Worrall, F., Boothroyd, I., Gardner, R., Howden, N., Burt, T. P., Smith, R., Mitchell, L., Kohler, T., & Gregg, R. (2019). The Impact of Peatland Restoration on Local Climate: Restoration of a Cool Humid Island. *Journal of Geophysical Research: Biogeosciences*, *124*(6), 1696-1713. https://doi.org/10.1029/2019JG005156

The impact of peatland restoration on local climate – restoration of a cool humid island

Fred Worrall[1], Ian M. Boothroyd[1], Rosie L. Gardner[1], Nicholas J.K. Howden[2], Tim P. Burt[3], Richard Smith[4], Lucy Mitchell[5], Tim Kohler[4] and Ruth Gregg[4]

1. Dept of Earth Sciences, Science Laboratories, South Road, Durham, DH1 3LE, UK.
2. Dept of Civil Engineering, University of Bristol, Queens Building, Bristol, BS8 1TR, UK.
3. Dept of Geography, Science Laboratories, South Road, Durham, DH1 3LE, UK.
4. Natural England, Humberhead Peatlands National Nature Reserve, Bawtry Road, Hatfield Woodhouse, Doncaster, DN7 6BF, UK.
5. Department of Biology, University of York, Wentworth Way, York, YO10 5DD, UK.

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, one 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,

---

[11] Corresponding author. Tel. no. +44 (0)191 334 2295; Fred.Worrall@durham.ac.uk,

dug for horticultural peat and after 2004 were restored with revegetation of bare soil and restoration of natural water tables. Over the eighteen years, the average annual daytime land surface temperature (LST) significantly decreased for 6 grid squares, 5 of which were on the restored peatland where LST 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.

Keywords: MODIS, Bowen ratio, evaporation, water tables, albedo.

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 and Jeghum, 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 (IPCC, 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. Worrall et al., 2003, Billett et al., 2004, Roulet et al., 2007, Nilsson et al., 2008), 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. Rowson et al., 2010; Clay et al., 2010; Herbst et al., 2013). 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 a 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 modelled the impact of land use change in the industrial period (deforestation since 1750) and showed that northern mid-latitudes are 1-2 ^{o}C cooler in winter and spring compared to their pre-industrial state solely due to the land use change.

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

$$\mathrm{R_n = H + G + \lambda E + P + e} \quad \text{(i)}$$

where: R_n = net radiation (Wm^{-2}); H – sensible heat flux (Wm^{-2}); G = soil heat flux (Wm^{-2}); λE – latent, or evaporative, heat flux (Wm^{-2}) where λ is the heat of vapourisation (2260 kJ kg^{-1}); P = primary production (Wm^{-2}); and e = 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):

$$B = \frac{H}{\lambda E} \qquad \text{(ii)} \qquad EF = \frac{\lambda E}{\lambda E + H} = \frac{1}{1+B} \qquad \text{(iii)}$$

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, eg. 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 and Dirmeyer, 2016) but few studies of peatland (see review in Luyssaert et al., 2014). Non-forested land tends to have a higher albedo than forested land (Betts and Ball, 1997) but lower surface roughness (Rotenberg and 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 (eg. 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 six-month period at a 20-minute 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 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-year long dataset for a UK blanket bog and found the median Bowen ratio was 0.11 with an inter-quartile 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). Rohli et al. (2004) found 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 UK, 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 4 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 & Methodology

The study considered the change in land surface temperature 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 land surface temperatures of the surrounding farmland on mineral soils. Thorne and Hatfield Moors were chosen because they are not only the largest area of lowland peat in England but because they are also in an area of flat land where topographic effects on temperature will be minimised. The approach used land surface temperatures as derived from the 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 artefacts at the base of the peat have been dated to 3580 ± 108 Calendar years BP (Shotton and Williams, 1983). Parsons (1878) recorded peat depths up to 6.1m on Thorne Moors, implying that the long-term accumulation rate would be of the order of 1.7 mm/yr. However, the discovery of a Neolithic trackway on Hatfield Moor dated to 4500 to 4900 Calendar years BP (Chapman and Geary, 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 UK 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 characterised and included in the study of Clay and Worrall (2015).

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. Land surface temperature (LST)

This study uses the MODIS product TERRA Land Surface Temperature 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 infra-red emissions bands with a pixel size of 1 km^2 and for ambient land surface temperatures the wavelengths used are in the region 10 – 12 μm (Bands 31 and 32 - Petitcolin and Vermote, 2002). Radiative temperature of the Earth surface must be corrected for atmopheric effects and the emissivity of that surface, Within this study as land use changes occur 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 and Dozier, 1996) that correct for atmospheric effects (including absorption and emission) and surface emissivity (inferred from MODIS land-cover calculations) by utilising the other bands bands from the 36 available on the MODIS sensor. The MODIS LST split-window algolrithm has been tested using a range of the available infra-red bands (Petitcolin and Vermote, 2002; Wan et al., 2002, 2004; Coll et al., 2005, 2009; Wan, 2014), but also found to be linearly related to actual air temperatures experienced at land surface (eg. Bosilovich, 2006; Tomlinson et al., 2012; Xu et al., 2011). The daily measurements, to reduce issues of missing data due to cloudy days, are summarised over 8-day periods. The use of 8-day periods means that consistent records between years is 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 dataset 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 (eg. 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.

2.4. Experimental design

In total 49, 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 non-peat squares. The non-peat 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. Non-peat squares were chosen on the north, south, east and west sides of both Thorne and Hatfield Moors with the caveat that the non-peat 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 non-peat 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 (Gount, 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 non-peat 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 non-peat squares change 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 non-peat 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 non-peat 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-square 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 LST were re-analysed but including an additional factor. The additional factor was restoration status (henceforward referred to as Restoration) with two levels – pre- and post-restoration. The pre-restoration 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 pre- and post-restoration periods the Year was nested within the restoration factor.

Albedo (α) data was analysed 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 summarised to each month of the year – this factor had twelve 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 and 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 generalised ω^2 (Olejnik and Algina, 2003) and values were presented as least-square 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 dataset. 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 assess whether this changes over time for the same factors as considered for LST. An initial Chi-squared test of the frequency of cloud cover across the chosen grid squares had suggested an exploration was worthwhile. So we analysed the proportion of missing data in each year (there should be 49 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 non-peat 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 re-initiated 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. Analysis of variance was used to assess the impact of three factors on the depth to the water table: firstly, the Moor factor as above defined above; secondly, the difference between years (henceforward referred to as the Year factor) with 4 levels one for each year between 2014 and 2017 inclusive; and, thirdly, 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 dataset 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 generalised ω^2 (Olejnik and Algina, 2003), and values are presented as least-square 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 night-time 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 day-time 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 in to 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 centre of the peatland (in a peat square) and the other was in the arable land (a non-peat 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 1st February 2018 to 26th September 2018. The air temperature measurement at 11 am 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 land surface temperature (LST) of the peatlands relative to surrounding agricultural land.

Over the study period it should have been possible to consider 40082, 8-day LST measurements in total over the 49 grid squares being examined. In total there were 35663 datapoints with 4418 occasions when no 8-day LST were recorded, an average 90 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 - β) was 1.00 giving a false negative rate of zero, i.e. despite only two levels to some factors in the ANOVA, the overall sample size of the dataset 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 dataset meant that no data were removed.

The ANOVA explained 80.1% of the variance in the dataset 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 (1st January, 2.8 ± 0.2 ^{o}C) and the warmest was day 209 (28th July, 23.8 ± 0.4 ^{o}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 ^{o}C) and the coldest 2001 (12.7 ± 0.2 ^{o}C). Thirdly, the difference between the Moors with Hatfield Moors (14.05 ± 0.06 ^{o}C) being significantly warmer than Thorne Moors (13.49 ± 0.05 ^{o}C). Finally, there was a significant difference due to the Peat factor with peat squares (13.68 ± 0.05 ^{o}C) warmer than non-peat squares (13.85 ± 0.05 ^{o}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 i.e. the change in the difference in the LST between the peat and non-peat 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 five years of the data available before 2005, the peat squares were significantly warmer than the surrounding non-peat squares. In 2000, the annual average LST on peat squares was 15.0 ± 0.1 ^{o}C compared to 14.3 ± 0.1 ^{o}C on the non-peat squares. Over the subsequent 13 years, peat squares never had a higher annual mean LST than non-peat squares, and indeed in 2016 the peat squares were significantly cooler than the surrounding non-peat squares, with an average on peat squares of 13.3 ± 0.1 ^{o}C compared to 13.8 ± 0.1 ^{o}C on non-peat squares. There was no significant trend in the annual average LST values for either the peat or non-peat 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 one year, all be at the end of the study, was the peatland actually significantly cooler than the surrounding non-peat landscape.

The difference between the peat and the non-peat squares is significantly different between the two levels of the Peat factor is considered for each of the Moors. For Hatfield Moors the peat squares were warmer than the non-peat squares in five 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 non-peat squares. Conversely, for Hatfield Moors there were five years where the peat squares were significantly cooler than the non-peat areas starting in 2008. The largest difference for when peat squares were cooler than non-peat squares was in 2013 with peat squares being 0.69 K cooler than the non-peat squares. Taking the least-square 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, P = 0.05) giving an average annual decline in LST for the peat squares on Hatfield Moors as 0.1 ± 0.05 K/yr, but there was no equivalent significant trend for the non-peat 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.

On Thorne Moors the peat squares were warmer than the non-peat 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 non-peat squares, but for 2016 the peat squares were cooler than the non-peat squares. There were no significant trends in the LST for either the peat or non-peat 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 6 showed a significant trend in their least-square means over the 18 years of the study. All 6 significant trends were significant declines and 5 out of the 6 were observed for peat squares; only 1 significant decreasing trend was observed for a non-peat square (expressed as the average change since 2000 - Figure 4). The magnitude of the significant trends varied from -0.07 K/yr to -0.11 K/yr 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/yr (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 non-peat square did show a slight rise in LST over the 18 years of the study but at rate of 0.0002 K/yr 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 north-east side of the Moors or adjacent to the north-east side of the Moors and that the greatest changes were on the peat squares rather than on the non-peat squares. The prevailing wind direction in the UK is from the south west to north east, i.e. air would normally move across the Moors from south west to north east and so any cooling effect would be most pronounced downwind. Furthermore, the settlements of Thorne and Moorends are on the south-west 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 north east. 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 5 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 pre- and post-restoration 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 post-restoration period. Comparing the annual cycle (Day factor) for the Peat factor with respect to Restoration factor shows how the LST between the different land type over the year has varied (Figure 5). Pre-restoration, on 37 out of 46 days the peat squares were warmer than non-peat squares and the greatest difference was with the peat squares 3.3 K warmer than the non-peat squares. Post-restoration, there were 23 out of 46 days when the peat squares were warmer than the non-peat squares and the greatest difference was with peat squares was 1.8 K. Both Pre-restoration and post-restoration, the peat squares were never more than 1 K colder than the non-peat 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 post-restoration 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 dataset.

3.2. Albedo (α)

The Anderson-Darling test suggested data should be log-transformed prior to analysis. Over the annual cycle, comparing 2001 (pre-restoration) with 2017 (post-restoration), it is possible to see that there is no significant difference at the 95% probability between these two years (Figure 6). In 2001, 2 out of 12 months (April and August) were significantly greater than 1, i.e. in just two months the albedo of the peat squares was significantly lower than the non-peat squares. However, in 2017, 7 out of 12 months were significantly different from 1 and given we have assumed constant land use across the study period for the non-peat squares the albedo of the peat squares must have decreased between 2001 and 2017.

3.3. Cloud cover

A simple Chi-squared test based upon the frequency of missing 8-day periods in the LST data suggested a significant difference between peat and non-peat squares, implying that there was significantly less cloud cover over the peat squares than non-peat 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 non-peat squares on its own or due to any of its interactions. The most important significant factor was the Moor factor, i.e. there was a significant difference between Thorne and Hatfield Moors, with Hatfield Moors having a lower proportion of missing data, i.e. 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%); non-peat soils (2%); and non-soil 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), i.e. 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 1783 measurements of water table depth, 18 were removed as being more than three 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-square 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 datasets between 2014 and 2017, 8 had least-square mean water tables above the surface; on Hatfield Moors, 2 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 ± 0.020m (Figure 8). The third most important factor was Year. Given the fact that the data only covered four 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 2017 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.

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:

$$T_{air} = 0.97T_{LST} \qquad n = 70, r^2 = 0.93 \qquad \text{(iv)}$$
$$(0.03)$$

Where: T_{air} = the air temperature at breast height (°C); and T_{LST} = 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 (iv) then the gradient of Equation (iv) is not significantly different from unity.

For the non-peat square location there were 64 occasions when there was an LST observation and an air measurement, the best-fit equation was:

$$T_{air} = 0.91T_{LST} \qquad n = 64, r^2 = 0.91 \qquad \text{(v)}$$
$$(0.04)$$

Equation (v) is significantly different from unity but not significantly different from Equation (y) 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 USA 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 (iv) and (v) 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 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, i.e. 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 (ii)). 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 km^2 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 but 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. Pre-restoration 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 summer-time 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 non-peat squares. Alternatively, Hemes et al. (2018) showed that albedo was higher on wetland sites in comparison to neighbouring alfafa fields but that sensible heat flux was lower during the day on wetlands and latent heat flux was higher at night-time 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 vapour 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 Greind 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 vapour 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 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. Zhao et al., 2014; Chen and Dimeyer, 2016; Rigden and Li, 2017). 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 analyse 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 8 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 8 pairs none had actually had undergone the land use change during the period of the study; no statistical comparison was made between the 8 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 land surface temperature. 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 one 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 non-peat 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 one 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 49 one-km^2 grid squares, six showed a significant change in daytime land surface temperature over the 18 years of the study, 5 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 non-peat 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

Acknowledgements

This study was in part funded as part of 'That's LIFE - Restoration of Humberhead Peatlands' project (LIFE 13NAT / UK /000451)', which is financially supported by LIFE, a financial instrument of the European Commission'. The MODIS data used in this study is available from https://terra.nasa.gov/about/terra-instruments/modis. The other data used are listed in the references.

References

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.

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.

Anderson, T.W., & Darling, D.A. (1952). Asymptotic theory of certain “goodness-of-fit” criteria based on stochastic processes. *Annals of Mathematical Statistics*, 23, 193–212.

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

Bonan, G.B. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science*, 320, 1444–144.

Betts, A.K., & Ball, J.H., (1997). Albedo over the boreal forest. *Journal of Geophysical Research – Atmospheres*, 102, D24, 28901-28909.

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.

Billett, M.F., Palmer, S.M., Hope, D., Deacon, C., Storeton-West, R., Hargreaves, K.J., Flechard, C., & Fowler, D. (2004). Linking land-atmosphere-stream carbon fluxes in a lowland peatland system. *Global Biogeochemical Cycles*, 18, 1, GB1024.

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. Institute of Hydrology, Wallingford.

Bosilovich, M.G. (2006) A comparison of MODIS land surface temperature with in situ observations. Geophysical Research Letters, 33, L20112.

Campbell, D.I., & Williamson, J.L. (1997). Evaporation from a raised peat bog. *Journal of Hydrology*, 193, 1-4, 142-160.

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, Art. No. 034002.

Clay, G.D. & Worrall, F. (2015). Estimating the oxidative ratio of UK peats and agricultural soils. *Soil Use & Management*, 31, 1, 77-88.

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 – Biogeosciences,* 115, G04037.

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, 2005

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

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.

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.

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.

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

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-Atmospheres*, 116, Art. No. D24113

Gorham, E. (1991). Northern peatlands: role in the carbon cycle and probable responses to climate warming. *Ecological Applications,* 1, 182-195.

Hemes, K.S., Eichelmann, E., Chamberlain, S.D., Knox, S.H., Oikawa, P.Y., Sturtevant, C., Verfaillie, J., Szutu, D., Baldocchi, D.D., (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, 7, 2072-2090.

Herbst, M., Friborg, T., Schelde, K., Jensen, R., Ringgaard, R., Vasquez, V., Thomsen, A.G., Soegaard, H. (2013). Climate and site management as driving factors for the atmospheric greenhouse gas exchange of a restored wetland. *Biogeosciences*, 10, 1, 39-52.

.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

IPCC (2013), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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, 21, Art. No. L21408

Kellner, E. (2001). Surface energy fluxes and control of evapotranspiration from a Swedish Sphagnum mire. *Agricultural and Forest Meteorology*, 110, 2, 101-123.

Kueppers, L.M., Snyder, M.A., & Sloan, L.C., (2007). Irrigation cooling effect: Regional climate forcing by land-use change. *Geophysical Research Letters*, 34, 3, Art. No. L03703

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, Art. No. 6603.

Liang, S.L., Fang, H.L., Chen, M.Z., Shuey, C.J., Walthall, C., Daughtry, C., Morisette, J., Schaaf, C., Strahler, A. (2002). Validating MODIS land surface reflectance and albedo products: methods and preliminary results. *Remote Sensing of Environment*, 83, 1–2, 149-162.

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.

Lohilas, A., Minkkinens, K., Laines, J., Savolainens, I., Tuovinens, J-P., Korhonens, L., Laurilas, T., Tietavainens, H., &.Laaksonens, A. (2010). Forestation of boreal peatlands: impacts of changing albedo and greenhouse gas fluxes on radiative forcing. *Journal of Geophysical Research*, 115. 1-15.

Loisel, 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.

Luyssaert, S., Jammet, M., Stoy, P.C., Estel, S., Pongratz, J., Ceschia, E., Churkina, G., Don, A., Erb, K., Ferlicoq, M., Gielen, B., Grunwald, T., Houghton, R.A., Klumpp, K., Knohl, A., Kolb, T., Kuemmerle, T., Laurila, T., Lohila, A., Loustau, D., McGrath, M.J., Meyfroidt, P., Moors, E.J., Naudts, K., Novick, K., Otto, J., Pilegaard, K., Pio, C.A., Rambal, S., Rebmann, C., Ryder, J., Suyker, A.E., Varlagin, A., Wattenbach, M., & Dolman, A.J. (2014). Land management and land-cover change have impacts of similar magnitude on surface temperature. *Nature Climate Change,* 4, 5, 389-393.

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,** 672–681.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Howard, T.P., Humphrey, K.A., McCarthy, M.P., McDonald, R.E., Stephens, A., Wallace, C., Warren, R., Wilby, R., & Wood, R.A. (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., Klemedtsson, L., Weslien, P., & Lindroth, A. (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.

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.

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

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. Agric*ultural and Forest Meteorology*, 252, 99-108.

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., Beharry-Borg, N., Buckmaster, S., Chapman, D., Chapman, P.J., Clay, G.D., Cornell, S.J., Dougill, A.J., Evely, A.C., Fraser, E.D.G, Jin, N., Irvine, B.J., Kirkby, M.J., Kunin, W.E., Prell, C., Quinn, C.H., Slee, B., Stagl, S., Termansen, M., Thorp, S., & Worrall, F., (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(13), 6814-6822

Rotenberg, E., & Yakir, D. (2010). Contribution of Semi-Arid Forests to the Climate System. *Science*, 327, 5964, 451-454.

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, 397-411.

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.

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.

Rydin, H., & Jeglum, J.K. (2013). *The Biology of Peatlands* Oxford University Press, Oxford.

Schultz, N.M., Lee, X., Lawrence, P.J., Lawrence, D.M., & Zhao, I. (2016). Assessing the use of subgrid land model output to study impacts of land cover change. *Journal of Geophysical Research – Atmosphere*, 121, 11, 6133-6147.

Shotton, F.W. & Williams, R.F.G. (1973). Birmingham radiocarbon dates Vii. Radiocarbon 15, 451-468.

Tiemeyer, B., Borraz, E.A., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., Drosler, M., Ebli, M., Eickenscheidt, T., Fiedler, S., Forster, C., Freibauer, A., Giebels, M., Glatzel, S., Heinichen, J., Hoffmann, M., Hoper, H., Jurasinski, G., Leiber-Sauheitl, K., Peichl-Brak, M., Rosskopf, N., Sommer, M., & Zeitz, J. (2016), Less High emissions of greenhouse gases from grasslands on peat and other organic soils. *Global Change Biology*, 22, 12, 4134- 4146.

Thompson, D.K., Baisley, A.S., & Waddington, J.M. (2015). easonal variation in albedo and radiation exchange between a burned and unburned forested peatland: implications for peatland evaporation. *Hydrological Processes*, 29, 14, 3227-3235.

Tian, J., Shangkun, S., Honglin, H.The relationship between soil emissivity and soil reflectance under the effects of soil water content. Physics and Chemistry of the Earth A/B/C, doi.10.1016/j.pce.2018.11.006.

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.

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.

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.

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, 163-180.

Wan, Z., Zhang, Y., Zhang, Q., & Zhao-liang, L. (2004). Quality assessment and validation of the MODIS global land surface temperature. Int. J. Remote Sensing, 25, 1, 261-274.

Wang, Z.S., Schaaf, C.B., Strahler, A.H., Chopping, MJ., Roman, M.O., Shuai, Y.M., Woodcock, C.E., Hollinger, D.Y., Fitzjarrald, D.R. (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.

Worrall, F., Reed, M.S., Warburton, J., & Burt, T.P. (2003). Carbon budget for British upland peat catchment. *Science of the Total Environment*, 312, 133-146.

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., 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.

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.

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.

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.

Table 1. The results of ANOVA for the four factors: Year, Peat, Day and Moor.

Factor (Interaction)	P	Proportion of variance explained (w^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

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

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.

Figure 3. The least mean squares (annual average daytime land surface temperature) for the interaction between Peat and Year factors, i.e. between the peat (peatland) and non-peat 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.

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.

Figure 5. The least mean squares (average daytime land surface temperature) for the interaction between Peat, Restoration and Day factors, i.e. between the peat (peatland) and non-peat squares (Arable land) over the course of the year. The error bar, 95% confidence interval, are within the size of the datapoint. a) Peat and Day factors pre-restoration; and b) Peat and Day factors post-restoration.

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

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

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.