature at the height that humans would experience. A number of studies have considered the calibration of MODIS LST data and air temperature. Tomlinson et al. (2012) considered LST from the MODIS AQUA for nighttime temperatures in comparison to measured air temperature over the city of Birmingham and found significant positive correlations between MODIS LST and measured air temperatures but did not test between the correlations, and so it is not possible to judge to what extent one linear relationship is reasonable between stations. Similarly, Xu et al. (2011) demonstrated significant linear relationships between daytime MODIS LST data and observed air temperatures for four different land uses (urban, water, forest, and cropland) but their results do not demonstrate whether there are significant differences between land uses or that the gradients of the relationships are significantly different from unity. Therefore, to calibrate the measurement of LST, this study compared the observed LST to air temperatures measured for the study site. As part of ongoing research into the greenhouse gas budgets of the field site, air temperature at breast height (approx. 1.3 m) has been measured at two locations that correspond with the 1-km^2 grid squares observed for LST. One location was in the approximate center of the peatland (in a peat square), and the other was in the arable land (a nonpeat square) on the north west side of the peatland. The air temperatures were recorded on a tiny tag 2 plus logger (Gemini data loggers, Chichester, West Sussex, UK) programmed to record air temperature every hour from 1 February 2018 to 26 September 2018. The air temperature measurement at 11 a.m. for both sites was compared to MODIS LST observation for that 1-km^2 grid square.

3. Results

The statistical analysis does show that there was a significant decline in the LST of the peatlands relative to surrounding agricultural land.

Over the study period it should have been possible to consider 40,082, 8-day LST measurements in total over the 49 grid squares being examined. In total, there were 35,663 data points with 4,418 occasions when no 8-day LSTs were recorded, an average ninety 8-day LST measurements missing per grid square or 11.1% missing data. The proportion of lost data is discussed further below. The power analysis showed that the achieved power ($1 - \beta$) was 1.00 giving a false negative rate of zero, that is, despite only two levels to some factors in the ANOVA, the overall sample size of the data set was more than sufficient.

3.1. ANOVA of LST

The Anderson-Darling test showed that the 8-day LST was normally distributed, and the data were not transformed. Furthermore, Box-Cox transformation and the size of the data set meant that no data were removed.

The ANOVA explained 80.1% of the variance in the data set, and all the factors and interactions considered were found to be significant at a probability of at least 95% (Table 1). By far the most important factor was the difference between days with the coldest day of the year being day 1 (1 January, 2.8 ± 0.2 °C) and the warmest was day 209 (28 July, 23.8 ± 0.4 °C). The second most important factor was Year, but there was no significant trend over the whole period showing that there was no general warming; the warmest year was 2011 (15.3 ± 0.2 °C) and the coldest 2001 (12.7 ± 0.2 °C). Third, the difference between the Moors with Hatfield Moors (14.05 ± 0.06 °C) being significantly warmer than Thorne Moors (13.49 ± 0.05 °C).

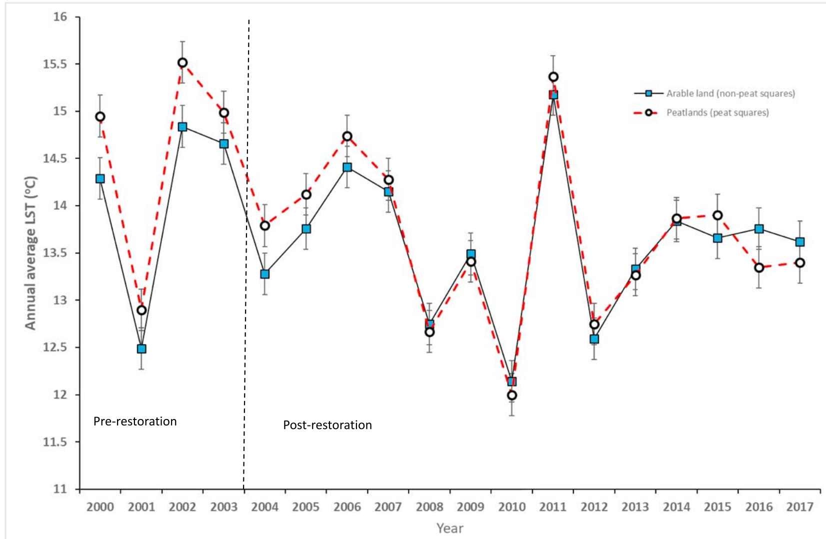

Figure 3. The least mean squares (annual average daytime land surface temperature) for the interaction between Peat and Year factors, that is, between the peat (peatland) and nonpeat squares (Arable land) over the years of the study. The error bars are given as the 95% confidence interval. The start of restoration on the study sites has been indicated by a dotted line. LST = land surface temperature.

Finally, there was a significant difference due to the Peat factor with peat squares (13.68 ± 0.05 °C) warmer than nonpeat squares (13.85 ± 0.05 °C). This latter effect must only be considered in the light of the significant interactions terms.

In relation to the aims of this study, it is the interaction terms that more directly answer the questions set, that is, the change in the difference in the LST between the peat and nonpeat squares over the time before and after restoration. The interaction between the Peat and Year factors demonstrates the change in daytime LST of the peatlands relative to the arable over period of the study (Figure 3). The post hoc analysis of the Peat-Year factor interaction shows that, in three out of the 5 years of the data available before 2005, the peat squares were significantly warmer than the surrounding nonpeat squares. In 2000, the annual average LST on peat squares was 15.0 ± 0.1 °C compared to 14.3 ± 0.1 °C on the nonpeat squares. Over the subsequent 13 years, peat squares never had a higher annual mean LST than nonpeat squares, and indeed, in 2016 the peat squares were significantly cooler than the surrounding nonpeat squares, with an average on peat squares of 13.3 ± 0.1 °C compared to 13.8 ± 0.1 °C on nonpeat squares. There was no significant trend in the annual average LST values for either the peat or nonpeat squares. The significance and time course of the Peat-Year factor in part demonstrates the study hypothesis. The study has proposed that peatland restoration has acted to modify local climate and acted to cool the local climate. However, the study had proposed that functioning peatlands would be a cool "island" in a landscape and the time course of the Peat-Year factor shows a cooling but only in 1 year, all be at the end of the study, was the peatland actually significantly cooler than the surrounding nonpeat landscape.

The difference between the peat and the nonpeat squares is significantly different between the two levels of the Peat factor that is considered for each of the Moors. For Hatfield Moors the peat squares were warmer than the nonpeat squares in 5 years, all the years up to and including 2005: the largest difference was in the year 2000 with the peat squares on Hatfield Moors being on average 0.65 K warmer than nonpeat squares. Conversely, for Hatfield Moors there were 5 years where the peat squares were significantly cooler than the nonpeat areas starting in 2008. The largest difference for when peat squares were cooler than nonpeat squares was in 2013 with peat squares being 0.69 K cooler than the nonpeat squares. Taking the least squares means for the peat squares on Hatfield Moors, there was a significant linear decline over the 18 years of the study ($r^2 = 0.16$, $n = 18$, 0.05) giving an average annual decline in LST for the peat squares on Hatfield Moors as 0.1 ± 0.05 K/year, but there was no equivalent significant trend for the nonpeat squares. The difference between the Moors maybe due to fact that prior to restoration Hatfield Moors was the area of more active peat extraction compared to Thorne Moors.

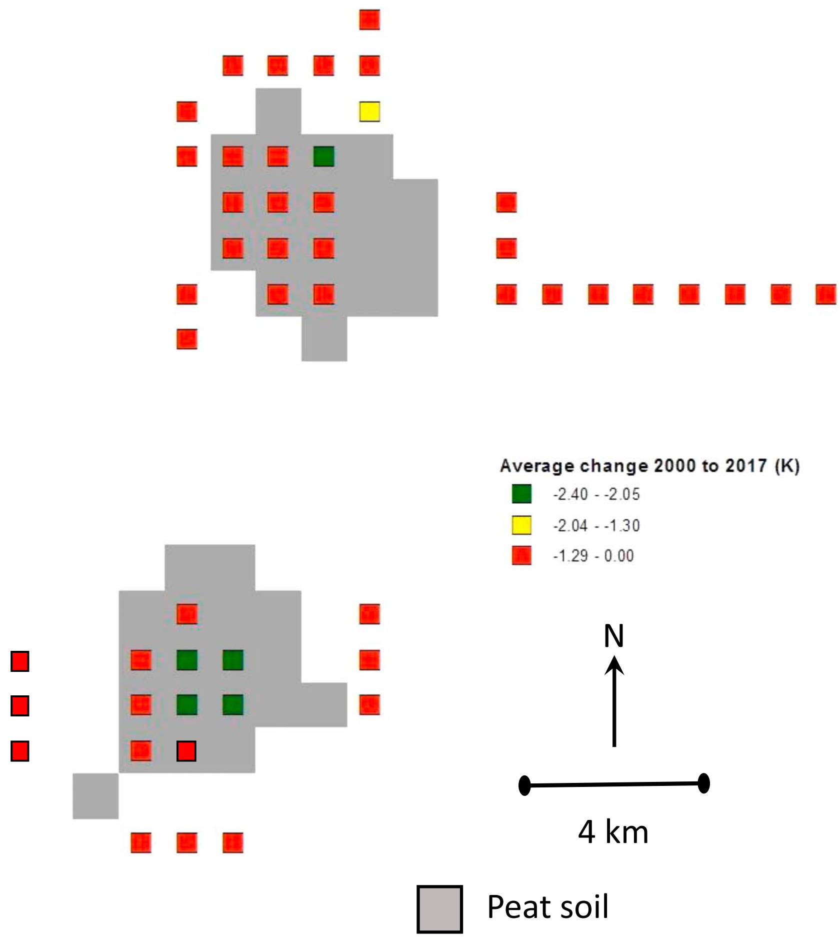

Figure 4. The trend in the least mean squares values of the Squares and Year interaction term, within the grid squares over the Thorne and Hatfield Moors.

On Thorne Moors the peat squares were warmer than the nonpeat squares on nine occasions with the most recent being in 2015 and the largest difference being 0.79 K in 2002. There were no years for the Thorne Moors when the peat squares were significantly cooler than the nonpeat squares, but for 2016 the peat squares were cooler than the nonpeat squares. There were no significant trends in the LST for either the peat or nonpeat squares on Thorne Moors. There was no significant three-way interaction between Peat, Year, and Day factors. and so it was not possible to consider when or if over the year the difference occurred.

The ANOVA was repeated using the Squares factor instead of the Peat factor, and there was a significant three-way interaction between the Squares, Moor, and Year factors. Of the 49 squares that could be examined, only six showed a significant trend in their least squares means over the 18 years of the study. All six significant trends were significant declines and five out of the six were observed for peat squares; only one significant decreasing trend was observed for a nonpeat square (expressed as the average change since 2000; Figure 4). The magnitude of the significant trends varied from −0.07 to −0.11 K/year or up to −2.4 K when expressed as the average change over 18 years of the study. The largest magnitude of the trends that was not significant at a 95% probability was −0.06 K/year (i.e., 1.1 K over the 18 years of the study), and this can be taken as detection limit for this analysis. Alternatively, and considering the trend for all squares, one nonpeat square did show a slight rise in LST over the 18 years of the study but at rate of 0.0002 K/year which was not significant. The spatial distribution of the trends across the studied squares shows that four squares with significant trends in LST were on Hatfield Moors and two were on Thorne Moors; it is interesting to note that the squares with significant change in LST are on the northeast side of the Moors or adjacent to the northeast side of the Moors and that the greatest changes were on the peat squares rather than on the nonpeat squares. The prevailing wind direction in the United Kingdom is from the southwest to northeast,

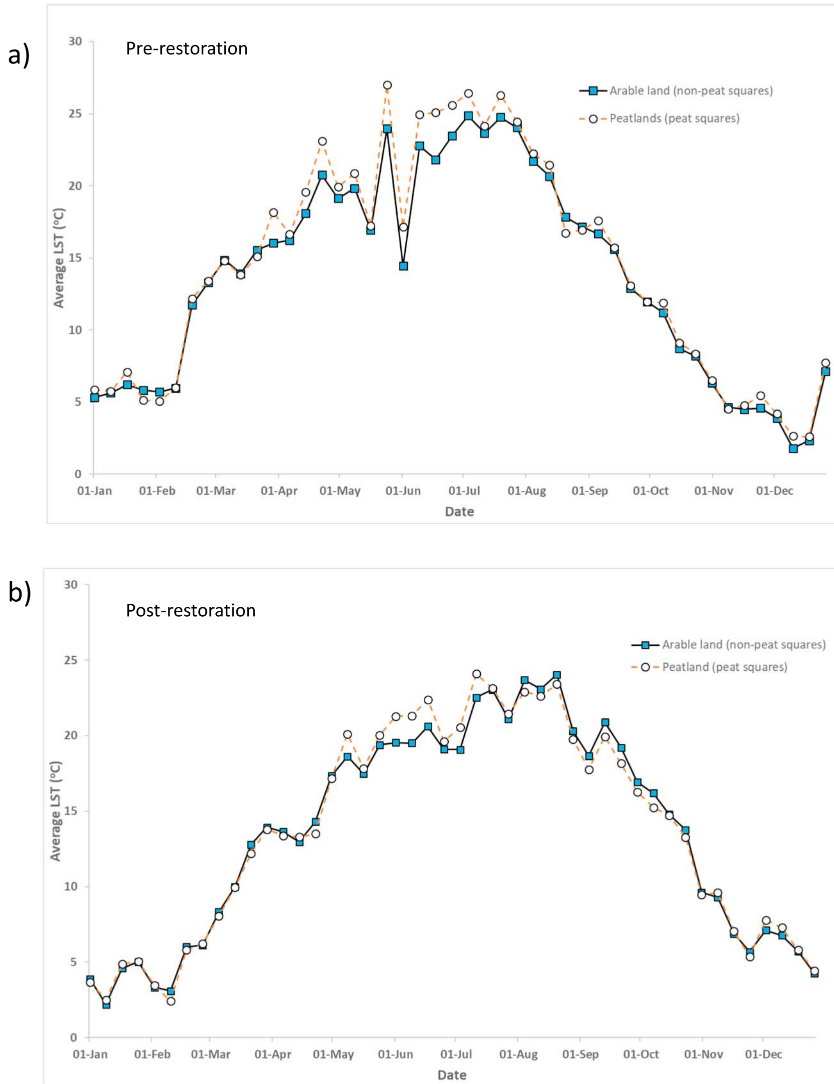

Figure 5. The least mean squares (average daytime land surface temperature) for the interaction between Peat, Restoration, and Day factors, that is, between the peat (peatland) and nonpeat squares (Arable land) over the course of the year. The error bars, 95% confidence interval, are within the size of the data point. (a) Peat and Day factors prerestoration. (b) Peat and Day factors postrestoration. LST = land surface temperature.

that is, air would normally move across the Moors from southwest to northeast and so any cooling effect would be most pronounced downwind. Furthermore, the settlements of Thorne and Moorends are on the southwest side of the Moors and so it could be that warm air coming off these “urban” areas is cooled across the Moors and exported downwind to the northeast. However, these settlements are probably too small to generate an urban heat island effect. In terms of the studies underlying hypothesis, then we might have expected all the peat grid squares to show a significant decline in LST whereas what was observed was that five out of the 20 peat squares showed a significant decline in LST.

The ANOVA including the Restoration factor showed that for Thorne Moors the LST decreased by 0.7 K between the prerestoration and postrestoration and for Hatfield Moors the LST change was a decrease of 1.4 K, while compared to the arable the peat squares were 0.3 K cooler in the postrestoration period. Comparing the annual cycle (Day factor) for the Peat factor with respect to Restoration factor shows how the LST between the different land types over the year has varied (Figure 5). Prerestoration, on 37 out of 46 days the peat squares were warmer than nonpeat squares and the greatest difference was with the peat squares 3.3 K warmer than the nonpeat squares. Postrestoration, there were 23 out of 46 days when the

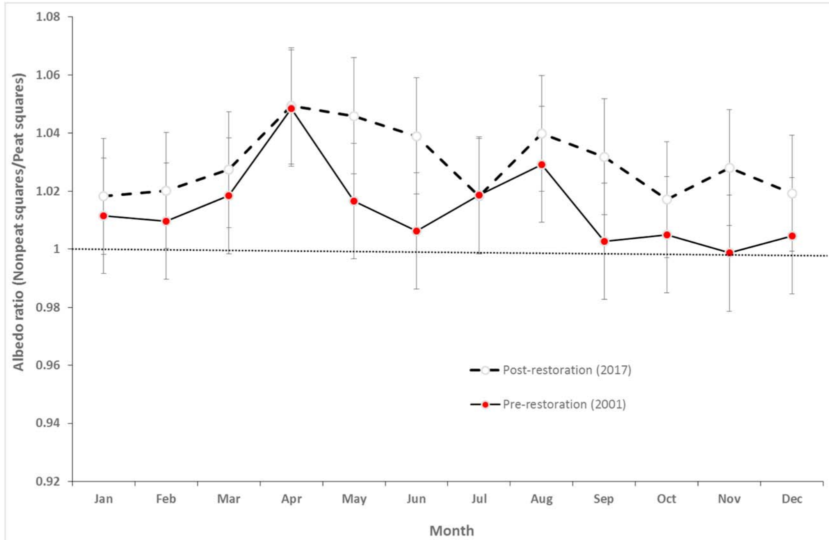

Figure 6. The main effects of the ratio of the visible band reflectance (taken as albedo [α]) on the nonpeat squares to that on the peat squares over the annual cycle for the two years 2001 and 2017.

peat squares were warmer than the nonpeat squares and the greatest difference was with peat squares was 1.8 K. Both prerestoration and postrestoration, the peat squares were never more than 1 K colder than the nonpeat squares. Of course, restoration of peatlands is progressive and so the largest temperature difference would be expected with time after the restoration, as shown in Figure 3. However, this comparison in Figure 6 shows that postrestoration there are still times when peat squares are warmer than the surrounding land but this period decreases in time and magnitude after restoration.

UKCP2009 (United Kingdom Climate Programme 2009 scenarios; Murphy et al., 2009) showed that the annual average daily temperature (not the daytime temperature as considered from the MODIS data and an assessment not based upon MODIS observations) for the Yorkshire and Humber region warmed by 1.5 K between 1961 and 2006 and predicts a warming of 3.1 K by the 2080s. That is, the estimated change in air temperature for the region is an increase yet a significant decrease has been observed for the many of the peat squares in this data set.

3.2. Albedo (α)

The Anderson-Darling test suggested that data should be log-transformed prior to analysis. Over the annual cycle, comparing 2001 (prerestoration) with 2017 (postrestoration), it is possible to see that there is no significant difference at the 95% probability between these two years (Figure 6). In 2001, two out of 12 months (April and August) were significantly greater than 1, that is, in just 2 months the albedo of the peat squares was significantly lower than the nonpeat squares. However, in 2017, seven out of 12 months were significantly different from 1 and given we have assumed constant land use across the study period for the nonpeat squares the albedo of the peat squares must have decreased between 2001 and 2017.

3.3. Cloud Cover

A simple Chi-square test based upon the frequency of missing 8-day periods in the LST data suggested a significant difference between peat and nonpeat squares, implying that there was significantly less cloud cover over the peat squares than nonpeat squares. However, the more detailed analysis possible with the binomial regression allowing for a range of factors showed that there was no significant difference between peat and nonpeat squares on its own or due to any of its interactions. The most important significant factor was the Moor factor, that is, there was a significant difference between Thorne and Hatfield Moors, with Hatfield Moors having a lower proportion of missing data, that is, more cloud-free days than Thorne Moors.

3.4. Habitat Change

The 2016 survey showed that of the 33.5 km^2, the measured habitats were woodland (11%), bare peat (9%), open water (11%), scrub (11%), grasses (4%), sedge (10%), heather (14%), bracken (25%), nonpeat soils (2%),

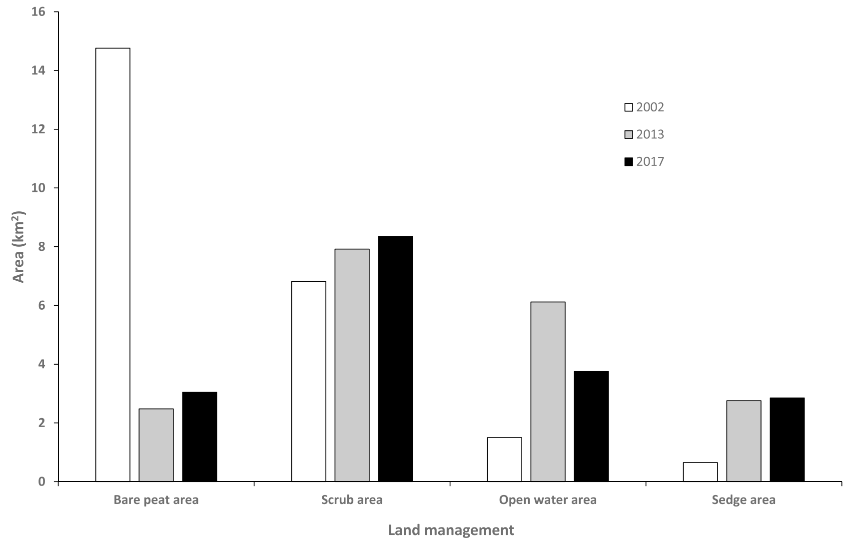

Figure 7. Change in land management from the habitat surveys of 2002, 2013, and 2017.

and nonsoil areas (3%). Examining the changes in the key management interventions shows that perhaps the imagined changes may not be as unidirectional as expected (Figure 7). The area of bare peat has decreased overall, although it rose from 2013 to 2017—an overall change of 11.7 km^2 but a rise of 0.6 km^2 since 2013. The area of open water rose from 2002 to 2013 then fell to 2017—an overall increase of 2.3 km^2 with a decline of 2.4 km^2 since 2013. The increase in area of open water could be due to raising of water tables after restoration. However, given the shallow nature of the open water on the Moors (typically 50 cm deep at maximum), the area of open water could alter radically depending upon the time of year or the antecedent weather conditions prior to any survey. The survey was over the summer in 2002, while in 2013 and 2016 the surveys were in early spring (February and March), that is, the initial survey was at time when one might expect low water tables and so a lower area of open water in the shallow cells/pools that exist on the Moors compared to what be naturally expected in early spring. The area of scrub has increased over the course of the study period—an overall increase of 2.2 km^2 with an increase of 0.1 km^2 since 2013—although this net change may mask the nature of the detailed change with increase in young birch scrub and decrease in more mature, taller birch and rhododendron. These habitat surveys show that since restoration bare soil has declined from 44% of the area of the Moors to just 9%—a 79% decline; equally, open water has risen from covering 4.4% of the Moors to 11.1% of the Moors in 2017. The changes seen over the period of the study are consistent with restoration of a peatland with higher water tables and more complete vegetation cover.

3.5. Depth to Water Table

Of the 1,783 measurements of water table depth, 18 were removed as being more than 3 standard deviations away from the mean (approximately 1.0%). All three factors included in the ANOVA were found to be significant ($R^2 = 10.17\%$). The most important factor was Moors (the difference between Thorne and Hatfield Moors) with Thorne Moors having significantly higher (closer to the surface) water tables, with a least squares mean of -0.063 ± 0.008 m compared to -0.192 ± 0.009 m on Hatfield Moors (the error is given as the standard error). Of the 15 dipwells on Thorne Moors that had complete data sets between 2014 and 2017, eight had least squares mean water tables above the surface; on Hatfield Moors, two out of 11 dipwells had water tables above the surface, The second most important factor was Month with water tables in February and March closest to the surface, after which water tables declined with each subsequent month to a low in October of -0.206 ± 0.020 m (Figure 8). The third most important factor was Year. Given the fact that the data only covered 4 years, it would not be possible to assess any trend in the depth to the water table. The depth to the water table was significantly lower in 2015 compared with 2014 and 2017m, but the other years were not significantly different from each other. The observed drawdown in water tables during 2015 was particularly evident during July to September.

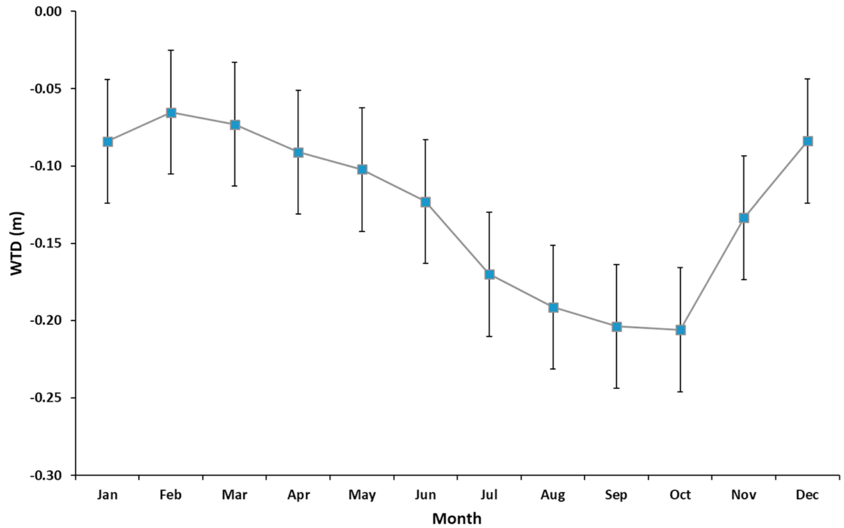

Figure 8. The main effects of the depth to water table (depth below peat surface) for the Month factor. Error bar is given as the 95% confidence interval. WTD = Water table depth.

3.6. Calibration

For the central peat square site there were 70 occasions when there was an LST and an air measurement and the best fit regression equation was

$$\begin{bmatrix} T_{\text{air}} = \underset{(0.03)}{0.97} T_{\text{LST}} & n = 70, r^2 = 0.93 \end{bmatrix} \tag{4}$$

where T_{air} is the air temperature at breast height (°C) and T_{LST} is land surface temperature as observed by MODIS (°C). The value in the bracket below the equation is the standard error in coefficient. Note that given the uncertainty in the coefficient term of equation (4), then the gradient of equation (4) is not significantly different from unity.

For the nonpeat square location there were 64 occasions when there was an LST observation and an air measurement; the best fit equation was

$$\begin{bmatrix} T_{\text{air}} = \underset{(0.04)}{0.91} T_{\text{LST}} & n = 64, r^2 = 0.91 \end{bmatrix} \tag{5}$$

Equation (5) is significantly different from unity but not significantly different from equation (5), and therefore, there is no statistical difference between the air temperature to LST measurement across the two current land uses for this study site. However, it is reasonable to conclude that LST slightly overestimates air temperature. Gallo et al. (2011) measured the relationship between LST and air temperature at 2-m height at 14 sites across the United States in both clear- and cloudy-sky conditions and found statistically significant linear relationships at all 14 locations and found Y intercepts between 0.57 and 6.26 and gradients 0.95 and 1.25. Any scatter in equations (4) and (5) could be due to changes in emissivity caused by a number of unmeasured variables such as wind speed and surface moisture (Tian et al., 2018).

4. Discussion

This study has been able to show that there was a statistically significant change in the LST across a landscape that parallels the restoration of a peatland. A priori this study has proposed that peatlands would be cool, humid islands in a landscape and that this could be ascribed to their relatively high water table leading to a greater proportion of the net radiation transferred to latent heat as opposed to sensible heat, that is, a lowering of the Bowen ratio. However, for a peatland being restored, the raising of water tables to change the Bowen ratio is only one possible mechanism by which restoring peatlands could significantly alter the local climate. Bonan (2008) proposed that land cover could influence surface climate through changes in Bowen ratio, surface roughness, or albedo. Indeed, in this study considerable changes in open water, bare soil, and vegetation have been shown for the peatlands. With respect to changes in Bowen ratio over the course of the study, we have proposed that raising water tables will increase the latent heat flux and lead to a lowering of the Bowen ratio (equation (2)). There are, however, no water table data for the Moors prior to restoration, but peat extraction could not have occurred with water tables at the current levels and so water tables may have risen. Equally, since 2002 the area of open water increased from 1.4 to 6.7 km^2 in 2013 but declining to 3.7 km^2 by 2017. However, the increase in area of open water was largest on the Thorne Moors rather on the Hatfield Moors where the more extensive, in area and magnitude, temperature changes occurred. Petrone et al. (2004) examined the impact of restoration of a peatland from a bare, milled surface to revegetated upon the surface energy budget of the peat. In the case reported by Petrone et al. (2004), a mulch used for restoration acted to increase the surface peat temperature and also demonstrated that evaporation was between 13% and 18% lower on the mulched, restored peatland compared to the unrestored, bare peat site. Worrall et al. (2015) showed that while latent heat and soil heat flux increased with a raising of the water table in a fully vegetated peatland, the sensible heat flux decreased as water tables rose.

In addition, the restoration of peatlands will bring about changes in albedo as in these Moors there is a decline in the area of bare peat. Prerestoration, the milled surface of the peat would have very dark surface with no canopy to shade it and it would be dry. Gascoin et al. (2009) showed that on a bare soil (although not a peat) the albedo was 0.26 when wet and 0.16 when dry, the opposite result to that reported by Idso et al. (1975) of 0.30 when dry (0% volumetric water content) to 0.14 when wet (32% volumetric water content). This study has seen that the albedo increases with rewetting of the peat surface but then the surface of the peat will become vegetated. Thompson et al. (2015) considered the effect of burning of forested boreal peatlands on albedo and radiation balance where conifer cover was replaced by shrub cover as a result of burning and in the snow free periods the albedo was 0.12. Lohila et al. (2010) found values of summertime albedo for vegetated, intact peatlands in Finland of between 0.11 and 0.14. This suggests that after restoration, within the context of the Thorne and Hatfield Moors, albedo would have declined upon restoration as surface soils wetted up and revegetated with shrubs. A decline in albedo would mean an increase in net radiation with respect to the atmosphere and so more energy entering the peatland ecosystem that has to be redistributed. Indeed, Figure 6 suggests that, although a calibrated measure of albedo was not available, the albedo of the peat squares declined relative to the albedo of the nonpeat squares. Alternatively, Hemes et al. (2018) showed that albedo was higher on wetland sites in comparison to neighboring alfafa fields but that sensible heat flux was lower during the day on wetlands and latent heat flux was higher at nighttime on wetlands soils compared to agricultural land. But the sites that were studied by Hemes et al. (2018) had no change in the proportion of bare soil as both were vegetated.

There is less evidence available for magnitude or variation of the surface roughness and correspondingly in surface resistance over peatlands of varying types. Kellner (2001) found that the most important control on the surface resistance was vapor pressure deficit rather than water table or vegetation properties—average for a vegetated peat surface was 160 s/m. The Lohammar equation predicts that the surface resistance is inversely related to the leaf area index (Lohammar et al., 1980). Therefore, for a peatland that is revegetating, such as in this case, it would be expected that surface resistance would decrease over the period and so increasing the sensible heat flux. Further, Van de Griend and Owe (1994) found that surface resistance of bare soil rose by 3 orders of magnitude between wet (field capacity) and dry conditions. Peichl et al. (2013) confirmed that the surface resistance was controlled by vapor pressure deficit over a boreal mire, but there was an approximate threefold increase in surface resistance with a drop in the water table from the surface to 25-cm depth. Therefore, going from a bare peat soil to a wet vegetated surface would decrease the surface resistance as Leaf area index (LAI) increases and water tables rise nearer the surface. A decrease in surface resistance would lead to an increase in evaporation and thus an increase in cooling of the peatland.

Lee et al. (2011) proposed a method for mathematically separating the effects of surface roughness, Bowen ratio, and albedo upon surface temperature impacted by land use change, and such methods have been updated in a number of ways by subsequent studies (eg. Chen & Dirmeyer, 2016; Rigden & Li, 2017; Zhao et al., 2014). These methods retain a number of assumptions that would make them unusable here but could be the focus of future modelling and monitoring studies.

Although MODIS has been used before to analyze land use (e.g., Li et al., 2015) or land use change (e.g., Luyssaert et al., 2014), there was a lack of statistical design and verification which must limit the findings of such studies. Furthermore, this study did not rely on the use of a space-for-time substitution to understand the impact of change. For example, Chen and Dirmeyer (2016) used eight pairs of eddy covariance towers to examine the impact of land cover and land use change (in actuality just deforestation was considered), but of these eight pairs none had actually had undergone the land use change during the period of the study; no statistical comparison was made between the eight pairs, and although the nearest pair were 0.69 km apart the furthest pair were 33.84 km apart.

It is difficult to understand the impact of the relative changes that restoration would have brought about between changes in Bowen ratio, albedo, or surface roughness; all we can say is that the overall result was a significant decrease in daytime LST. However, the hypothesis of this study has only be partially met. Our prediction was that restoration of peatland would lead to cooling of the local environment, and this was observed, but we also predicted that upon return to being a functioning peatland the peatland would be cooler than the surrounding landscape. Although a cooling trend has been observed for the study peatlands, in only 1 year (2016) was the peatlands observed to be cooler than the surrounding land. The fact that the peatland has been cooler only once during the study period either means that the hypothesis of peats being a cool island in the landscape is not true or that the peatlands of this study have yet to return to being a full functioning peatland.

5. Conclusions

This study has shown that daytime surface temperatures over a restoring peatland significantly decreased relative to the surrounding arable farmland. Prior to peatland restoration, the annual average daytime temperature over the peat soils was 0.7 K significantly warmer than the surrounding farmland on nonpeat soils and were significantly warmer until 2004 when restoration started and after 2005 the peatland was never again significantly warmer than the surrounding mineral soils. However, in only 1 year of the study (2016, 12 years after restoration) was the peatland significantly cooler than the surrounding farmland on mineral soils and even after restoration the peatland was warmer than the surrounding farmlands on 50% of observations over the year. Of the forty-nine 1-km^2 grid squares, six showed a significant change in daytime LST over the 18 years of the study, five of which were on peat soils and only one was on a mineral soil but that was adjacent to and downwind of the peatlands. For the five squares on peatland, the significant decline in temperature was 2 K over the 18 years of the study, while for the one grid square on agricultural nonpeat soil that showed a significant decrease over the course of the study period was 1.3 K. The 1-km^2 grid squares that showed the significant changes were on the downwind side of the peatlands. Given the extensive revegetation from bare soil and the raising of the water tables on the peatlands as part of restoration, it is not possible to ascribe the reason for the temperature change observed. Future research should focus on the understanding the controls on the components of the surface energy partition in peatlands.

Acknowledgments
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References

Adegoke, J. O., Pielke, R. A., Eastman, J., Mahmood, R., & Hubbard, K. G. (2003). Impact of irrigation on midsummer surface fluxes and temperature under dry synoptic conditions: A regional atmospheric model study of the U.S. high plains. *Monthly Weather Review*, *131*(3), 556–564. https://doi.org/10.1175/1520-0493(2003)131<0556:IOIOMS>2.0.CO;2

Admiral, S. W., Lafleur, P. M., & Roulet, N. T. (2006). Controls on latent heat flux and energy partitioning at a peat bog in eastern Canada. *Agricultural and Forest Meteorology*, *140*(1-4), 308–321. https://doi.org/10.1016/j.agrformet.2006.03.017

Allen, R. A., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration—Guidelines for computing crop water requirements*. Rome, Italy: FAO Irrigation and drainage paper 56.

Anderson, T. W., & Darling, D. A. (1952). Asymptotic theory of certain "goodness-of-fit" criteria based on stochastic processes. *Annals of Mathematical Statistics*, *23*(2), 193–212. https://doi.org/10.1214/aoms/1177729437

Betts, A. K., & Ball, J. H. (1997). Albedo over the boreal forest. *Journal of Geophysical Research*, *102*(D24), 28901–28909. https://doi.org/10.1029/96JD03876

Betts, R. A., Falloon, P. D., Goldewijk, K. K., & Ramankutty, N. (2007). Biogeophysical effects of land use on climate: Model simulations of radiative forcing and large-scale temperature change. *Agricultural and Forest Meteorology*, *142*(2-4), 216–233. https://doi.org/10.1016/j.agrformet.2006.08.021

Billett, M. F., Palmer, S. M., Hope, D., Deacon, C., Storeton-West, R., Hargreaves, K. J., et al. (2004). Linking land-atmosphere-stream carbon fluxes in a lowland peatland system. *Global Biogeochemical Cycles*, *18*, GB1024. https://doi.org/10.1029/2003GB002058

Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, *320*(5882), 1444–1449. https://doi.org/10.1126/science.1155121

Boorman, D. B., Hollis, J. M., & Lilly, A. (1995). *Hydrology of soil types: A hydrologically-based classification of the soils of the United Kingdom*. Institute of Hydrology Report No.126. Wallingford: Institute of Hydrology.

Bosilovich, M. G. (2006). A comparison of MODIS land surface temperature with in situ observations. *Geophysical Research Letters*, *33*, L20112. https://doi.org/10.1029/2006GL027519

Campbell, D. I., & Williamson, J. L. (1997). Evaporation from a raised peat bog. *Journal of Hydrology*, *193*(1-4), 142–160. https://doi.org/10.1016/S0022-1694(96)03149-6

Chapman, H. P., & Gearey, B. R. (2013). *Modelling Archaeology and Palaeoenvironments in Wetlands*. Oxbow Books. ISBN 1782971742

Chen, L., & Dirmeyer, P. A. (2016). Adapting observationally based metrics of biogeophysical feedbacks from land cover/land use change to climate modelling. *Environmental Research Letters*, *11*(3).

Clay, G. D., & Worrall, F. (2015). Estimating the oxidative ratio of UK peats and agricultural soils. *Soil Use & Management*, *31*(1), 77–88. https://doi.org/10.1111/sum.12155

Clay, G. D., Worrall, F., & Rose, R. (2010). Carbon budgets of an upland blanket bog managed by prescribed fire—Evidence for enhanced carbon storage under managed burning. *Journal of Geophysical Research*, *115*, G04037. https://doi.org/10.1029/2010JG001331

Coll, C., Caselles, V., Galve, J. M., Valor, E., Niclòs, R., Sánchez, J. M., & Rivas, R. (2005). Ground measurements for the validation of land surface temperatures derived from AATSR and MODIS data. *Remote Sensing of Environment*, *97*, 288–300.

Coll, C., Wan, Z., & Galve, J. M. (2009). Temperature-based and radiance-based validations of the V5 MODIS land surface temperature product. *Journal of Geophysical Research*, *114*, D20102. https://doi.org/10.1029/2009JD012038

Faul, F., Erdfelder, F., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Feddema, J. J., Oleson, K. W., Bonan, G. B., Mearns, L. O., Buja, L. E., Meehl, G. A., & Washington, W. M. (2005). The importance of land-cover change in simulating future climates. *Science*, *310*(5754), 1674–1678. https://doi.org/10.1126/science.1118160

Gallo, K., Hale, R., Tarpley, D., & Yu, Y. (2011). Evaluation of the relationship between air and land surface temperature under clear- and cloudy-sky conditions. *Journal of Applied Meteorology and Climatology*, *50*(3), 767–775. https://doi.org/10.1175/2010JAMC2460.1

Gascoin, S., Ducharne, A., Ribstein, P., Lejeune, Y., & Wagnon, P. (2009). Dependence of bare soil albedo on soil moisture on the moraine of the Zongo glacier (Bolivia). *Geophysical Research Letters*, *36*, L02405. https://doi.org/10.1029/2009JD011709

Gaunt, G.D. (1976). The Quaternary geology of the southern part of the Vale of York. PhD Thesis, University of Leeds.

Georgescu, M., Moustaoui, M., Mahalov, A., & Dudhia, J. (2011). An alternative explanation of the semiarid urban area "oasis effect". *Journal of Geophysical Research*, *116*, D24113. https://doi.org/10.1029/2011JD016720

Gorham, E. (1991). Northern peatlands: Role in the carbon cycle and probable responses to climate warming. *Ecological Applications*, *1*(2), 182–195. https://doi.org/10.2307/1941811

Hemes, K. S., Eichelmann, E., Chamberlain, S. D., Knox, S. H., Oikawa, P. Y., Sturtevant, C., et al. (2018). A unique combination of aerodynamic and surface properties contribute to surface cooling in restored wetlands of the Sacramento-San Joaquin Delta, California. *Journal of Geophysical Research: Biogeosciences*, *123*, 2072–2090. https://doi.org/10.1029/2018JG004494

Herbst, M., Friborg, T., Schelde, K., Jensen, R., Ringgaard, R., Vasquez, V., et al. (2013). Climate and site management as driving factors for the atmospheric greenhouse gas exchange of a restored wetland. *Biogeosciences*, *10*(1), 39–52. https://doi.org/10.5194/bg-10-39-2013

Idso, S. B., Jackson, R. D., Reginato, R. J., Kimball, B. A., & Nakayama, F. S. (1975). Dependence of bare soil albedo on soil water content. *Journal of Applied Meteorology*, *14*(1), 109–113. https://doi.org/10.1175/1520-0450(1975)014<0109:TDOBSA>2.0.CO;2

Intergovernmental Panel on Climate Change (2013). In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate Change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Juang, J. Y., Katul, G., Siqueira, M., Stoy, P., & Novick, K. (2007). Separating the effects of albedo from eco-physiological changes on surface temperature along a successional chronosequence in the southeastern United States. *Geophysical Research Letters*, *34*, L21408. https://doi.org/10.1029/2007GL031296

Kellner, E. (2001). Surface energy fluxes and control of evapotranspiration from a Swedish Sphagnum mire. *Agricultural and Forest Meteorology*, *110*(2), 101–123. https://doi.org/10.1016/S0168-1923(01)00283-0

Kueppers, L. M., Snyder, M. A., & Sloan, L. C. (2007). Irrigation cooling effect: Regional climate forcing by land-use change. *Geophysical Research Letters*, *34*, L03703. https://doi.org/10.1029/2006GL028679

Lee, X., Goulden, M. L., Hollinger, D. Y., Barr, A., Black, T. A., Bohrer, G., et al. (2011). Observed increase in local cooling effect of deforestation at higher latitudes. *Nature*, *479*, 384–387. https://doi.org/10.1038/nature10588

Li, Y., Zhao, M. S., Motesharrei, S., Mu, Q. Z., Kalnay, E., & Li, S. C. (2015). Local cooling and warming effects of forests based on satellite observations. *Nature Communications*, *6*.

Liang, S. L., Fang, H. L., Chen, M. Z., Shuey, C. J., Walthall, C., Daughtry, C., et al. (2002). Validating MODIS land surface reflectance and albedo products: Methods and preliminary results. *Remote Sensing of Environment*, *83*(1-2), 149–162. https://doi.org/10.1016/S0034-4257(02)00092-5

Lohammar, T., Larsson, S., Linder, S., & Falk, S. O. (1980). FAST—Simulation models of gaseous exchange in Scats pine. In: T. Persson (Editor), Structure and function of northern coniferous forests—An ecosystem study. *Ecological Bulletin (Stockholm)*, *32*, 505–523.

Lohila, A., Minkkinens, K., Laines, J., Savolainens, I., Tuovinens, J.-P., Korhonens, L., et al. (2010). Forestation of boreal peatlands: Impacts of changing albedo and greenhouse gas fluxes on radiative forcing. *Journal of Geophysical Research*, *115*. https://doi.org/10.1029/2010JG001327

Loisel, J., Yu, Z., Beilman, D. W., Camill, P., Alm, J., Amesbury, M. J., et al. (2014). A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. *The Holocene*, *24*(9), 1028–1042. https://doi.org/10.1177/0959683614538073

Luyssaert, S., Jammet, M., Stoy, P. C., Estel, S., Pongratz, J., Ceschia, E., et al. (2014). Land management and land-cover change have impacts of similar magnitude on surface temperature. *Nature Climate Change*, *4*(5), 389–393. https://doi.org/10.1038/nclimate2196

Muñoz, I., Campra, P., & Fernández-Alba, A. R. (2010). Including CO_2-emission equivalence of changes in land surface albedo in life cycle assessment. Methodology and case study on greenhouse agriculture. *International Journal of Life Cycle Assessment*, *15*(7), 672–681. https://doi.org/10.1007/s11367-010-0202-5

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., et al. (2009). UK climate projections science report: Climate change projections. Met Office Hadley Centre, Exeter

Nilsson, M., Sagerfors, J., Buffam, I., Laudon, H., Eriksson, T., Grelle, A., et al. (2008). Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire: A significant sink after accounting for all C-fluxes. *Global Change Biology*, *14*(10), 2317–2332. https://doi.org/10.1111/j.1365-2486.2008.01654.x

Olejnik, S., & Algina, J. (2003). Generalized eta and omega squared statistics: Measures of effect size for some common research designs. *Psychological Methods*, *8*(4), 434–447. https://doi.org/10.1037/1082-989X.8.4.434

Parsons, H. T. (1878). The alluvial strata of the lower Ouse valley. *Procedings of the Yorkshore Geological Polytechnical Society*, *6*, 211–238.

Peichl, M., Sagerfors, J., Lindroth, A., Buffam, I., Grelle, A., Klemedtsson, L., et al. (2013). Energy exchange and water budget partitioning in a boreal minerogenic mire. *Journal of Geophysical Research: Biogeosciences*, *118*, 1–13. https://doi.org/10.1029/2012JG002073

Petitcolin, F., & Vermote, E. (2002). Land surface reflectance, emissivity and temperature from MODIS middle and thermal infra-red data. *Remote Sensing of Environment*, *83*, 112–134.

Petrone, R. M., Price, J. S., Waddington, J. M., & von Waldow, H. (2004). Surface moisture and energy exchange from a restored peatland, Quebec, Canada. *Journal of Hydrology*, *295*(1-4), 198–210. https://doi.org/10.1016/j.jhydrol.2004.03.009

Ping, Y., Qiang, Z., Yang, Y., Liang, Z., Hongli, Z., Xiaocui, H., & Xuying, S. (2018). Seasonal and inter-annual variability of the Bowen smith ratio over a semi-arid grassland in the Chinese Loess Plateau. *Agricultural and Forest Meteorology*, *252*, 99–108. https://doi.org/10.1016/j.agrformet.2018.01.006

Rautiainen, M., Stenberg, P., Mottus, M., & Manninen, T. (2011). Radiative transfer simulations link boreal forest structure and shortwave albedo. *Boreal Environment Research*, *16*, 91–100.

Reed, M. S., Hubacek, K., Bonn, A., Burt, T. P., Holden, J., Stringer, L. C., et al. (2013). Less anticipating and managing future trade-offs and complementarities between ecosystem services. *Ecology and Society*, *18*(1), 5.

Rigden, A. J., & Li, D. (2017). Attribution of surface temperature anomalies induced by land use and land cover changes. *Geophysical Research Letters*, *44*, 6814–6822. https://doi.org/10.1002/2017GL073811

Rotenberg, E., & Yakir, D. (2010). Contribution of semi-arid forests to the climate system. *Science*, *327*(5964), 451–454. https://doi.org/10.1126/science.1179998

Roulet, N. T., LaFleur, P. M., Richards, P. J., Moore, T. R., Humphreys, E. R., & Bubier, J. (2007). Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. *Global Change Biology*, *13*(2), 397–411. https://doi.org/10.1111/j.1365-2486.2006.01292.x

Rowson, J. G., Gibson, H. S., Worrall, F., Ostle, N., Burt, T. P., & Adamson, J. K. (2010). The complete carbon budget of a drained peat catchment. *Soil Use and Management*, *26*(3), 261–273. https://doi.org/10.1111/j.1475-2743.2010.00274.x

Ruhli, R. V., Hsu, S. A., Lofgren, B. M., & Binkley, M. R. (2004). Bowen ratio estimates over Lake Erie. *Journal of Great Lakes Research*, *30*(2), 241–251. https://doi.org/10.1016/S0380-1330(04)70342-1

Rydin, H., & Jeglum, J. K. (2013). *The Biology of Peatlands*. Oxford: Oxford University Press. https://doi.org/10.1093/acprof:osobl/9780199602995.001.0001

Shotton, F. W., & Williams, R. F. G. (1973). Birmingham radiocarbon dates VII. *Radiocarbon*, *15*(03), 451–468. https://doi.org/10.1017/S0033822200008924

Thompson, D. K., Baisley, A. S., & Waddington, J. M. (2015). Seasonal variation in albedo and radiation exchange between a burned and unburned forested peatland: Implications for peatland evaporation. *Hydrological Processes*, *29*(14), 3227–3235. https://doi.org/10.1002/hyp.10436

Tian, J., Shangkun, S., & Honglin, H. (2018). The relationship between soil emissivity and soil reflectance under the effects of soil water content. *Physics and Chemistry of the Earth A/B/C*, *110*, 133–137. https://doi.org/10.1016/j.pce.2018.11.006

Tiemeyer, B., Borraz, E. A., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., et al. (2016). Less high emissions of greenhouse gases from grasslands on peat and other organic soils. *Global Change Biology*, *22*(12), 4134–4149. https://doi.org/10.1111/gcb.13303

Tomlinson, C. J., Chapman, L., Thornes, J. E., Baker, C. J., & Prieto-Lopez, T. (2012). Comparing night-time satellite land surface temperature from MODIS and ground measured air temperature across a conurbation. *Remote Sensing Letters*, *3*(8), 657–666. https://doi.org/10.1080/01431161.2012.659354

Van de Griend, A. A., & Owe, M. (1994). Bare soil surface resistance to evaporation by vapor diffusion under semiarid conditions. *Water Resources Research*, *30*(2), 181–188. https://doi.org/10.1029/93WR02747

Venalainen, A. H., Rontu, L., & Solantie, R. (1999). On the influence of peatland draining on local climate. *Boreal Environmental Research*, *4*, 89–100.

Wan, Z. (2014). New refinements and validation of the collection-6 MODIS land-surface temperature/emissivity products. *Remote Sensing of Environment*, *140*, 36–45. https://doi.org/10.1016/j.rse.2013.08.027

Wan, Z., & Dozier, J. (1996). A generalized split-window algorithm for retrieving land-surface temperature from space. *IEEE Transactions on Geoscience and Remote Sensing*, *34*, 892–905.

Wan, Z., Zhang, Y., Zhang, Q., & Zhao-liang, L. (2002). Validation of the land-surface temperature products retrieved from Terra Moderate Resolution Imaging Spectroradiometer data. *Remote Sensing of Environment*, *83*(1-2), 163–180. https://doi.org/10.1016/S0034-4257(02)00093-7

Wan, Z., Zhang, Y., Zhang, Q., & Zhao-liang, L. (2004). Quality assessment and validation of the MODIS global land surface temperature. *International Journal of Remote Sensing*, *25*(1), 261–274. https://doi.org/10.1080/0143116031000116417

Wang, Z. S., Schaaf, C. B., Strahler, A. H., Chopping, M. J., Roman, M. O., Shuai, Y. M., et al. (2014). Evaluation of MODIS albedo product (MCD43A) over grassland, agriculture and forest surface types during dormant and snow-covered periods. *Remote Sensing of Environment*, *140*, 60–77. https://doi.org/10.1016/j.rse.2013.08.025

Worrall, F., Burt, T. P., Clay, G. D., & Moody, C. S. (2015). A 19-year long energy budget of an upland peat bog, northern England. *Journal of Hydrology*, *520*, 17–29. https://doi.org/10.1016/j.jhydrol.2014.11.019

Worrall, F., Clay, G. D., Burt, T. P., & Rose, R. (2012). The multi-annual nitrogen budget of a peat-covered catchment—Changing from sink to source? *Science of the Total Environment*, *433*, 176–188.

Worrall, F., Reed, M. S., Warburton, J., & Burt, T. P. (2003). Carbon budget for British upland peat catchment. *Science of the Total Environment*, *312*(1-3), 133–146. https://doi.org/10.1016/S0048-9697(03)00226-2

Xu, T. R., Liu, S. M., Liang, S. L., & Qin, J. (2011). Improving predictions of water and heat fluxes by assimilating MODIS land surface temperature products into the common land model. *Journal of Hydrometeorology*, *12*(2), 227–244. https://doi.org/10.1175/2010JHM1300.1

Yao, J. M., Zhao, L., Gu, L. L., Qiao, Y. P., & Jiao, K. O. (2011). The surface energy budget in the permafrost region of the Tibetan Plateau. *Atmospheric Research*, *102*(4), 394–407. https://doi.org/10.1016/j.atmosres.2011.09.001

Yu, Z., Loisel, J., Cahrman, D. J., Beilman, D. W., & Camil, P. (2014). Holocene peatland carbon dynamics in the circum-Arctic region: An introduction. *The Holocene*, *24*, 1–7.

Zhao, L., Lee, X., Smith, R. B., & Oleson, K. (2014). Strong contributions of local background climate to urban heat islands. *Nature*, *511*(7508), 216–219. https://doi.org/10.1038/nature13462