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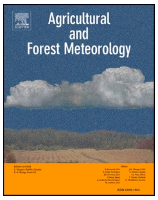

Biometeorological feedbacks on peatlands: Raising the water table to reduce meteorologically-related stress on cattle

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ABSTRACT

Peatland restoration is an important mitigation action in the fight against climate change. Researchers encourage farmers to rewet deep-drained lands on organic soil to a shallow water table depth (WTD) to reduce carbon emissions. Raising WTD under grasslands will likely affect local air temperature (TA) and increase relative humidity (RH), with uncertain consequences during heat waves on cattle welfare. We used WTD, TA and RH data (both measured between 1.25 and 2 m above ground) from 22 peatland sites globally to evaluate peatlands' overall Temperature Humidity Index (THI), an indicator correlated to cattle welfare used in dairy farms (THI>68 increases heart rate, breathing rate and reduces milk yield). We compared them with THI at state weather stations located on neighbouring lands with short grass on non-organic soil, and assessed the impact of WTD.

At most sites, peatlands with shallow WTD had lower TA, higher RH, and an overall lower THI than surrounding lands, compared to those with deep WTD. In most cases, THI decreased with increasing WTD, especially at night in the temperate region, except for coastal peatlands. Shallow and submerged sites had 20 % less hours with stressful meteorologic conditions (high THI) than surrounding areas. In contrast, the number of hours with high THI did not change significantly on peatlands with WTD under 20 cm below ground level compared to control sites. Our results confirm the influence of WTD on local temperature and THI, and suggest that raising WTD on drained peatlands will slightly improve cattle welfare with reduced THI during heat waves, but also acknowledge that local geographic characteristics add complexity to this relationship. Our research indicates that raising WTD to ground level in sections of grasslands could provide "heat wave shelters" and increase cattle resilience to climate change while contributing to the global reduction of carbon emissions.

1. Introduction

1.1. Raising water table depths, a climate change mitigation action

In 2021, world leaders agreed to "hold the increase in the average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change" (UNFCCC, 2021, p. 3). Unfortunately, since 2010, global anthropogenic greenhouse gas emissions have increased, and Agriculture, Forestry, and Other Land Use (AFOLU) represented 22 % of global emissions in 2019 (IPCC, 2022), with variability across world regions (Lamb et al., 2021). In Ireland and New Zealand, AFOLU sector emissions represent more than 40 % of total emissions (EPA, 2022; New Zealand Ministry for the Environment, 2022), exacerbated by the economic importance of their peatlands for peat extractions, with

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applications in the energy and horticulture sector and for agricultural land use. Consequently, these countries' wetlands moved from being carbon sinks to becoming sources of greenhouse gas (GHG) emissions to the atmosphere (Feehan et al., 2008; New Zealand Ministry for the Environment, 2022). Research has highlighted that peatland rewetting projects are essential elements of climate change mitigation (Renou-Wilson et al., 2022; Wilson et al., 2022). Climate change will also exert pressure on peatlands with increasing frequency of high temperature and drought events (IPCC, 2021). In this context, policy-makers and land-owners received recommendations for early restoration of drained peatlands and long-term monitoring (Renou-Wilson and Wilson, 2018). However, land fragmentation and ownership diversity are challenges (Joosten and Clarke, 2002).

Evans et al. (2021) analysed the annual GHG balance over a wide range of peatlands and established that their CO_2 emissions are correlated to mean Water Table Depth (WTD). They suggested an "optimal rewetting" scenario to mitigate GHG emissions would be to elevate the water table to 10 cm below ground level. They also defined an "agricultural mitigation" that brings the water table to 25 cm under grassland and 45 cm under cropland as a compromise; this would eliminate most CO_2 emissions from peat decomposition while still enabling the land-owners to produce food and limiting methane emissions of peatlands in anaerobic conditions, when water table depth is above 30 cm below ground level (Evans et al., 2021). It is the background to the advice to farmers from Teagasc, the Irish national agricultural advisory body, to raise grassland water table levels, with the target of rewetting either 40, 000 ha of organic grassland soils in the country or converting 65,000 ha from a deep to a shallow drained state (Lanigan et al., 2019). While Teagasc provides economic background to this land management proposition, they do not explore further consequences at the farm level.

Research has previously established that local weather conditions change according to land type and land use. In temperate climates, wetlands in China influenced local air temperature in urban (Hou et al., 2013) and agricultural areas, with a cooling and moistening effect during the day and a warming-moistening one at night (Liao et al., 2013). Peatlands in the United Kingdom (Worrall et al., 2022) and wetlands in Finland (Aalto et al., 2022) also showed similar relationships. In warm continental climates such as Iran, the increasing soil dryness in Gavkhouni wetland since the year 2000 increased the mean seasonal air temperature by 1.6 °C in spring and 1 °C in summer (Azadi et al., 2022). We expect that changing peatlands WTD will likely affect local weather conditions, such as air temperature and relative humidity on the land.

1.2. *Climate change and concerns for animal welfare in grasslands*

Mammals have developed different mechanisms to cope with air temperature variations to regulate their internal body temperature. This includes behavioural (seeking or avoiding shade, staying in a group or away from each other) and physiological (variations of fur through seasons, pulse rate variations, sweating, panting, erection of hair mechanisms) adaptations. In the case of cattle and sheep, animal coats adapt to seasonal variations, but their ability to sweat is limited, so they are sensitive to temperature stress (Oke, 1987). Milk productivity and quality are impacted negatively during summer months if they do not have access to cooling systems (Valtorta and Gallardo, 2004). Berry et al. (1964) adapted a discomfort index originally developed for humans to create the Temperature Humidity Index (THI) that evaluates cattle heat stress (Hahn et al., 2009; Collier et al., 2012; Dahl, Tao and Laporta, 2020; Adhikari et al., 2022). The farming sector, including in Ireland, now uses THI as a management monitoring tool (Teagasc, 2021a) as concerns from climate change grow, threatening grazing herds with intense heat and THI with an increasing frequency (Morignat et al., 2014; Lees et al., 2019; Adhikari et al., 2022). Most extreme heatwaves were found to be linked with mortality rate increases and highlighted the limited ability of cows to dissipate heat during the night (Vitali et al., 2015). In our study, we will consider THI as an indicator of local climate, and therefore will use it not only on lands used for grazing, but on all peatlands with varying WTD.

When raising WTD, we expect air temperature (TA) to decrease and relative humidity (RH; both measured between 1.25 and 2 m above ground) to increase on peatland sites (Liao et al., 2013; Worrall et al., 2022). These two outcomes have opposite effects on animal welfare, leaving dairy professionals uncertain about the potential consequences of Teagasc's grassland management proposition. In our appreciation of current literature, the evaluation of the impact on local THI and cattle welfare from peatland restoration with partial rewetting has not been established yet. In this study, we first confirmed the relationship between peatlands WTD and local TA and THI. We then considered the impacts from WTD on the frequency of extreme weather events to which cattle are exposed. Lastly, we reviewed how peatlands WTD can impact local THI through summer circadian cycles to provide details on the potential impact on night-time recovery from heat waves.

2. Methods

2.1. *Sites selection*

Ecosystem weather variables, including true TA and RH, are amongst the data collected on eddy covariance towers, which emerged at the beginning of the 21st century as an innovative way to measure net CO_2 and H_2O exchanges from a whole ecosystem with the atmosphere (Baldocchi, 2003). Technological progress, notably in data processing capacity and sensors, increased their use to study ecosystems' carbon cycling, such as grasslands, forests, wetlands, or croplands (Liang and Wang, 2020).

The analysis used eddy covariance data published on AmeriFlux (https://ameriflux.lbl.gov/) and European Fluxes Database Cluster (http://www.europe-fluxdata.eu/), United Kingdom Centre for Ecology & Hydrology (UK-CEH) (Evans et al., 2021) and the Service National d'Observation Tourbières (SNO Tourbières) (Gogo et al., 2021), that include hourly and/or half hourly TA, RH, and WTD. Below ground WTD have negative values, while positive values represent sites with water above ground level. The hourly datasets from UK-CEH did not include WTD, so we used mean WTD from publications that investigated its correlations with GHG flux and carbon balances shown in Table 1 (Evans et al., 2016, 2021). A dataset supporting the work on CO_2 emissions from dairy farms on drained peatlands in New Zealand was kindly provided by the Principal Investigator (Campbell et al., 2021a). This first selection enabled the retrieval of 38 peatland site datasets. Half hourly records were converted to hourly datasets to enhance data structure consistency.

To evaluate the impacts on local temperature and relative humidity of peatland sites, we also collected these variables from neighbouring National Weather Stations (NWS) from governmental weather services, ensuring that these stations were not on peatlands, over short grass vegetation as per the World Meteorological Organisation guidelines, at a distance from the study sites of less than 50 km, and at a similar altitude. Table 2 presents the selected meteorological sites.

Twenty-three peatland sites were selected based on the criteria above, including proximity to NWS (see Table 1). We used the International Geosphere-Biosphere Programme (IGBP) to categorise peatlands as Wetlands "WET" with mean WTD ranging from −0.46 m (below ground level) to +0.62 m (above ground level). We included also a rice paddy, US-Twt, with shallow WTD (average −0.11 m), and a lettuce and potato production farm, UK-MH (average WTD −0.52 m) defined as a croplands, "CRO"; two drained sites used as Grasslands "GRA", US-Sne (mean WTD = 0.141 m, flooded since 2016, Valach et al., 2021b) and NZ-Moa-SD (Mean WTD = −0.69 m), and a grassland on non-organic soil used as a baseline for our analysis (Loveland and Belward, 1997; IGBP, 2015). Throughout the manuscript, we refer to all sites on peat soil as 'peatland' regardless of their land use. We refer to sites classified as

Table 1
List of study sites, locations, and data sources with means of Water Table Depth (WTD), Relative Humidity (RH) and Air Temperature (TA) per site across the retrieved data.

Network/ research centre	Site code	Site name	Climate	Land type	Latitude	Longitude	Mean WTD (M)	Mean RH (%)	Mean TA (°C)	Data source
AmeriFlux	CA-DBB	CA-Delta Burns Bog	Csb	WET	49°07′45′’N	112°59′05′’W	−0.062	83.1	10.4	(Christen and Knox, 2021; Knox, 2021)
	CA-WP1	CA-La Biche River	Dfc	WET	54°57′13′’N	112°28′01′’W	−0.456[a]	73.1	2.0	(Flanagan, 2018; Flanagan and Syed, 2011)
	US-Myb	US-Mayberry Wetland	Csa	WET	38°02′59′’N	121°45′54′’W	0.567	66.9	15.6	(Hatala Matthes et al., 2021)
	US-Sne	US-Sherman Island Restored Wetland	Csa	GRA[b]	42°44′32′’N	70°49′48′’W	0.141	67.2	15.4	(Shortt et al., 2021)
	US-Tw1	US-Twitchell Wetland West Pond	Csa	WET	38°02′12′’N	121°45′16′’W	0.473	64.7	15.0	(Valach et al., 2021a)
	US-Tw4	US-Twitchell East End Wetland	Csa	WET	38°06′26′’N	121°38′48′’W	0.263	62.8	15.4	(Eichelmann et al., 2021)
	US-Tw5	US-East Pond Wetland	Csa	WET	38°06′09′’N	121°38′28′’W	0.621	64.5	15.1	(Valach et al., 2020)
	US-Twt	US-Twitchell Island	Csa	CRO	38°06′25′’N	121°38′33′’W	−0.117	68.0	14.8	(Knox et al., 2018)
	US-PHM	US-Plum Island High Marsh	Dfa	WET	38°06′31′’N	121°39′11′’W	−0.054	71.1	10.0	(Giblin, 2021; Forbrich, Giblin and Hopkinson, 2018)
Europe Fluxdata	DE-Hte	DE-Huetelmoor	Cfb	WET	54°12′36′’N	12°10′33′’E	−0.272	79.8	9.8	(Jurasinski, 2018)
	DE-Zrk	DE-Zarnekow	Dfb	WET	53°52′33′’N	12°53′20′’E	0.444	83.7	9.8	(Sachs, 2020)
	IE-Dri	IE-Dripsey	Cfb	GRA	51°59′13′’N	08°45′07′’W	−1.084	86.4	9.6	(Kiely, 2010; Jaksic et al., 2006)
	IE-Kil	IE-Glencar	Cfb	WET	51°58′04′’N	09°54′00′’W	−0.035	82.3	10.5	(Kiely, 2011; Koehler, Sottocornola and Kiely, 2011)
UK-CEH	UK-AF1	UK-Anglesey 1	Cfb	WET	53°18′36′’N	04°17′24′’W	−0.07	85.2	9.8	(Evans et al., 2021; Morrison et al., 2021)
	UK-AF2	UK-Anglesey 2	Cfb	WET	53°18′36′’N	04°18′−01′’W	−0.07	83.2	9.8	
	UK-CW	UK-Conwy	Cfb	WET	52°59′24′’N	03°48′−01′’W	−0.04	83.2	9.8	
	UK-CG	UK-Cairngorms	Cfb	WET	51°12′36′’N	02°49′48′’W	−0.10	86.5	6.0	(Artz et al., 2021)
	UK-IG	UK-Moor House	Cfb	WET	54°42′00′’N	02°23′24′’W	−0.02	92.7	6.4	(Morrison et al., 2021)
	UK-MH	UK-Redmere 2	Cfb	CRO	52°27′00′’N	00°25′12′’E	−0.59	84.5	9.4	
	UK-SA	UK-Tadham_Moor_2	Cfb	GRA	56°55′47′’N	03°09′36′’W	−0.36	82.4	10.4	
SNO Tourbières	FR-Frn	FR-Frasne	Cfb	WET	46°50′24′’N	06°10′40′’E	−0.132	83.4	7.0	(Toussaint et al., 2020; Jacotot et al., 2021)
	FR-LGt	FR-La Guette	Cfb	WET	47°19′22′’N	02°17′02′’E	−0.117	83.2	10.7	(Binet et al., 2020; Gogo et al., 2022)
Waikato University	NZ-Moa-SD	NZ-Moanatuatua, “Surface-Drained” site	Cfb	GRA	37°57′14′’S	175°23′09′’E	−0.691	84.32	14.74	(Campbell, 2022)

[a] La Biche River data WTD winter data was missing from datasets.
[b] Sherman Island site is classified as grassland until 2016 but the wetland was restored since. This analysis is on the restoration years with increased WTD.

"WET" and "GRA" according to IGBP in their site description as ’wetland’ and ’grassland’, respectively.

We also characterised the peatlands of the study using climate classification established by Köppen–Geiger (Beck et al., 2018). Most sites of the analysis are in an oceanic climate (“Cfb”), such as peatlands in Ireland, the UK, France, Germany and New Zealand, and Mediterranean hot summer climate (“Csa”). Three sites are currently in continental climate (prefixed “D”) in Canada, Germany, and the United States.

We included an Irish grassland on gleysol, Dripsey, as a baseline as it is one of the few grasslands monitored by eddy covariance measurements that includes hourly WTD. It has a deep WTD (−1.08 m on average) and represents the conditions currently prevalent in Irish grasslands (Peichl, Leahy and Kiely, 2011).

2.2. Temperature Humidity Index measurements

The THI index is essential to farmers: when it reaches the thresholds displayed in Table F.1 (Appendix F), herds are under increasing heat stress.

The hourly mean Temperature Humidity Index, THIm (Eq. (1)), is a function of local hourly mean air temperature (TAm) in degree Celsius (°C) and hourly mean relative humidity (RHm) percentage (%) (Hahn et al., 2009; Collier et al., 2012).

$$THIm = 0.8 * TAm + RHm * (TAm - 14.4) + 46.4 \tag{1}$$

For each study site and meteorological site, we represented TA, THI and WTD over time, as shown in the example of Zarnekow peatland in Germany, and the associated weather station Teterow (Appendix A). These variables are also presented in Appendix B for all selected sites, and in Appendix C for all weather stations.

To evaluate cattle stress from weather conditions and especially from heat waves, we calculated the hourly differences of temperature (δTA) (Eq. (2)) and THI (δTHI) (Eq. (3)) between the peatlands of the study and adjoining NWS.

$$\delta TA = StudySiteTAm - NationalWeatherStationTAm \tag{2}$$

$$\delta THI = StudySiteTHIm - NationalWeatherStationTHIm \tag{3}$$

Negative values indicate a reduction of TA or THI at the peatland compared to NWS.

Table 2
List of National Weather Stations (NWS), location coordinates, study sites to which the meteorological site is assigned, and distance in kilometres to the associated study site. Mean Relative Humidity (RH) and Temperature (TA) are reported for the period of analysis of each study site.

NWS	Latitude	Longitude	Associated site	Distance (km)	Mean RH (%)	Mean TA (°C)	Study from	Study to	Source
Vancouver Sea Island	49°10′58′′N	123°11′13′′W	CA-DBB	16	80.1	10.8	09/06/15	31/12/20	Environment and Climate Change Canada - Meteorological Service of Canada, 2022
Lac La Biche	54°46′12′′N	112°01′11′′W	CA-WP1	16	70.5	2.4	01/11/03	30/09/09	
Brentwood	37°55′40′′N	121°39′35′′W	US-Myb	16	60.7	16.5	27/10/10	27/05/21	California Irrigation Management Information System (CIMIS), 2022
			US-Sne	15	59.7	17.4	24/05/16	30/12/20	
			US-Tw1	20	60.3	16.9	11/04/11	31/12/20	
			US-Tw4	19	60.6	16.9	25/11/13	27/05/21	
			US-Tw5	20	58.4	17.5	17/04/18	29/01/20	
			US-Twt	15	62.4	16.0	27/10/10	04/04/17	
Durham	47°29′56′′N	02°25′37′′E	US-PHM	42	70.8	8.8	01/01/13	30/12/20	National Centre for Environmental Information (NCEI), 2001
Sanitz	54°04′15′′N	12°19′26′′E	DE-Hte	18	81.9	9.0	01/01/09	31/12/18	Deutscher Wetterdienst (German Weather Service) Climate Data Centre (CDC), 2022
Teterow	53°45′39′′N	12°33′25′′E	DE-Zrk	25	80.4	10.2	22/03/13	01/01/21	
Cork Airport	51°50′49′′N	08°29′09′′W	IE-Dri	24	86.6	9.8	01/01/04	31/12/10	Met Éireann, 2022
Kerry Valencia	51°56′16′′N	10°14′27′′W	IE-Kil	27	81.7	11.2	01/09/02	27/07/12	
Valley	53°15′00′′N	04°32′24′′W	UK-AF1	18	81.7	10.7	01/01/15	20/03/20	National Meteorological Library and Archive – Met Office, 2022
Valley	53°15′00′′N	04°32′24′′W	UK-AF2	17	81.7	10.7	01/01/15	20/03/20	
Balmoral	57°02′23′′N	03°13′12′′W	UK-CG	13	81.4	8.4	04/07/18	04/11/19	
Rhyl No 2	53°15′35′′N	03°30′35′′W	UK-CW	36	79.5	11.5	04/07/18	04/11/19	
Carlisle	51°00′35′′N	02°38′24′′W	UK-IG	26	81.3	10.8	01/01/17	25/04/20	
Cambridge Niab	54°55′47′′N	02°57′35′′W	UK-MH	45	80.5	10.0	21/06/18	21/06/19	
Yeovilton	52°15′00′′N	00°06′00′′E	UK-SA	31	80.9	9.5	26/10/18	12/04/20	
Pontarlier	46°54′07′′N	06°20′27′′E	FR-frn	14	77.8	8.6	06/11/08	08/04/20	Données Publiques / Publithèque Météo-France (2022)
Aubigny-Sur-Nère	47°29′56′′N	02°25′37′′E	FR-lgt	17	79.3	11.8	10/12/10	01/01/22	
Ruakura	38°14′26′′S	175°18′18′′E	NZ-Moa-SD	21	80.6	14.3	01/01/19	01/01/22	CliFlo (NIWA, 2022)

In the second part of the analysis, we reviewed the length of time with extreme weather events defined by the number of hours at each site with THI above each threshold per calendar month (h_{THI68}, h_{THI72}, and h_{THI80}).

The expression of differences between the peatlands of the study and the NWS are shown in Equations 4, where $\Delta h_{THI.Threshold}$ represents hours difference with THI above the welfare thresholds defined in Appendix F.

$$\Delta h_{\mathrm{THI.Threshold}} = h_{\mathrm{THI.Threshold}}(Peatlands) - h_{\mathrm{THI.Threshold}}(NWS) \tag{4}$$

When $\Delta h_{THI.Threshold}$, i.e. Δh_{THI68}, Δh_{THI72} and Δh_{THI80} are below 0, they indicate an extreme THI time reduction at the peatland compared to the NWS.

2.3. Data analysis

We controlled the quality of the data collected using the methodology of meteorological time series from Faybishenko et al. (2022), to produce clean and standardised datasets for the analysis, represented in Figs. B.1 and C.1 and summarised in Table D.1 in the Appendix.

Each hourly dataset constructed above was processed using R Programming to build a master database representing each calendar month for each study site data, associated with their respective NWS data (Grolemund and Wickham, 2011; Dowle and Srinivasan, 2021; R Core Team, 2021; Wickham et al., 2021; RStudio PBC, 2022; Wickham and Girlich, 2022). We excluded outliers, duplicates and reported missing data, to exclude from our analysis calendar months with less than 75 % valid data. We then calculated in R hourly mean air temperature (TAm) and relative humidity (RHm), and hourly mean water table depth (WTDm) for each peatland site and associated NWS in the new datasets to eliminate potential bias from measurement frequency variations between datasets.

Data retrieved from NWS are collected from probes between 1.25 and 2 m above ground as per international standard (World Meteorological Organization, 2021). We also controlled probe characteristics at the study sites. TA and RH data were also collected between 1.25 and 2 m above ground on most sites. For TA, the true TA was used as identified by the site PI (i.e. this already included the necessary corrections if based on sonic anemometer measurements). US-Myb, US-Tw1, US-Tw4, US-Tw5, US-Sne in the United States and CA-WP1 in Canada were recorded 5 m above ground, and US-Twt probe was 2.8 m above ground. The emergent vegetation at four of the California sites (US-Myb, US-Tw1, US-Tw4 and US-Tw5) has a canopy height of between 2 and 3 m, mainly a mixture of cattails (*Typhas* spp.) and tules (*Schoenoplectus acutus*), which means that the air temperature sensors are mounted approximately 2 m above the canopy, comparable to the weather station set up (Eichelmann et al., 2018; Hemes et al., 2018). US-PHM site, on the Eastern coast of the US, had data taken at 14 m above ground (Forbrich, Giblin and Hopkinson, 2018). TA and RH measurements on Dripsey (Ireland) grassland site used as a baseline were taken 3 m above ground (Jaksic et al., 2006). We note that this discrepancy in sensor mounting height at a small number of sites is a possible cause of data variability in this research.

Over the 22 peatland sites, we obtained 1413 validated monthly entries for our study. In order to investigate data variability, we represented *δTA* and *δTHI* in separate site and period classes (with an average monthly THI above or below 60). We also evaluated the impact on mean *δTA* and *δTHI* from other site characteristics such as distance to coastal area or distance to associated NWS using students' *t*-tests. We evaluated *δTA* and *δTHI* against WTD with linear regression and reviewed data variability homoscedasticity and normality. Lastly, we used analysis of covariance to determine the influence of distance to NWS or to the sea, to understand in further details the role of these factors on the relationship between WTD and variations of temperatures and THI. Linear regression information is presented with 95 % Confidence Intervals (CI) calculated using R, and presented between square brackets in the format [95 % CI Lower limit; Upper limit of CI].

3. Results

3.1. Global influence of WTD on local temperature and THI

3.1.1. Baseline for grasslands of temperate climate

We represented each calendar month with valid data with a dot on the graphs shown in Fig. 1 to assess δTA and δTHI as a function of WTDm. On the baseline grassland in Dripsey (Ireland), variations of WTD did not modify δTA or δTHI over the seven years of monitoring (p= 0.53 and 0.76, respectively). TA and THI appear slightly reduced on the grassland compared to the Cork Airport weather station, 42 km away, with negative δTA and δTHI averages over the whole range of WTD found on the site. The intercept of the Dripsey δTA trendline is −0.28 °C [95 % CI: −0.46 °C; −0.10 °C], and the δTHI intercept is −0.69 [95 % CI: −1.18; −0.20].

3.1.2. General overview of peatlands WTD and local TA and THI

The monthly WTD averages from the datasets selected for the study ranged from −1.27 m (below ground level) to +0.90 m (above ground level, Fig. 1). We investigated the relationships between WTD and δTA or δTHI using diagnostic plots for both variables in Appendix E. The normality of the δTA or δTHI is challenged, with standardised residuals away from the trend line at the extreme theoretical quantiles (Fig. E.1b and f). Consequently, additional datasets collected at peatlands with deep WTD would improve this study. The downward curves in Fig. E.1a and E.1e and the trendline slopes in Fig. E.1c and E.1g show that the relationship between WTD and TA / THI are heteroscedastic

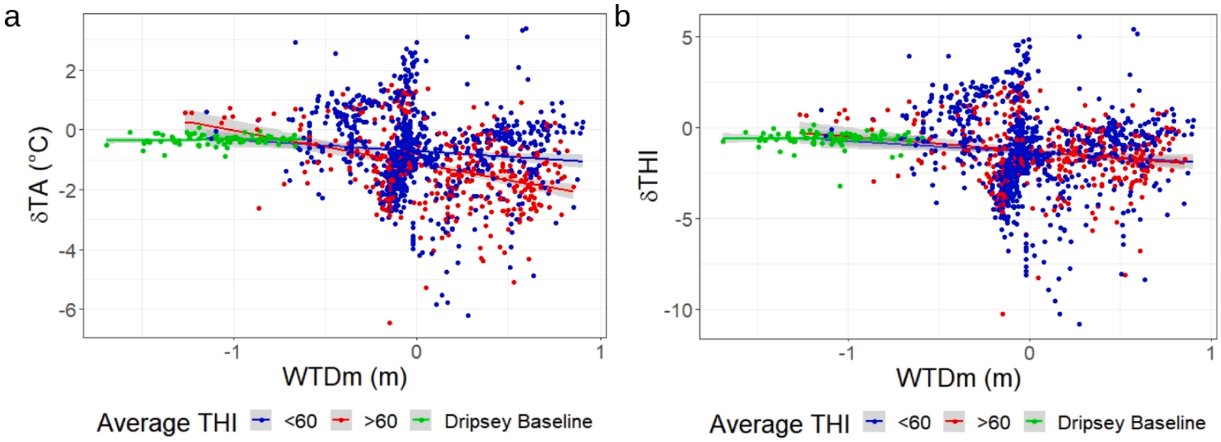

Fig. 1. (a) Monthly mean Temperature difference (δTA) and (b) Temperature Humidity Index difference (δTHI) represented against monthly mean Water table depth (WTDm), between study sites and neighbouring national weather stations. In both graphs, red dots represent the calendar month with average THI above 60; blue dots are calendar months with average THI below 60. Dripsey grassland in Ireland (in green) is represented as a baseline.

Table 3
Global regression equations and regression factors between mean water table depth (WTDm) and differences of air temperature and Temperature Humidity Index between peatlands and neighbouring national weather stations (δTA and δTHI).

Data selection	Regression equation	Regression coefficients	Slope	Intercepts
All sites, all months	δTA= −0.75 WTDm −0.8	$R^2 = 0.043$, $p< 0.001$, $n = 1413$.	−0.75 [95 % CI: −0.93; −0.57]	−0.84 °C [95 % CI: −0.91; −0.78 °C]
	δTHI = −0.67 WTDm −1.3	$R^2 = 0.013$, $p< 0.001$, $n = 1413$.	−0.67 [95 % CI: −0.98; −0.36]	−1.34 [95 % CI: −1.44; −1.23]
THI < 60	δTA= −0.38 WTDm – 0.7	$R^2 = -0.0096$, $p = 0.002$, $n = 1028$.	−0.38 [95 % CI: −0.61; −0.14]	−0.72 °C [95 % CI: −0.79; −0.64]
	δTHI = −0.61 WTDm – 1.3	$R^2 = -0.0079$, $p = 0.004$, $n = 1028$.	−0.61 [95 % CI: −1.02; −0.19]	−1.35 [95 % CI: −1.48; −1.22]
THI > 60	δTA= −1.1 WTDm – 1.1	$R^2 = -0.12$, $p< 0.001$, $n = 385$.	−1.10 [95 % CI: −1.40; −0.80]	−1.12 °C [95 % CI: −1.25; −1.00]
	δTHI = −0.8 WTDm – 1.3	$R^2 = -0.032$, $p< 0.001$, $n = 385$.	−0.80 [95 % CI: −1.23; −0.36]	−1.29 [95 % CI: −1.47; −1.11]

(Beckerman, Childs, and Petchey, 2017). The variance is affected by additional factors to those considered in the analysis, especially for peatlands with WTD above ground levels.

While δTA and δTHI show considerable variability, they have a significant negative relationship with WTD ($p < 0.001$ in both cases), with regression equations presented in Table 3.

Fig. 1 shows that δTA and δTHI are on average below 0 [95 % CI] on peatlands with shallow and submerged water levels, which means that temperatures and THI on peatlands are, on average, below the temperatures and THI in the associated NWS.

Further data analysis established that the relationships between WTDm and δTA or δTHI and its variability are affected by the distance from the study sites to the NWS ($F= 19.23$; df $=1$; $p < 0.001$) and by the distance to coastlines ($F= 12.93$; df $= 1$; $p < 0.001$). This is an expected result as increased distance between compared sites covers more environmental variability (e.g. topography, vegetation cover); tidal variations are also expected to impact coastal areas WTD and meteorological data variability.

We then repeated the analysis to evaluate correlations between WTDm and δTA and δTHI, excluding sites with a distance between the study site and NWS above 40 km (Plum Island High Marsh, US-PHM and Moor House Blanket Bog, UK-MH), as well as sites within 5 km from coastlines (Huetelmoor fen, DE-I and Plum Island High Marsh, US-PHM). While this had the consequence of reducing the variability of

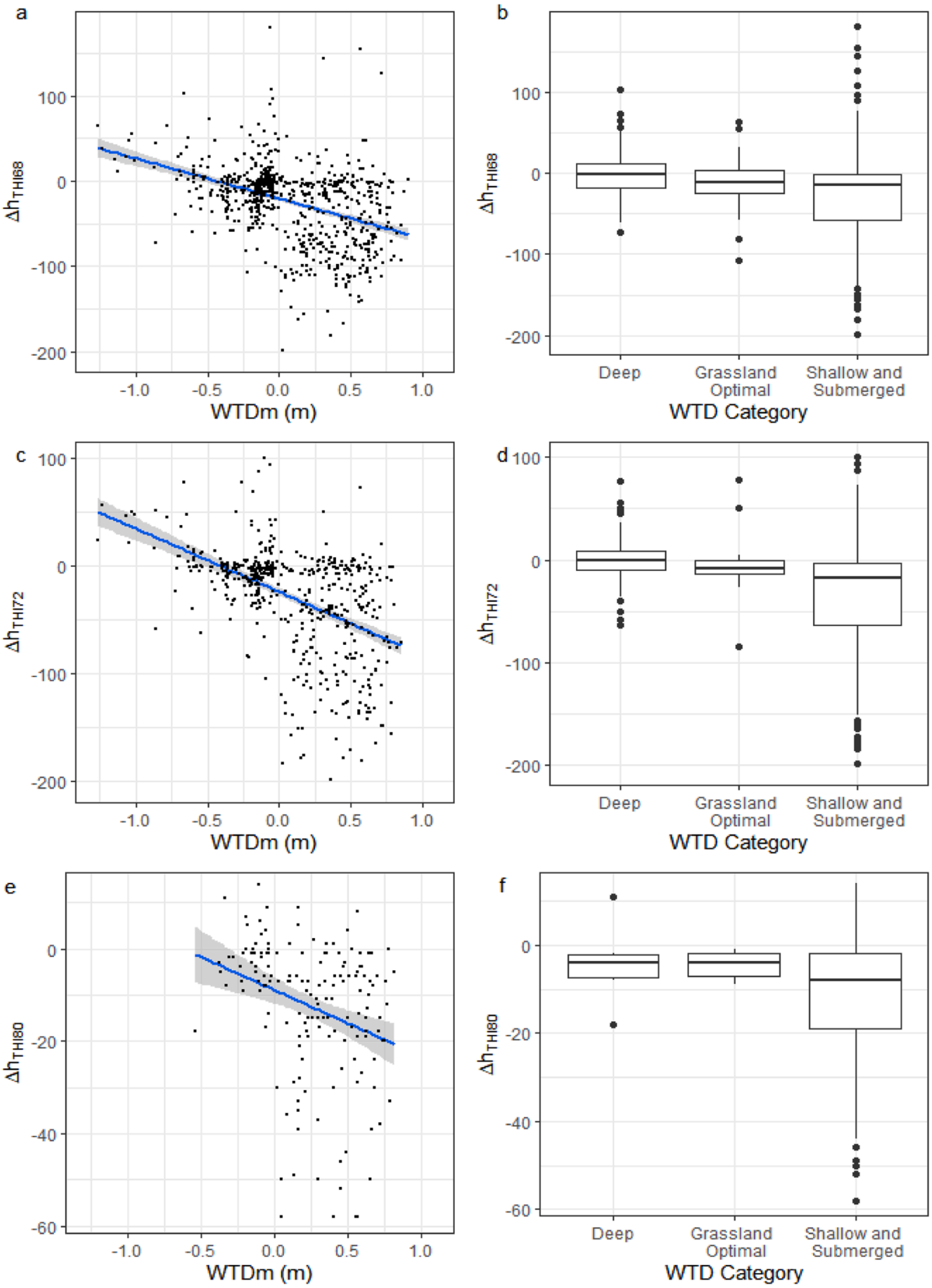

Fig. 2. Monthly mean Water Table Depth (WTDm) impacts on the monthly frequency of 3 levels of extreme weather events: Temperature Humidity Index (THI) >68 (a, b), 72 (c, d), and 80 (e, f) on peatlands, compared to neighbouring National Weather Station. Difference of hours under extreme weather expressed as ΔhTHI68, ΔhTHI72, and ΔhTHI80, (a, c, e) on a linear representation, and (b, d, f) comparing WTD agriculture categories: Deep (< −0.30 m); Grassland Optimal (−0.30 to −0.20 m), and Shallow and Submerged (>−0.20 m).

the datasets, these sites do not change the relationships established in the analysis, and add significance to the regression between water table and meteorological data in the global dataset. We therefore decided to keep these datasets as part of the study.

3.1.3. Peatlands WTD influence on local TA and THI for months with highest THI

We distinguished calendar months with average THI on study sites below and above 60 at the NWS (Fig. 1). Summer-time conditions with high average temperatures and relative humidity over a month with THI > 60 are represented in red. These sites had an increased negative relationship between δTA and WTD, compared to sites with average monthly THI < 60 (Fig. 1a and Table 3). However, the response difference at sites with higher THI is not emerging on δTHI variations. While THI is still significantly decreasing as WTD rises, its slope is not as steep as the temperature decrease gradient in areas and seasons with high THIs (Fig. 1b, Table 3).

Peatlands' response to TA and THI in summery conditions still has a significant variability that is reduced compared to the global datasets, as shown on the data diagnostic charts Fig. E.2 in Appendix.

We also confirmed that the inclusion of data from peatlands located between 40 and 50 km from NWS and in coastal areas do not modify general trends, but they improve the relationship significance while increasing data variability.

3.2. Global influence of WTD on the frequency of stressful weather

Stress thresholds impacting cattle welfare are at THI = 68, 72, and 80 (Appendix F). The longer the animals are under extreme weather, the more serious their symptoms, from milk yield decrease to the risk of death in the most extreme and prolonged heat waves (Collier et al., 2012; Polsky and von Keyserlingk, 2017). To understand the impact of raising the WTD of drained peatlands on extreme THI frequency, we considered sub-datasets with positive values of h_{THI68}, h_{THI72}, and h_{THI80} on the NWS. We compared the differences Δh_{THI68}, Δh_{THI72}, and Δh_{THI80} between peatlands and NWS to local WTD (Fig. 2a, c and e).

Despite the variability observed, the negative correlations between WTD and Δh_{THI68}, Δh_{THI72}, and Δh_{THI80}, are statistically significant (Table 4).

Evans et al. (2021) defined an optimal grassland rewetting mitigation by raising WTD to −0.20 m, reducing GHG emissions while enabling pasture. Fig. 2b, d and f show that this mitigation has a low impact on the frequency of extreme weather events characterised by THI above 68, 72, and 80. However, extreme weather events are significantly reduced on sites with shallow and submerged WTD, i.e. above −0.2 m. As above, we confirmed that peatlands between 40 and 50 km from NWS and in coastal areas did not modify the general trends (similar R and p factors), but improved the relationship significance (increased R-value, reduced p-value) while also increasing their variability.

3.3. Influence of peatlands on diurnal variation of THI

During heatwaves, cattle's ability to recover at night is essential to their health, and their ability to cope with heat stress depends on night-time THI (Vitali et al., 2015; Vallée, 2021; Adhikari et al., 2022). In the following section, we investigated further how the THI on peatland sites differed from THI on NWS throughout the days, hour by hour, during the three warmest months of the year (from June to August for sites in the northern hemisphere and December to February in the southern hemisphere). We aimed to establish if circadian patterns occur in the THI difference between peatland sites and NWS.

Every site follows the expected summer diurnal cycle THI hourly patterns, with the lowest values at night and highest values at mid-day (local time without daylight saving time adjustment). The example of the Zarnekow site in Germany, with TA and THI on the study site (in blue) and NWS in Teterow (in red), is shown in Appendix G, Fig. G.1a and b. On this site specifically, we can observe that between 9pm and 4am, the nocturnal THIm on the peatland is slightly lower than THIm at Teterow NWS. However, during the daytime, we observe a slightly higher THIm on the peatland than at the NWS.

We represented a global overview of summer months mean δTHI, hour-by-hour for each study site in Appendix H. Mean δTA is also included in Appendix I, Fig. I.1. Table 5 presents for each site, location climate classification (Beck et al., 2018); mean TA (°C) at NWS and mean WTD from analysed datasets above; night-time (6pm to 6am) and day-time (6am to 6pm) THI mitigation from "- - -" (THI at the peatland is 6 points lower than the NWS THI) to "+++" (6 points higher). We found four different types of THI differences at peatlands to nearby NWS: Full Mitigation: Peatland THI is lower than at meteorological stations, nights and days; Night Time Mitigation: Peatland THI is lower than at meteorological stations at night but not during the day; Day Time Mitigation: Peatland THI is lower than at meteorological station during the day but not at night. Lastly, No Mitigation, where the peatlands THIm was higher or equal to the NWS THI for the entire day.

Sites with day-time mitigation are mostly in temperate Csa climate, characterised by hot and dry summers, with a water table above ground level. In these cases, the peatlands have a tempering effect on THI, decreasing its amplitude between nights and days. Sites with full mitigation are all in oceanic (Cfb) climates (temperate and wet with dry summers). Sites with night-time only THI mitigation are in Cfb, Dfc (Continental, wet with warm summers), and Dfb (continental, wet with cold summers). Moanatuatua site in New Zealand shows increased (day-time) or equal (night-time) THI during summer days compared to the NWS site. The Dripsey site, used as a baseline for our analysis, showed slight THI mitigation nights and days.

4. Discussion

In this study, we sought to establish the consequences on grazing cattle welfare from raising water table depth (WTD) on drained peatlands by determining the effects on the Temperature Humidity Index (THI). Data collected from twenty-two peatland sites, deep drained to submerged, confirmed that in most cases WTD management affects local temperature and THI.

Table 4

Regression equations and regression factors between monthly mean Water Table Depth (WTDm) and the difference between extreme weather frequency of peatlands and neighbouring National Weather Station, with threshold Temperature Humidity Index (THI) > 68, > 72, and >80.

Regression equation	Regression coefficients	Gradient	Intercepts
$\Delta h_{THI68} = -47$ WTD – 21	$R^2 = -0.16$; $p< 2.2e^{-16}$; $n = 765$	−47 [95 % CI: −55; −39]	−21h [95 %CI: −23; −18 h]
$\Delta h_{THI72} = -59$ WTD – 24	$R^2 = -0.23$; $p< 2.2e^{-16}$; $n = 528$	−59 [95 % CI: −68; −50]	−24h [95 %CI: −28; −20 h]
$\Delta h_{THI80} = -14$WTD – 9	$R^2 = -0.09$; $p< 0.001$; $n = 163$	−14 [95 % CI: −21; −7]	−9h [95 %CI: −12; −6 h]

Table 5

Peatland sites of the study, with information on climate classification (Beck et al., 2018), calculated mean Air Temperature (TA) at neighbouring National Weather Station (NWS) and Peatland mean Water Table Depth (WTD); Appreciation of night and day Temperature Humidity Index (THI) mitigation levels (from strong decrease on peatland compared to neighbouring NWS "- - -" to strong increase "+++") during Day time (from 6am to 6pm) and night time (from 6pm to 6am).

Study Site	Climate	Mean TA(°C) at NWS	Peatland Mean WTD (m)	Day time	Night Time	THI Mitigation
IE-Dripsey	Cfb	9.80	- 1.08	-	-	Full Mitigation
US-Plum Island High Marsh	Dfa	8.84	- 0.05	-	+++	Daytime Mitigation
DE-Huetelmoor	Cfb	9.02	- 0.27	-	++	Daytime Mitigation
US-Mayberry Wetland	Csa	16.51	0.57	--	+	Daytime Mitigation
US-Twitchell Island	Csa	16.01	- 0.12	---	+	Daytime Mitigation
US-Sherman Island Restored Wetland	Csa	17.38	0.14	---	+	Daytime Mitigation
US-Twitchell East End Wetland	Csa	16.92	0.26	---	+	Daytime Mitigation
US-Twitchell Wetland West Pond	Csa	16.87	0.47	---	+	Daytime Mitigation
US-East Pond Wetland	Csa	17.51	0.62	---	+	Daytime Mitigation
UK-Tadham_Moor_2	Cfb	10.83	- 0.36	-	-	Full Mitigation
UK-Conwy	Cfb	11.53	- 0.04	-	--	Full Mitigation
UK-Cairngorms	Cfb	8.42	- 0.10	---	--	Full Mitigation
FR-Frasne	Cfb	8.61	- 0.13	-	---	Full Mitigation
UK-Moor House	Cfb	10.02	- 0.02	---	---	Full Mitigation
UK-Redmere 2	Cfb	9.46	- 0.59	0	-	Night Time Mitigation
IE-Glencar	Cfb	11.20	- 0.03	0	-	Night Time Mitigation
DE-Zarnekow	Dfb	10.17	0.44	+	-	Night Time Mitigation
CA-Delta Burns Bog	Csb	10.84	- 0.06	+	--	Night Time Mitigation
CA-La Biche River	Dfc	2.39	- 0.46	0	---	Night Time Mitigation
FR-La Guette	Cfb	11.78	- 0.12	0	---	Night Time Mitigation
UK-Anglesey 1	Cfb	10.65	- 0.07	0	---	Night Time Mitigation
UK-Anglesey 2	Cfb	10.66	- 0.07	0	---	Night Time Mitigation
NZ-Moanatuatua	Cfb	14.34	- 0.69	+	0	No Mitigation

4.1. Global influence of WTD on local temperature and THI

4.1.1. Temperatures

Sites on shallow and submerged WTD presented decreased average air temperatures compared to surrounding areas, as previous research identified (Hou et al., 2013; Liao et al., 2013; Worrall et al., 2022). This observation was intensified during periods with a monthly THI average above 60, characterised by summers with high average temperatures and high relative humidity compared to milder times of the year. In this first approach, we find that the natural and restored peatlands can help mitigate the effects of climate change on biodiversity and ecosystems by decreasing the average temperature during the warmest months at the studied sites.

The increased water availability for evaporation at the land's surface or in soil pores can explain the impact of WTD rise in peatland on temperature. Latent heat of vaporisation describes the amount of energy needed for water to change from liquid to vapour without a change in its temperature (Monteith and Unsworth, 2013); air temperature decreases while relative humidity rises where evaporation takes place. The same evaporative cooling process occurs within plants during transpiration, a phenomenon that highly depends on plant species (Campbell et al., 2021b).

While the temperature decrease can have benefits on its own, the associated humidity increase can have detrimental impacts on grazing herds. The trade-off between these two effects has not been investigated in detail in the literature. We therefore also analysed the relationship between WTD and THI.

4.1.2. Temperature humidity index

The benefit of natural or rewetted peatland compared to drained sites on THI for animals is confirmed but is moderate compared to the impact on temperature only (Fig. 1.b). This highlights the importance of also considering relative humidity when raising water table of drained sites used for grazing.

Unfortunately, most study sites available for this work had a shallow water table or were submerged: less than 5 % of monthly mean WTD were below −0.50 m. Adding data from drained peatlands with deeper WTD would provide further information to this analysis. We could evaluate if these lands have a similar average temperature and THI as surrounding "dry" and non-organic lands. Drained peatlands are indeed responsible for significant carbon dioxide emissions through the decomposition of organic matter (Morris, 2021; Renou-Wilson et al., 2022). The litter decomposition rate has a linear relationship with the mean annual temperature (Campbell et al., 2021a). Research also established that peat decomposition is sensitive to temperature (Hilasvuori et al., 2013). THI on deep-drained peatlands may increase due to heat generated by decomposition (Khvorostyanov et al., 2008). This would increase the benefit of raising water table depths on these lands used for farming. As research programmes progress to monitor soil GHG emissions, with the example of the National Agricultural Soil Carbon Observatory in Ireland (Teagasc, 2021b), the integration of deep-drained peatlands to this analysis could extend the understanding of WTD impacts on local THI.

4.1.3. Variability due to other factors

Relationships established in this study between peatlands WTD against the local decrease of TA and THI were not linear. They presented an increased variability when the monthly mean water level was close to and above ground levels. We confirmed that site-specific characteristics partially explained these variations. Proximity to seashores increased the variability of the local temperatures and THI on peatlands. Research has described the effects of marine winds on local air temperatures, for example, the influence of the North Atlantic Oscillations on the European continent (Årthun et al., 2018). A study on Norway spruce forest in Denmark identified the influence of the North Sea on evapotranspiration in winter (Ringgaard et al., 2014), that could explain the influence of proximity to the sea on local temperatures and THI. We nevertheless found that coastal peatlands brought valuable information to the analysis of variations of WTD.

We observe that the sites have different geographical and methodological characteristics that may influence meteorological measurements. We acknowledged that some of the study sites had TA and RH recorded at probes located above the standard height adopted at NWS, between 1.25 and 2 m, which could explain result variability. We also observed that WTD distribution was unequal between climates represented in the studied datasets. Data from additional submerged wetlands in Oceanic climates (Cfb) and drained lands in hotter and dryer climates (Csa) would extend understanding of the role of climate in temperature and THI response to WTD variations.

Other factors also contribute to the local air temperature and relative humidity. Goulden et al. (2007) and Eichelmann et al. (2018) suggested that vegetation canopy density and the presence of areas with open water impact evapotranspiration. Peatland morphology, including vegetation cover density and height, may also impact the response from WTD variation on local TA and THI, especially at ground level and above. The integration of these vegetation cover characteristics as potential factors to variations of THI could be investigated in future studies.

4.2. *Global influence of WTD on the frequency of stressful weather*

The THI thresholds of 68, 72, 80 and 90 have been defined using the following dairy cattle symptoms: heart rate, respiration rate, rectal temperature, reproductivity and milk production yield (Collier et al., 2012). We evaluated the response from peatlands considering the number of hours per calendar month with THI above these thresholds compared to nearby NWS (i.e., Δh_{THI68}, Δh_{THI72}, and Δh_{THI80}). We found a negative correlation between monthly mean WTD and the corresponding Δh_{THI68}, Δh_{THI72}, and Δh_{THI80} (Table 4 and Fig. 2a, c, and e). Peatlands with WTD above ground level showed an amplified reduction. This relationship confirms that WTD management is a tool that may help farmers prevent some of the adverse consequences of heat waves.

We split peatlands by WTD groups to investigate this correlation further. The second representation of the relationship shows that despite the result above, the lands with a WTD at the “grassland optimal” of −0.25 m (below ground level) estimated by Evans et al. (2021) do not benefit from further reduced hours of extreme weather from lands with deep WTD (Fig. 2b, d and f). As explained in Section 4.1, the amount of data analysed to study the extreme weather occurrences on deep-drained peatlands may be insufficient. The addition of datasets providing TA, RH, and WTD on organic soil with large peat layers exposed to oxygen from drainage below −0.70 m will strengthen this analysis and better inform farmers on the effect of deep-drainage for grazing, as the occurrences of extreme events increase as a consequence of climate change (IPCC, 2021).

However, shallow and submerged peatland areas (i.e., with a WTD greater than −0.20 m), significantly reduce extreme weather events (Fig. 2b, d and f). The coping strategy against increasing heat waves on farmlands sitting on organic soil can be informed using this result. Farmers could integrate both aspects in their land management: most of their grazing areas WTD could be managed to −0.25 m (below ground level) to reduce carbon emissions from the soil, with a small portion of land fully rewetted, like ponds, to provide heat wave protection areas for cattle and local biodiversity. This procedure will nevertheless need financial support from governing stakeholders: the benefit from the reduction of THI in summer may not justify the costs associated with this mitigation action alone in the current financially tense times for farmers in Ireland (Lanigan et al., 2019; Teagasc, 2021c).

An illustration of this presented option is available in an extensive organic cattle farm in Picherande, France (Fig. J.1): it can cope with grazing lands on shallow water depths because land management of this extensive farm requires less machinery than others. Ponds, manually dug into the wet soil, are included in the farm’s mitigation plan to protect cattle against the increasingly occurring heat waves.

4.3. *Influence of peatlands on THI during the day*

Previous studies on peatlands evaluated local circadian patterns on different abiotic factors: CO_2 flux and latent energy in four Californian wetlands (Hemes et al., 2018); land surface temperatures in two raised bogs in England (Worrall et al., 2022). We investigated the hourly profile of local temperature and THI during summer days at the twenty-two peatlands of this analysis (Table 5).

All sites in hot climates with dry summers (Csa) also had WTD above ground level. They all shared day-time mitigation: THI was reduced up to 6 points and temperature reduced up to 6 °C during the day on average compared to associated NWS, but THI at night increased up to 2 points (temperature increased up to 4 °C), as observed appendix Figs. H.1 and Fig. I.1. These results are similar to observations by Hemes et al. (2018), who compared temperatures at the three wetlands (US-Myb, US-Tw1, and US-Tw4) with neighbouring alfalfa cropland. They also noted variability of temperature response between the peatland sites. Hot and dry conditions around the peatlands seemed to be influenced by the local vegetation cover. A high vegetation density has been shown to decouple the water layer from the atmosphere (Goulden et al., 2007; Eichelmann et al., 2018), therefore reducing water availability for evaporation and reducing the cooling effect during the day while sheltering the soil at night and reducing heat loss.

Most sites on oceanic Cfb climates in western Europe and New Zealand had, on the contrary, lowered THI at night compared to surrounding areas. During the day, THI was comparable to nearby NWS or slightly increased for sites with shallow or submerging WTD. The previous study on two restored English bogs running on a twenty-year study cycle found reduced temperatures during the day of up to 1.1 °C compared to adjacent arable land, while no mitigation was observed at night (Worrall et al., 2022). Oceanic climates are defined with higher relative humidity and milder daily temperature than Csa climates (Beck et al., 2018). These conditions reduce the strength at which water evaporates, and plants undergo transpiration during the day. This explains the reduced day-time mitigation compared to Californian peatlands.

Dairy farm owners have already had to change grazing patterns under extreme weather (le Du, 2019; Garcia, 2021; Teagasc, 2021a; Vallée, 2021) after the sector found reduced feed intake, weight loss, and milk yield reduction during summer heat waves (Polsky and von Keyserlingk, 2017; Manica et al., 2022). Lowering summer night THI in farmlands of oceanic climates by rewetting areas on organic soil could benefit cattle for nocturnal recovery during prolonged heat waves.

The outcomes of the review of circadian THI variations on peatlands raise caution to farmers on drained coastal peatlands such as Huetelmoor (Germany) with shallow WTDm (−0.27 m) or marshes as Plum Island High Marsh (USA) with a WTDm of −0.05 m. These two sites display an increased THI at night, up to 4 to 6 points (Table 5). In these locations, grazing herds may not be able to recover at night during heat waves and will need an alternative mitigation strategy.

5. Conclusion

In this study, we analysed data from twenty-two peatlands to assess the impacts of raising water table depth on cattle welfare through local variations of the THI. We established that this climate change mitigation action has consequences on the local environment with reduced air temperatures and increased relative humidity. On average, the overall THI is slightly reduced, especially on drained peatlands in the oceanic temperate climate, characterised by warm and wet summers. We also observed that the THI reduction varies through the circadian cycle.

Temperatures and THI variations on peatlands are not only a function of local WTD; their relationship carries a high variability. We observed the influence of local climates and the distance to the sea on this correlation. We also hypothesised that peatlands vegetation characteristics (species composition, vegetation density and indirectly grazing intensity, presence of trees and their height and density) would also impact local THI. The determination of these factors in future studies would be beneficial for the farming sector. Future research could also evaluate the impact of raising WTD on latent energy flux by comparing this variable between peatland and surrounding areas. This would bring valuable scientific information on the mechanisms influencing variations of THI.

Farmers with cattle grazing on drained peatlands in oceanic climates can include our findings to the recommendations from Teagasc (Lanigan et al., 2019) and Evans et al. (2021) to inform their land management. Raising the water table depth to 25 cm below ground level will decrease the THI average slightly, especially at night, offering livestock more chance to recover during heat waves. We nevertheless advise caution to farmers of coastal sites as this land type category in our study did not follow the general trend of THI improvement compared to adjacent lands.

We also assess that fully rewetting portions of grasslands on organic soil would benefit cattle. This was the condition observed within our datasets to reduce occurrences of most acute heat waves.

This work used a parameter, THI, that the scientific community has evaluated against cattle symptoms, including production yields (Collier et al., 2012). THI, originally adapted from the discomfort index in humans (Hahn et al., 2009), could be extrapolated to biodiversity to further understand the impacts of climate change and their mitigation. It could support the association between climate-related geoscience research and studies about impacts on biodiversity.

CRediT authorship contribution statement

Wanda Gherca: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Inke Forbrich:** Writing – review & editing, Data curation. **Adrien Jacotot:** Writing – review & editing, Data curation. **Sara H. Knox:** Writing – review & editing, Data curation. **Paul G. Leahy:** Writing – review & editing, Data curation. **Ross Morrison:** Writing – review & editing, Data curation. **Torsten Sachs:** Writing – review & editing, Data curation. **Elke Eichelmann:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The European Eddy Fluxes Database Cluster (http://www.europe-fluxdata.eu/) is an initiative to improve standardisation, integration and collaboration between databases that are part of European research projects. It has been created with the aim to host in a single infrastructure fluxes measurements between ecosystems and atmosphere and to provide standard and high-quality data processing and data sharing tools. The authors acknowledge the contribution of Matteo Sottocornola (d. 2019) in collecting and analysing the data from the Glencar site.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2024.110279.

Data availability

Most data used in this research are available open access through AmeriFlux, the SNO Tourbières observing system, or the European Eddy Fluxes Database Cluster. Links noted in Acknowledgements.

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