Estimated emissions from peat soils in the Broads

Ian Holman, Nicholas Girkin, Ian Truckell

Commissioned by The Broads Authority

Project Manager Andrea Kelly (Broads Authority)

April 2023

School of Water, Energy and Environment, Cranfield University, Cranfield, Bedfordshire MK43 0AL

Published by Broads Authority, Yare House, 62-64 Thorpe Rd, Norwich NR1 1RY

Funded by Broads Authority as part of the Nature for Climate Peatland Grant Scheme, Broads Peat Project

Table of Contents

List of Figures

List of Tables

Summary

This report describes work commissioned by the Broads Authority and carried out by Cranfield University to improve the accuracy of estimates of past wastage by installing rust rods and surface rods to monitor peat wastage and to estimate carbon dioxide (CO_2) and methane (CH_4) emissions from peat stocks.

36 sets of rust rods and surface rods were installed across 5 peatland sites between 11th-13th and 19th-20th April 2022 to cover a range of landuses (grassland, woodland and fen) and drain water levels (low, medium and high). The sites were re-visited on the 5th-6th October 2022 following the exceptionally hot and dry summer to measure the rust lines and the watertable depth.

The estimated depths of the orange rust (iron oxide) on the rust rods were (within the exception of a single rod) deeper than the watertable measured in adjacent auger hole, with a median difference of about 5 cm (but up to +/-23 cm). Duplicate sets of rods installed at one peatland site showed broadly consistent rust deposits when installed close together, suggesting results are broadly replicable.

The estimates of carbon dioxide (CO_2) and methane (CH_4) emissions from peat stocks in the Broads were derived from a novel method that integrated a Lidar-based approach to estimating drain water levels and drain freeboard (height difference between the drain water level and the field); spatial analysis of field geometry, daily watertable modelling and the application of pre-existing regressions equations between mean effective watertable depth and emissions. The methodology was applied to the area of peat soils from Heppell et al. (2020) updated by the Broads Authority in 2023. The method was validated against Environment Agency gauge board data, IDB pump on-off levels and Environment Agency shallow dipwell monitoring data.

The total CO_2 balance and CH_4 flux from the peat soils of the Broads National Park were estimated at 17,866 tC/yr (uncertainty range of 3302 – 32,522 tC/yr) and 693 tC/yr (uncertainty range of 347 – 1,041 tC/yr), respectively.

Using a 100-year Global Warming Potential for CH_4 of 27.9, the total radiative forcing from emissions of the two gases is estimated at 91,389 t CO_{2eq}/yr (uncertainty range of 25,049 – 158,068 t CO_{2eq}/yr), of which 72% is associated with CO_2 and 28% with CH_4 emissions.

This report has, for the first time, provided a high resolution spatial assessment of estimated greenhouse gas emissions from the peats in The Broads, that takes account of land cover, watertable depth and weather. It suggests that the peats of the Broads are associated with highly spatially varying carbon emissions in the form of CO_2 from drained areas and CO_2 and CH_4 from semi-natural areas, but with the lowest emissions and climate forcings generally from fen habitat and the highest from agricultural areas.

1. Introduction

In 2020-2021, the Broads Authority commissioned a preliminary investigation into the Broads peat resource and its condition in relation to carbon storage/release, titled "Assessing carbon stocks within the peat of the Broads National Park" (Heppell et al., 2020). This demonstrated the considerable carbon storage within the lowland peats of Broadland, but also recognised that few are in a near natural state due to ongoing agricultural management and/or drainage.

The Broads Peat Partnership was awarded a Discovery Grant through the Nature for Climate Peatland Grant Scheme (NCPGS) by Natural England in the Broads area, covering 13 sites in each valley of the Broads. Part of the objectives of the NCPGS grant was to address some of the knowledge gaps identified by the Heppell et al. (2020) regarding carbon stocks and emissions from peatlands within the Broads National Park. In particular, improving the estimates of carbon storage, carbon capture and potential emissions by extending areal coverage of peat sampling and quantifying key peat metrics in order to refine carbon estimates and apply technical outputs to potential remedial work on peatlands.

As part of this, the Broads Authority commissioned Cranfield University to:

1. Improve the accuracy of estimates of past wastage as well as projections of future wastage by installing rust rods and surface rods to monitor peat wastage [Task 3 of the Invitation to Tender]
2. Estimate carbon dioxide (CO_2) and methane (CH_4) emissions from peat stocks [Task 4]

2. Installation of rust rods and surface-level rods to monitor peat wastage

2.1 Site installation

Rust rods and surface-level rods were installed at a series of peat sites identified and prioritised by the Broads Authority. These aim to provide the basis for collecting local empirical data, replacing the literature-based wastage rates of Holman and Kechavarzi (2011) that were used by Heppell et al. (2020), in future peat wastage assessments in the Broads. Having considered the range of site selection criteria, available budget, pros and cons of the range of approaches and the expected longevity, it was agreed that sites would be installed using the Eyes on the Bog[1] methods (Lindsay et al., 2019). Surface-level rods were installed down to the mineral substrate to assess peat wastage/accumulation and rust rods to identify watertable depth. This also provides methodological consistency with sites in the Broads Eyes on the Bog / IUCN UK Peatland Programme.

The sampling design (Table 1) was informed by the conclusion of Evans et al. (2021) that mean annual effective water table depth (the average depth of the aerated peat layer) overrides all other ecosystem- and management-related controls on greenhouse gas fluxes. It incorporated both the classification of peatland types of Evans et al. (2021) and different levels of drainage, although woodland sites were also identified, which are not included in Evans et al. (2021).

Rods were installed at sites between 11th-13th and 19th-20th April 2022. The location of the sampling points was constrained by landowner requirements so as to minimise the likelihood of disturbance by grazing livestock or planned management activities. Consequently, for a number of sites, monitoring points were located close to the field margin. In total 36 sets of rust rods and surface-level rods were installed at 5 sites (Tables 1 & 2 and Appendix 1). At each monitoring location, the following assessment was undertaken:

- Augered to the base of the peat using a peat auger and peat thickness and starting depth recorded (Appendix 1);
- Install a surface-level rod and rust rod according to Eyes on the Bog installation manual (Lindsay et al., 2019);
- High resolution digital photographs of the site vicinity were taken in cardinal directions to aid re-location;
- Colourfully marked bamboo canes were placed to mark the sites and aid re-location

[1] https://www.iucn-uk-peatlandprogramme.org/get-involved/eyes-bog

- The ordnance survey grid references was recorded using a GPS with an accuracy of within 1m (Appendix 1)
- Watertable depth within the auger bore was recorded

Table 1 Sampling design for rust-rod and surface rod installation

Landuse	Drainage regime		
	Low drain water levels	**Medium drain water levels**	**High drain water levels**
Arable	None identified	N/A	N/A
Grassland	Manor House Farm 1, 2, 3, 4, 5, 6	White House Farm 1, 2, 3 Beccles Farm 1, 2, 5	Beccles Farm 3, 4 Leiths Farm 2a/b, 3a/b, 4a/b
Fen	N/A	None identified	Upton 1, 2, 3, 4, 5, 6 Woodbastwick 1, 3, 4, 5
Woodland	None identified	White House Farm 4, 5, 6	Woodbastwick 2, 6

2.2 Rust-rod observations

The sites were re-visited on the 5th-6th October 2022 following the exceptionally hot and dry summer, with all but one set of rods (located at Manor House Farm) re-located (Table 2). At each set, the rust lines, watertable depth in a newly augered hole and changes in the surface-level rods were recorded. Several observations were made from the rust-rods:

- It was quite difficult to measure the rust lines unambiguously, as the rods had between 1 and 3 lines or zones associated with either orange rust (iron oxide) or a lower black (reduced iron) deposits (Figure 1 A&B).
    - Whilst the orange rust zone is conventionally interpreted as identifying the unsaturated zone, the meaning of the black (reduced iron; Figure 1B) deposits and their relationship to the higher iron oxide layer is unclear – it may indicate the depth of permanent (as opposed to seasonal) waterlogging that provides the anoxic conditions but also possibly the greater presence of groundwater sources rather than surface water. Many rods showed inconsistent patches of black deposits.
    - Duplicate rods installed at each point at Leith's Farm showed broadly consistent rust deposits when installed close together, suggesting results are broadly replicable. (Figure 1C).
- The estimated depths of the orange rust (iron oxide) on the rust rod were always deeper than the watertable measured in adjacent auger hole, with the exception of a single rod at Beccles Farm (Figure 2). The median difference was about 5 cm, but went up to +/-23 cm (Figure 2)
    - This difference may have been due to the rainfall experienced in the weeks prior to the re-visit raising the watertable so that the rust-line was not equilibrated with the higher watertable. However, whilst watertable depths were higher in some sites compared to at the time of installation (mostly those with high watertables), this was not the case in all sites (Figure 3) including the deep drained sites at Manor House Farm where the soil profile still had a significant soil moisture deficit and there was strong watertable control from the nearby drains. Consequently, this systematic difference may be an inherent methodological characteristic of rust rods in lowland environments – possibly reflecting the presence of oxygen within the upper few centres of the saturated zone enabling rusting to occur below the watertable. However, this requires further investigation to be conclusive.

Figure 1 (A) Point of measurement of orange rust (iron oxide); (B) Point of measurement for orange rust (iron oxide) and lower black (reduced iron) deposits; (C) Replicated points of measurement at Leist's Farm.

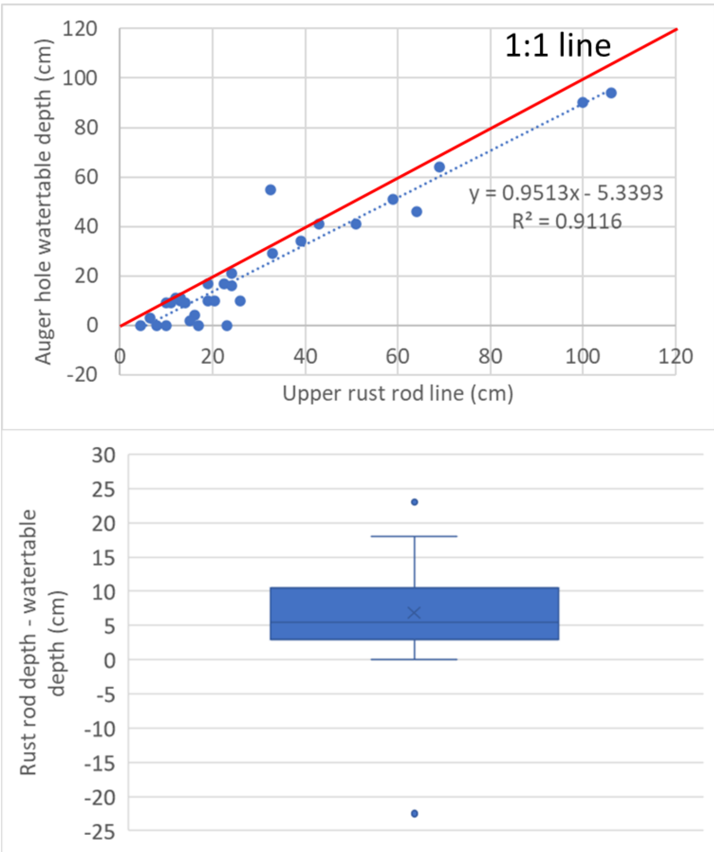


Figure 2 (Upper) Comparison of the rust rod depth and watertable depth in October 2022 and (lower) the distribution of the difference

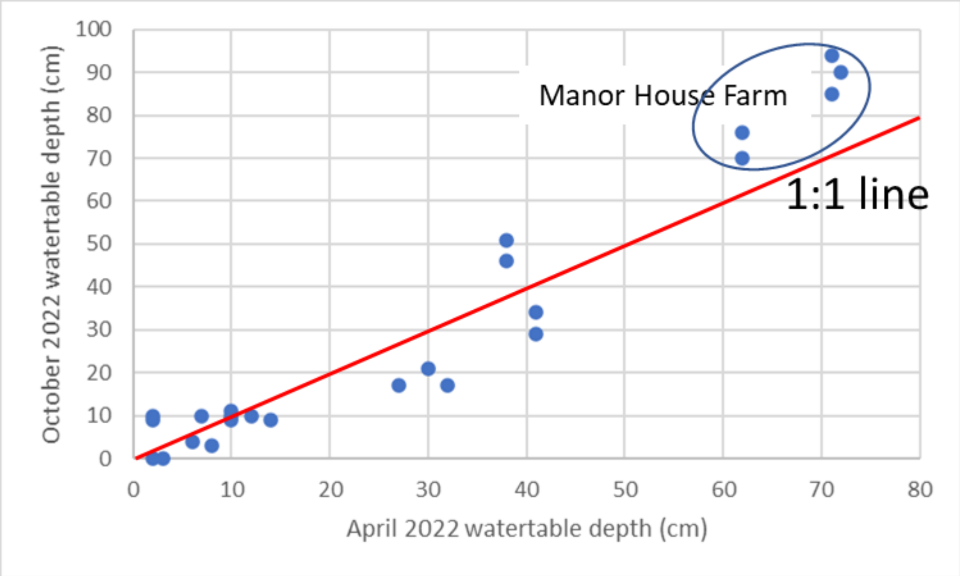


Figure 3 Comparison of watertable depth in April and October 2022 showing that watertable depth was generally lower in October in the locations with deeper watertables and vice versa

2.3 Surface-level rod observations

Changes in the surface level rods were observed between installation in April and the revisit in October 2022 (Figure 4), with a median change in the ground level across all surface-level rods of -3mm although, due to the short period of time since their installation, it is unlikely that these changes are (solely) due to wastage. The largest changes of between -20 and -50 mm were observed at Upton Fen and may reflect seasonal movement in the wetland surface due to changes in the watertable.

Longer-term monitoring of the surface-level rods is required to confidently assess peat wastage or accumulation. However, the results suggest caution should be taken in comparing measurements taken at different times of the year.

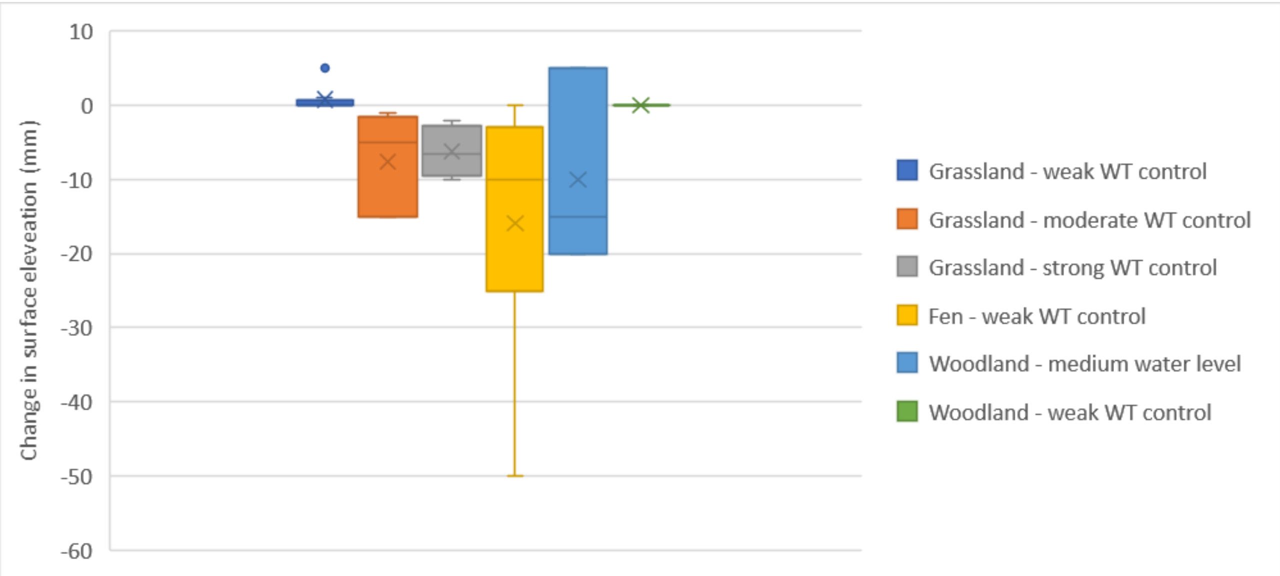


Figure 4 Distribution of the change in the surface level rods between April and October 2022

Table 2 Summary of the data from the rust rod and surface rod installation (April 2022) and revisit (October 2022)

Site	Habitat	Peat starting depth (cm)	Total peat thickness (cm)	April 2022	October 2022				
				Watertable depth (cm)	Watertable depth (cm)	Rust rod (upper depth) (cm)	Rust rod (lower depth) (cm)	Approx. ditch water level depth (cm)	Change in surface elevation (mm)[1]
WhiteHouse1	Permanent grassland (with rushes)	28	222	41	29	33	59	50	Bent
WhiteHouse2	Permanent grassland (with rushes)	100	110	41	34	39	65		-5
WhiteHouse3	Permanent grassland (with rushes)	45	165		41	51	69		-15
WhiteHouse4	Woodland (dry)	20	120		64	69	82		-20
WhiteHouse5	Woodland (dry)	0	180	38	46	64			5
WhiteHouse6	Woodland (dry)	53	202	38	51	59			-15
Woodbastwick1	Fen (open, sedge)	20	130	32	17	19	35	20	-3
Woodbastwick2	Wet woodland	0	165	7	10	19	26	10	0
Woodbastwick3	Reedbed	0	110	6	4	16			-3
Woodbastwick4	Fen (open, sedge, rushes)	0	340	3	0	23			0
Woodbastwick5	Fen boundary (phrgamites/open fen)	0	220	2	0	17	20		-3
Woodbastwick6	Wet woodland	0	235		0	8	21		0
Upton1	Reedbed	0	81	27	17	22.5		20	-15
Upton2	Typha / phragmites	0	270	10	10	26	40	10	-5
Upton3	Fen (sphagnum)	0	353	10	11	13	47.5	10	-20
Upton4	Fen (sphagnum)	0	355	2	10	13	45	15	-40
Upton5	Fen (sphagnum)	0	452	2	9	14	43		-20
Upton6	Typha / phragmites in woodland	0	525		16	24	38		-50
Beccles1	Rushy grassland	66	50		41	43	54	50	-15
Beccles2	Rushy grassland	0	112	30	21	24	34	30	-2
Beccles3	Rushy grassland	0	115	10	9	11	20	10	0
Beccles4	Rushy grassland	0	103	12	10	20.5	47	20	5
Beccles5	Rushy grassland	0	152		55	32.5	44	50	-1
ManorHouse1	Ley grassland	0	148	72	90	100	150	130	-2
ManorHouse2	Ley grassland	0	142	71	94	106	109	110	-8
ManorHouse3	Ley grassland	0	177						
ManorHouse4	Ley grassland	0	245	62	70	74		110	-5
ManorHouse5	Ley grassland	0	216	62	76	92	105	85	Run over

ManorHouse6	Ley grassland	0	232	71	85	94		110	-10
Leists2a	Rushy grassland	0	305	8	3	6.5			0
Leists2b	Rushy grassland	As 2a	As 2a	As 2a	2	15			0
Leists3a	Rushy grassland	0	380	14	9	10		5	0
Leists3b	Rushy grassland	As 3a	As 3a	As 3a	11	12		5	0
Leists4a	Rushy grassland	0	268		0	10	15		1
Leists4b	Rushy grassland	As 4a	As 4a	As 4a	0	4.5	20		0

[1] Compared to April 2022

3. Estimating carbon dioxide and methane emissions from peat stocks

3.1 Overview of methodology

Our modelling-based methodology to estimating emissions from the area of peat soils was based on:

1. Estimating drain water level height for all fields within the areas of peat soils;
2. Estimating the average freeboard (difference between the elevation of the drain water level and the field) for each field;
3. Estimating drain spacing for all fields based on field geometry;
4. Simulating water table depth for all fields, taking account of freeboard, drain spacing and landcover;
5. Calculating annual average effective watertable depth to take account of peat thickness;
6. Calculating CO_2 balance and CH_4 fluxes using regression equations from Evans et al. (2021)

The methodology was applied to the area of peat soils from Heppell et al. (2020) updated by the Broads Authority in 2023 with additional soil auger data from Discovery Grant activities (Figure 5), and accounted for the main landcovers from Land Cover Map 2021 (Figure 6).

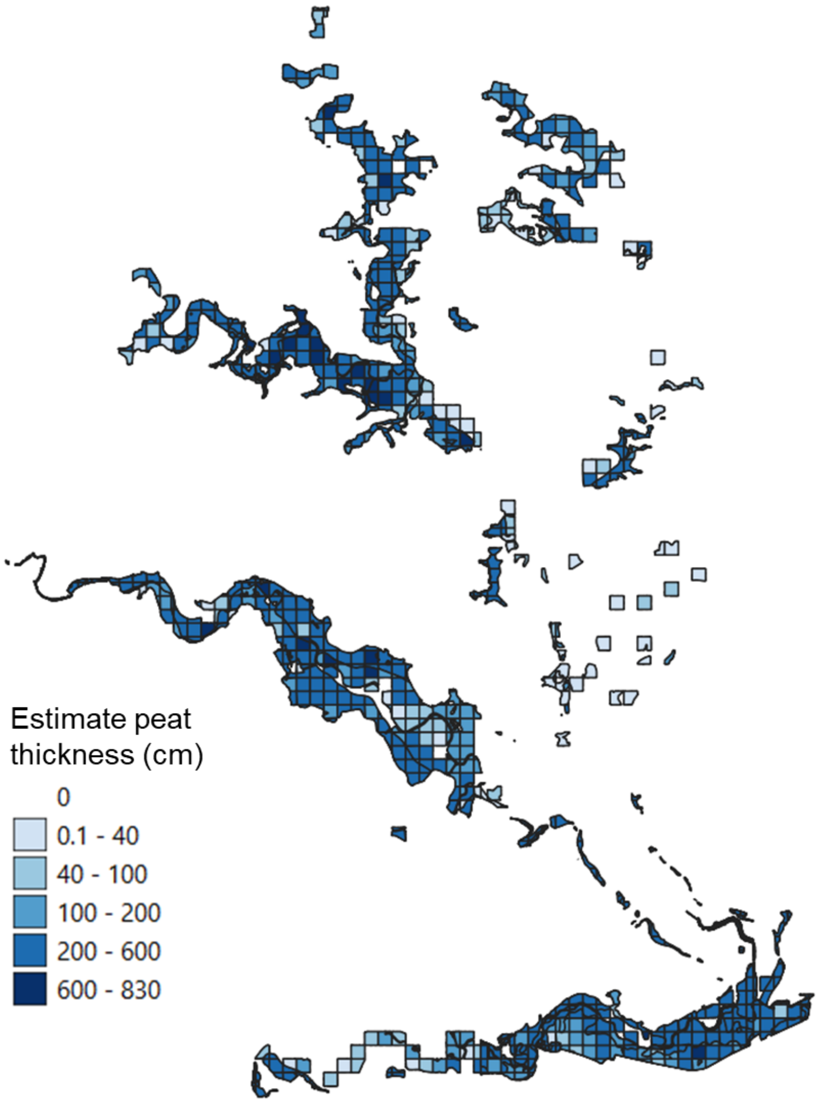


Figure 5 Area of peat soils and their estimated 2020 thickness (based on Heppell et al., 2020, updated by Broads Authority in 2023 ©Broads Authority 2020. Modelled using data licenced by Cranfield University) (Ordnance Survey data © Crown copyright [and database rights] 2023 OS 100021573)

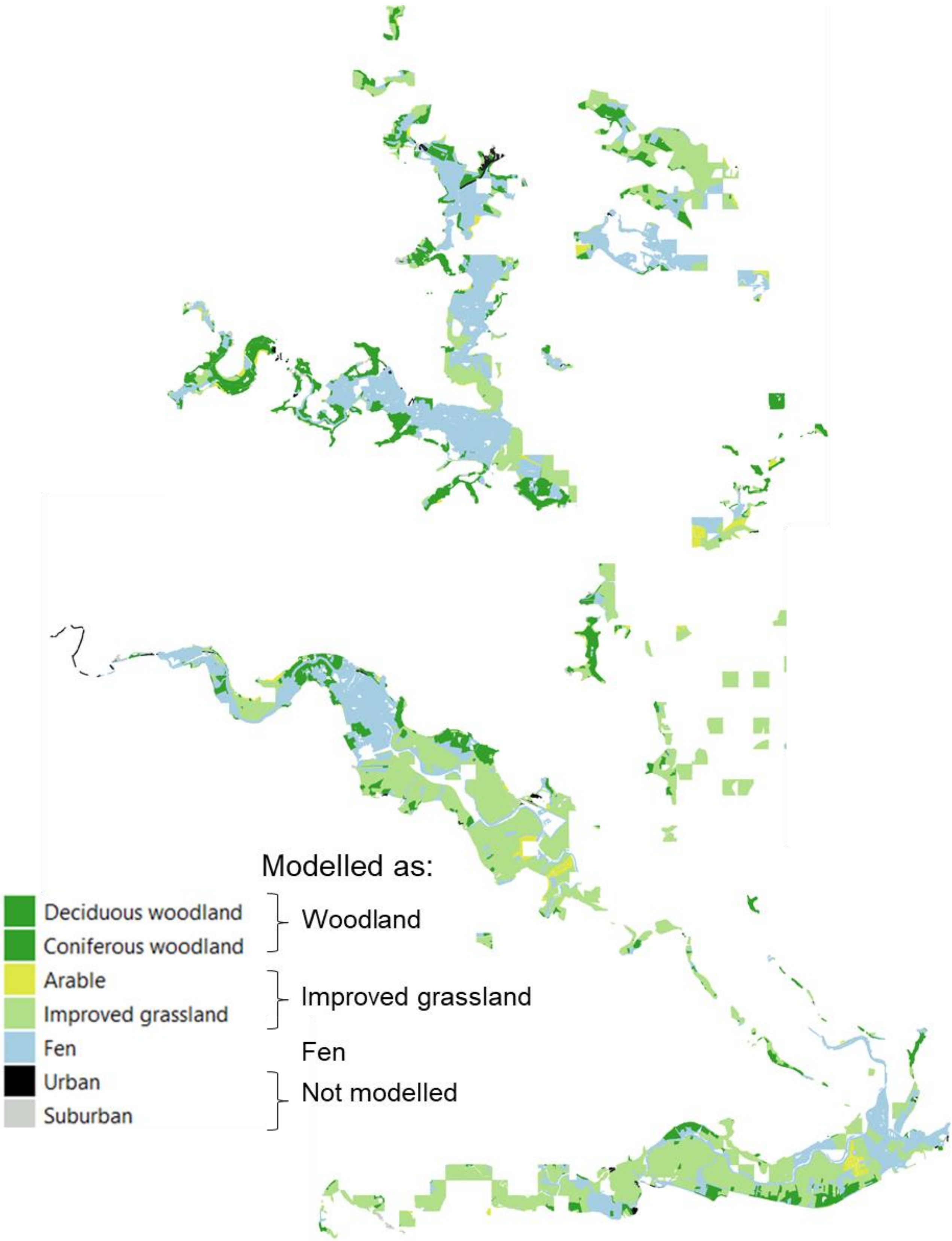


Figure 6 Simplified Landcover Map 2021 for Broads and the model representation (Based upon LCM2021 ©UKCEH 2022. Contains Ordnance Survey data ©Crown Copyright 2007, Licence number 100017572)

3.2 Methodological steps and results

3.2.1 Estimating drain water level height

The methodology to derive drain water level height within the area of peat soils was based on the method of Dutta (2022). Environment Agency Lidar point cloud data were used, which was mostly flown in November 2017 to March 2018. The Lidar points were processed to selected minimum height values within a 2 m bin to sub-select those Lidar datapoints that were most likely to represent the soil/land surface rather than vegetation. The Ordnance Survey MasterMap Water Network was used to identify drains and selected Lidar values within a buffered distance of the ditch centre line were used to identify the drain water level (relative to ordnance datum).

To assess the performance of the drain water level height methodology, the derived drain water levels were compared against IDB summer / winter on-off water levels and EA gaugeboard analyses using (1) the lowest drain water level within 20 m radial distance of the grid reference of each IDB pumphouse and (2) the nearest drain water level to the grid reference of each EA gaugeboard. As the exact date of the Lidar-derived water level was not known and the IDB pumps typically change from summer to winter levels and vice versa around November and March (Tom Jones, *pers. comm*.), the evaluation considered whether the derived drain water level heights were within the range of the IDB on-off water levels and the EA gauge board observations (Table 3). Overall, the root mean square error for the deviation from these ranges was only 0.1 m. Table 3 shows that the majority of sites were within the 'observed' range, and of those outside most were within 0.1 m. We consider that this demonstrates that this first ever spatial assessment of drain water levels in the Broads provides an acceptable dataset from which to produce subsequent emissions estimates.

For additional validation, Figure 7 shows the derived drain water level heights within part of the Upper Thurne. In particular, this shows:

- The lower drain water levels in the intensively drained Brograve and Somerton Drainage Levels, compared to the higher water levels maintained in the Horsey, Heigham Holme and Eastfield Levels;
- The generally lower water levels within the Brograve Main Drain compared to the side drains due to landowner drain management and/or water control structures;
- The high drain water levels within the Breydon Marshes and Norfolk Wildlife Trust's Hickling Reserve;
- The higher water levels within the undrained areas around the western side of Hickling Broad and the around Martham Broad compared to the nearby IDB drained areas e.g. Potter Heigham Level.

Table 3 Evaluation of the Lidar-derived drain water levels against range of IDB pump on-off levels and EA gaugeboard observations

No. of sites	All sites	IDB pumps	EA gaugeboards
Total number	95	37	58
Within range	58	18	40
Outside range	37	19	18
Below observed range	18	15	3
Above outside range	19	4	15
Outside by >10cm	13	8	5
Outside by >25cm	9	6	3
Outside by >50cm	7	5	2

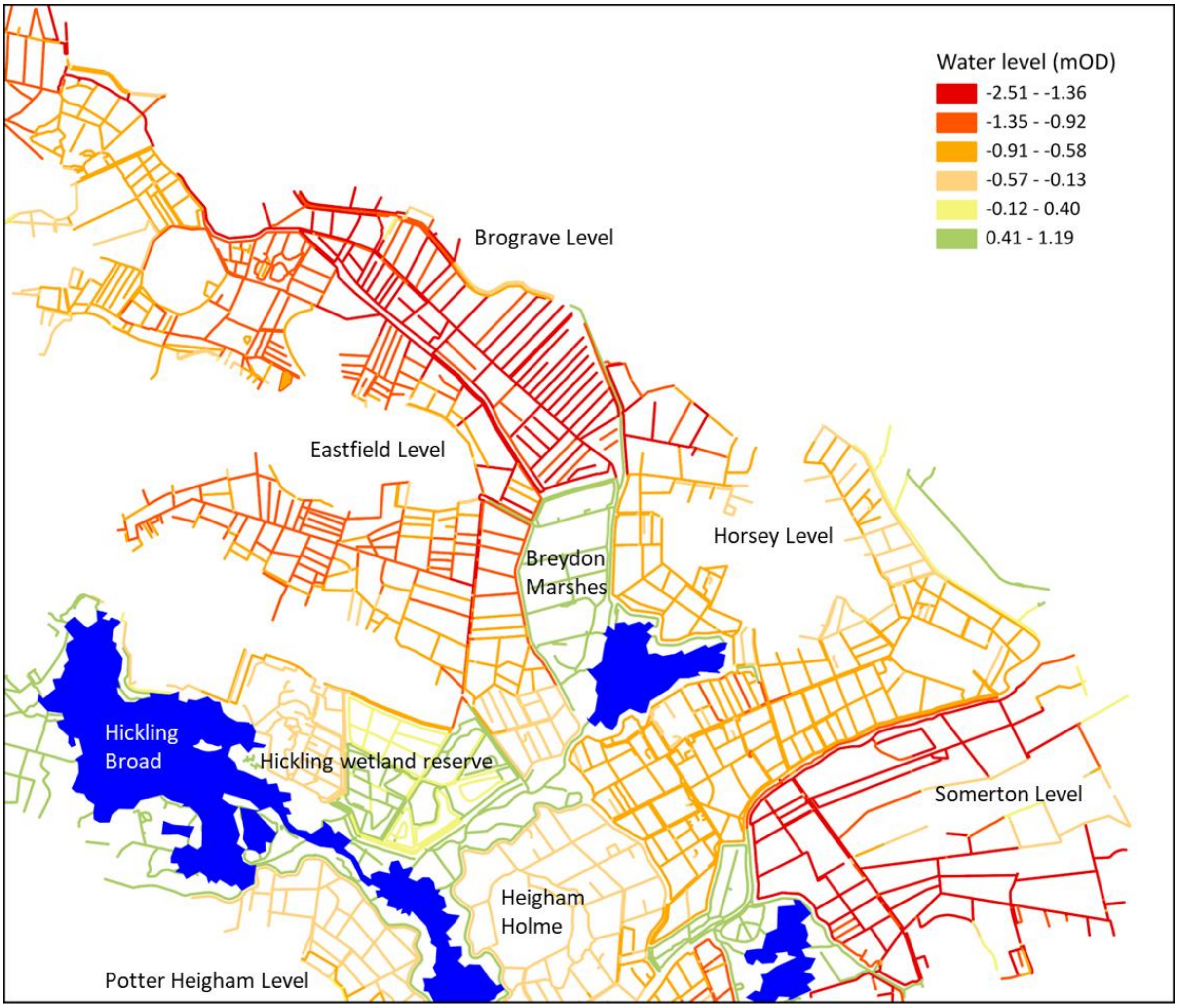


Figure 7 Derived drain water levels for part of the Upper Thurne (Ordnance Survey data © Crown copyright [and database rights] 2023 OS 100021573. Lidar data © Environment Agency copyright and/or database right 2015. All rights reserved.)

3.2.2 Estimating the average freeboard for each field

Fields within the area of peat soils were extracted from the OS Mastermap topography dataset and the median elevation of the Lidar binned minima values within the field boundaries were calculated as being representative of the average field elevation. The drains from the previous step were linked to the field and the freeboard (Figure 8) calculated as the height difference between the mean water level elevation of the field's associated drains and the field elevation.

3.2.3 Estimating drain spacing

The typical field width calculated from the geometry of the field polygon was used as a surrogate for drain spacing, given the variable field shapes and the lack of information on the presence and performance of under-drainage. Of the options available in ArcGIS (Figure 9), the width given by the convex_hull (where the width is given by the shortest distance between any two vertices of the convex hull) and rectangle_by_width (where the width equals the length of the shorter side of the resulting rectangle) were used, although both approaches were found to provide the same derived width.

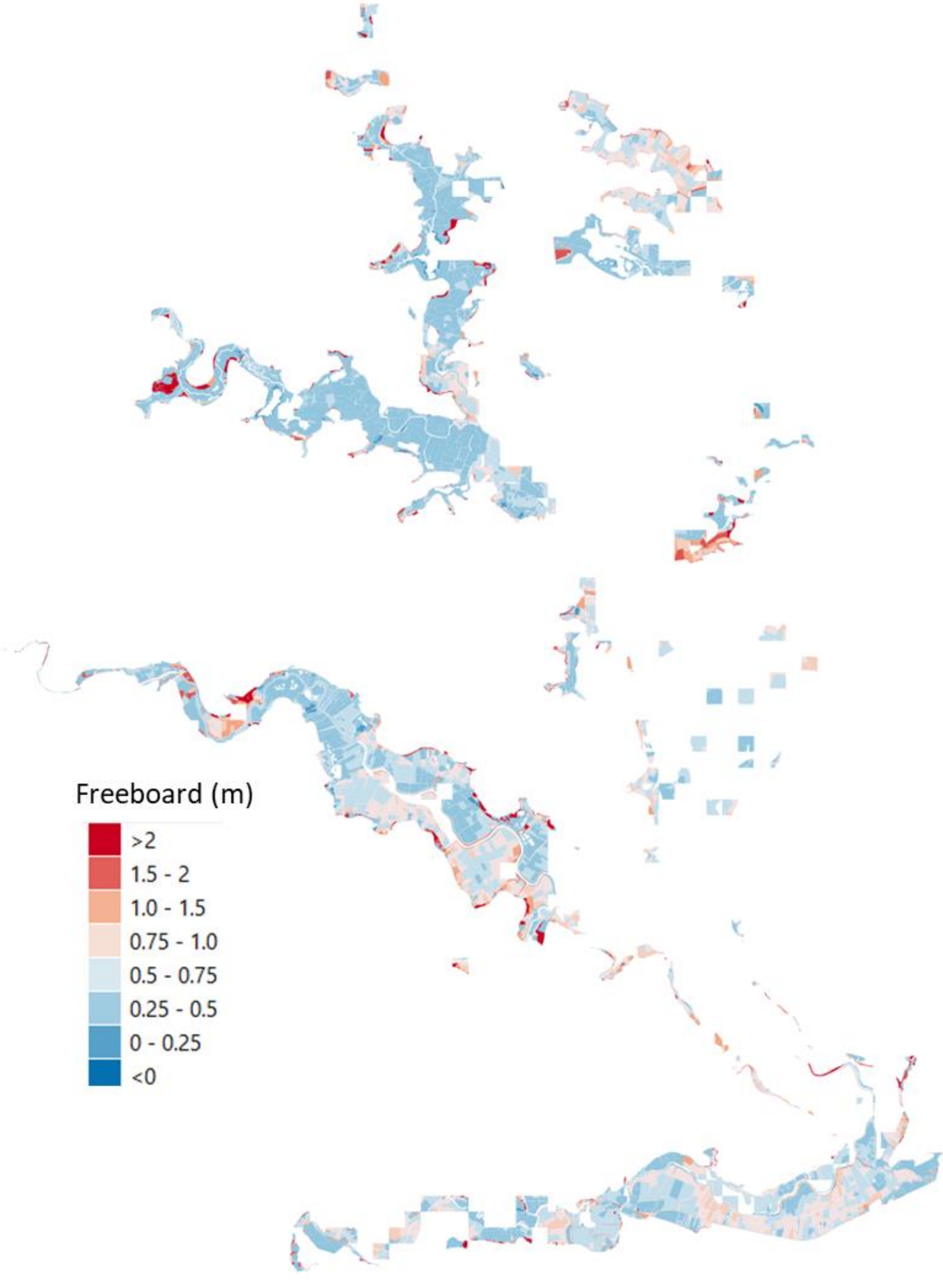


Figure 8 Derived field-level freeboard for peat areas in the Broads (Ordnance Survey data © Crown copyright [and database rights] 2023 OS 100021573; Lidar data © Environment Agency copyright and/or database right 2015. All rights reserved. LCM2021 ©UKCEH 2022; peat soils ©Broads Authority 2020, modelled using data licenced by Cranfield University)

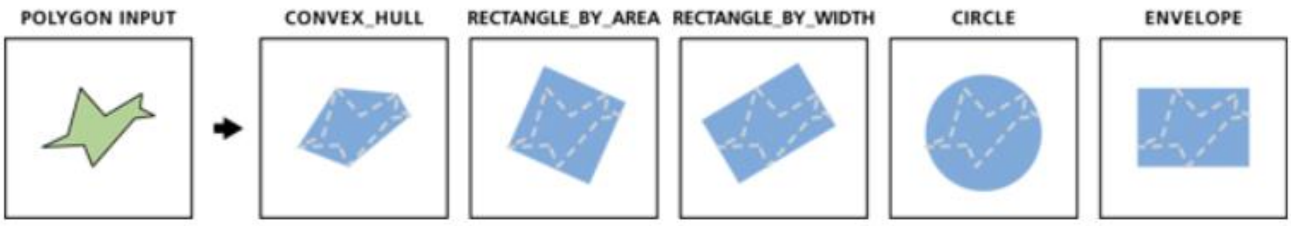


Figure 9 Illustrative approaches to deriving polygon geometry in ArcGIS

3.2.4 Simulating water table depth

The watertable depth was simulated using the WaSim model (Hess & Counsell, 2000; Hess et al., 2010; Holman et al., 2011) which is a one-dimensional daily soil water balance model that simulates the interactions between inputs (precipitation, groundwater inflow), outputs (actual evapo-transpiration, surface runoff and drainage) and changes in soil water storage. The soil is divided into up to five time-varying compartments (Figure 10). Water moves from upper compartments to lower compartments when the soil layer exceeds field capacity. Drain flow occurs when the water table is above the height of the ditches or drain and is a function of the mid drain water table height (after Youngs et al., 1989). Surface runoff comprises the infiltration-excess runoff (estimated using the widely recognised SCS curve number method of Conservation Engineering Division, 1986) and runoff due to saturated soil. Any precipitation that does not run off is assumed to infiltrate.

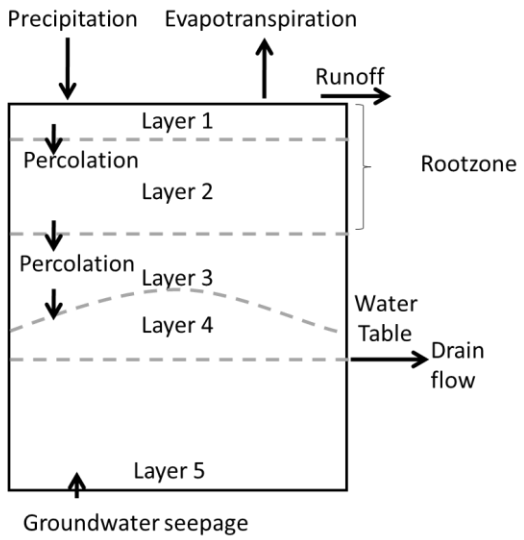


Figure 10 Schematic of the WaSim model

WaSim was initially used to model watertable depth for the 46 fields in which the Environment Agency have shallow (< 5 m) monitoring dipwells. The measured groundwater levels in mOD were converted to a depth below ground level (m bgl) using the EA ground level (mOD) measurement provided for each dipwell. Due to uncertainties in the accuracy of calculated negative depths (i.e. the measured groundwater level was above ground level), these were set at zero depth (ground level).

WaSim was set-up to allow ponding of up to 20 mm depth in Fens, the maximum ponding depth in Evans et al. (2021). Particularly uncertain WaSim input parameters (e.g. the crop coefficient for Fen and woodland, rooting depth for woodland, and seepage rate) were adjusted so that the distribution of daily simulated watertable depth across the 46 fields approximately matched that of the dipwell monitoring data (Figures 11-13). The intention was for WaSim to appropriately simulate the overall watertable response of the different landcovers, rather than to fit the model to each individual dipwell. In general there was a good match with the interquartile ranges overlapping, particularly for the Fen sites. The modelled watertable was slightly too shallow for the deciduous woodland sites but the difference is less than 0.06 m.

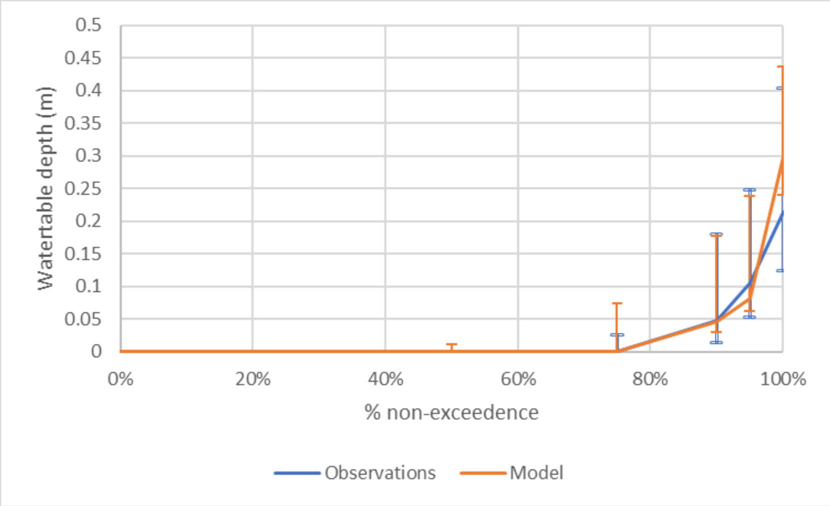


Figure 11 Distribution of median (line) and inter-quartile range (bars) of simulated and observed watertable depth for Fen sites (n=32)

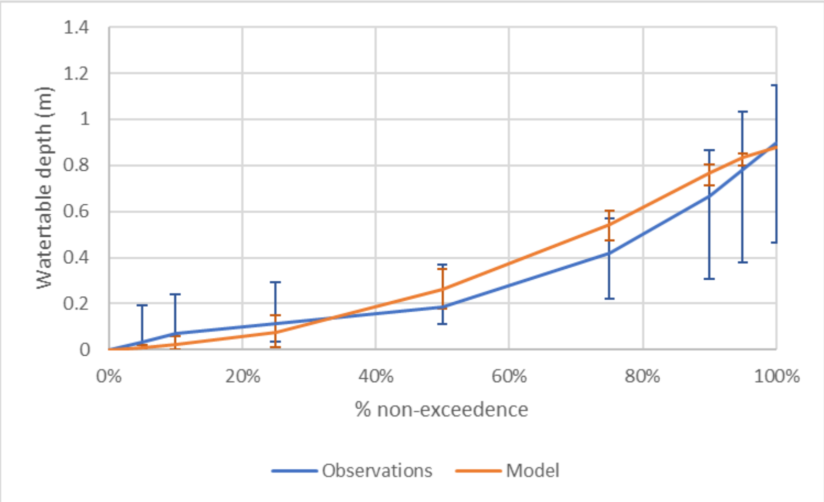


Figure 12 Distribution of median (line) and inter-quartile range (bars) of simulated and observed watertable depth for improved grassland (n=8)

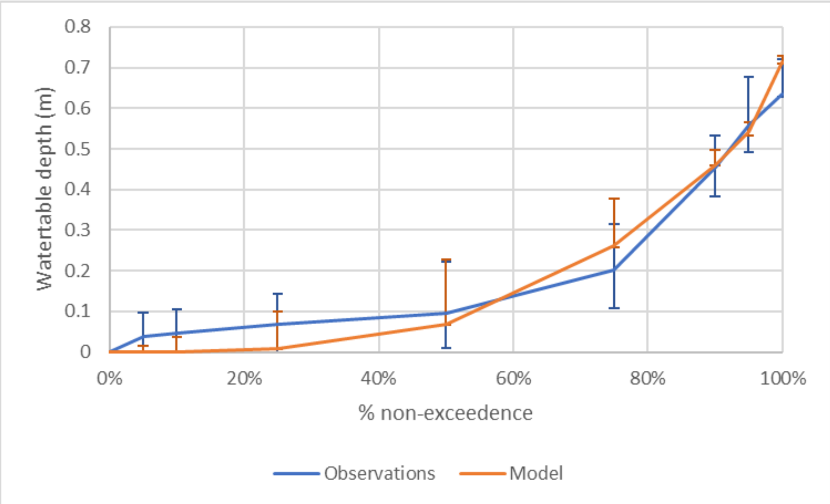


Figure 13 Distribution of median (line) and inter-quartile range (bars) of simulated and observed watertable depth for deciduous woodland (n=6)

As there were over 9500 fields in the study area with a wide range of drain spacing and freeboard, the derived drain spacings from < 3 m to > 5000 m were split into 19 classes and the drain freeboard from zero to > 4 m was split into 16 classes. WaSim was then used to simulate daily watertable depth for each of the 912 combinations of drain spacing class, freeboard class and three landcovers (grassland, deciduous woodland and fen) for the years 2000 - 2015 using precipitation (Robinson et al., 2020a) and reference evapotranspiration (Robinson et al., 2020b) data from the Climate, Hydrology and Ecology Research Support System.

3.2.5 Calculating annual average effective watertable depth

For each field, the daily simulated watertable depth for the appropriate drain spacing and freeboard class were extracted and the daily effective watertable depth calculated based on the average peat depth from the updated peat map. Finally mean annual effective watertable depth was calculated for each field (Figure 14).

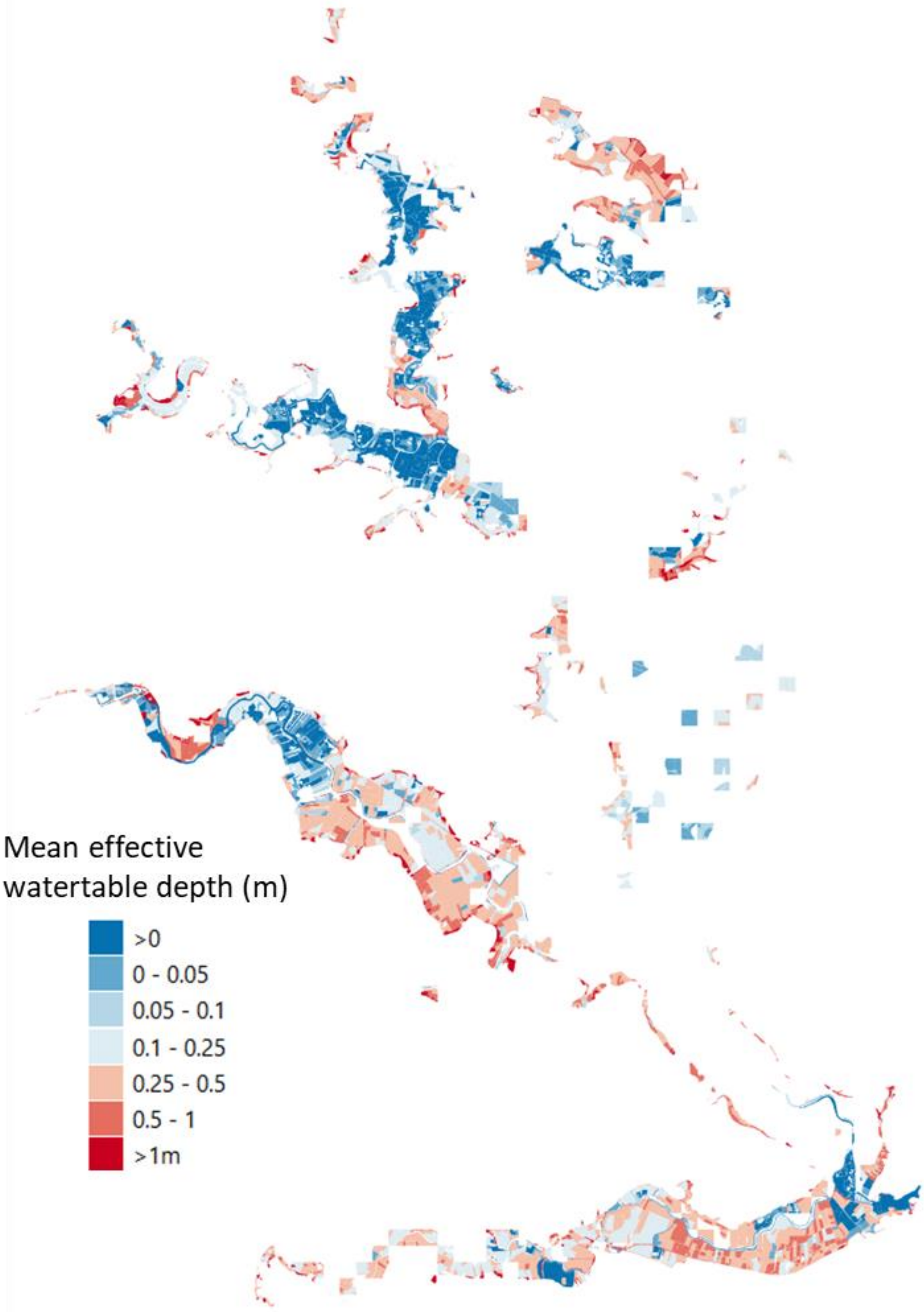


Figure 14 Simulated average effective watertable depth for the peat soils of the Broads (Ordnance Survey data © Crown copyright [and database rights] 2023 OS 100021573; Lidar data © Environment Agency copyright and/or database right 2015. All rights reserved. LCM2021 ©UKCEH 2022; peat soils ©Broads Authority 2020, modelled using data licenced by Cranfield University)

3.2.6 Calculating carbon dioxide and methane emissions

The CO_2 balance (CO_2 flux) and CH_4 emissions were calculated from the simulated mean annual effective watertable depth using the UK regression equations from Evans et al. (2021). The median CO_2 balance is +3.0 tC/ha/yr (average = 5.1 tC/ha/yr) reflecting losses of CO_2 to the atmosphere, and the median CH_4 flux is 0.004 tC/ha/yr (average = 0.030 tC/ha/yr) (Figure 15). Based on the updated peat area, the total CO_2 balance and CH_4 flux from the peat soils of the Broads National Park are 17,866 tC/yr and 693 tC/yr, respectively, representing a net loss to the atmosphere of 18560 tC/yr.

Using a 100-year Global Warming Potential for CH_4 of 27.9 (from Table 7SM.7 of Smith et al., 2021), the total radiative forcing from emissions of the two gases (Figure 16) is estimated at 91,389 tCO_{2eq}/yr, of which 72% is associated with CO_2 and 28% with CH_4 emissions.

Finally, Figures 17 and 18 show the estimated spatial distribution of emissions of CO_2 and CH_4, both expressed in tCO_{2eq}/ha/yr.

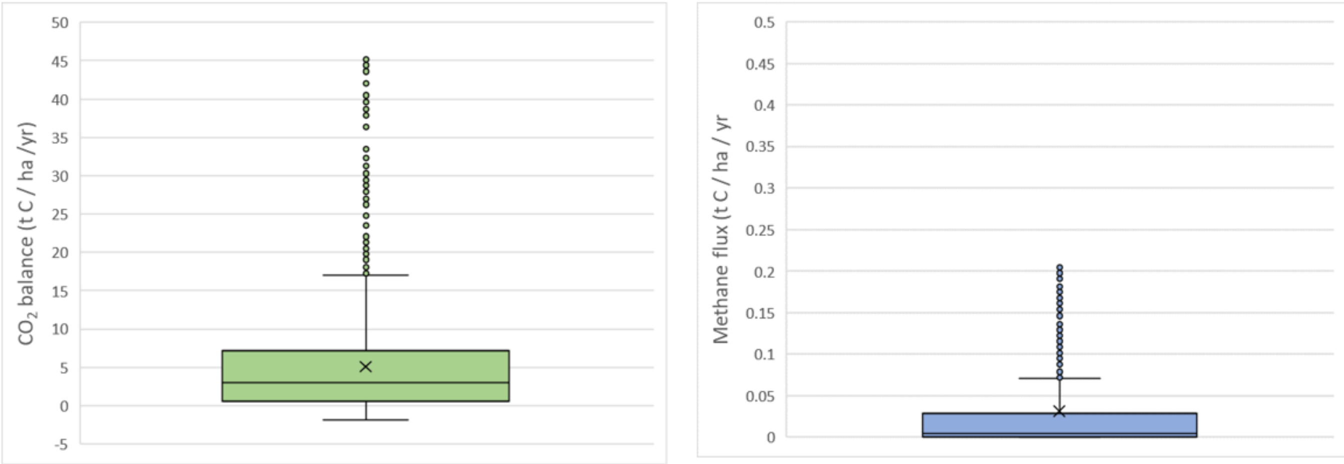


Figure 15 Distribution of CO2 balance and CH4 fluxes in tC/ha/yr) [Note that the y axis of the CO2 graph is 100 times higher than the CH4 graph]

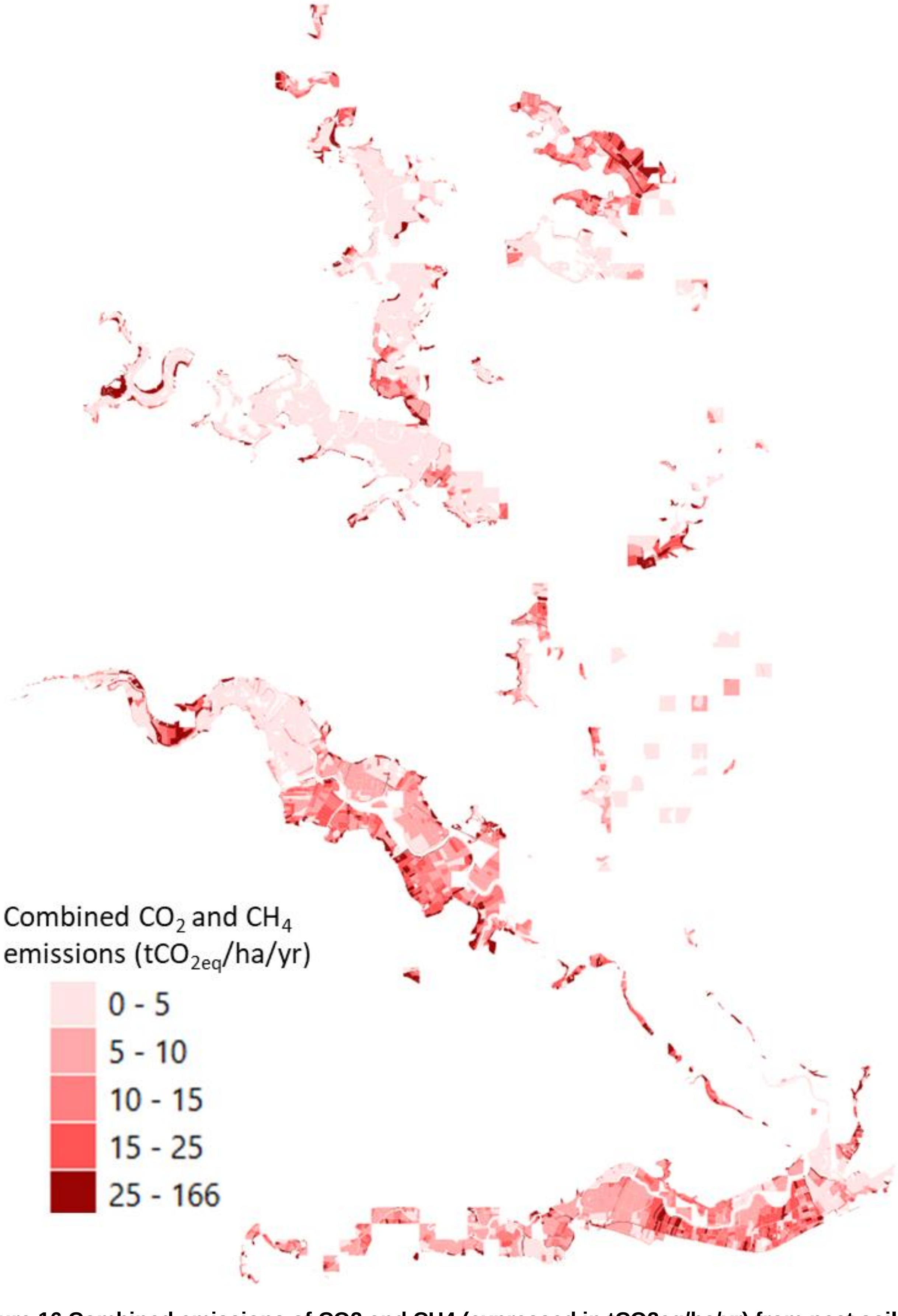


Figure 16 Combined emissions of CO2 and CH4 (expressed in tCO2eq/ha/yr) from peat soils in the Broads (Ordnance Survey data © Crown copyright [and database rights] 2023 OS 100021573; Lidar data © Environment Agency copyright and/or database right 2015. All rights reserved. LCM2021 ©UKCEH 2022; peat soils ©Broads Authority 2020, modelled using data licenced by Cranfield University)

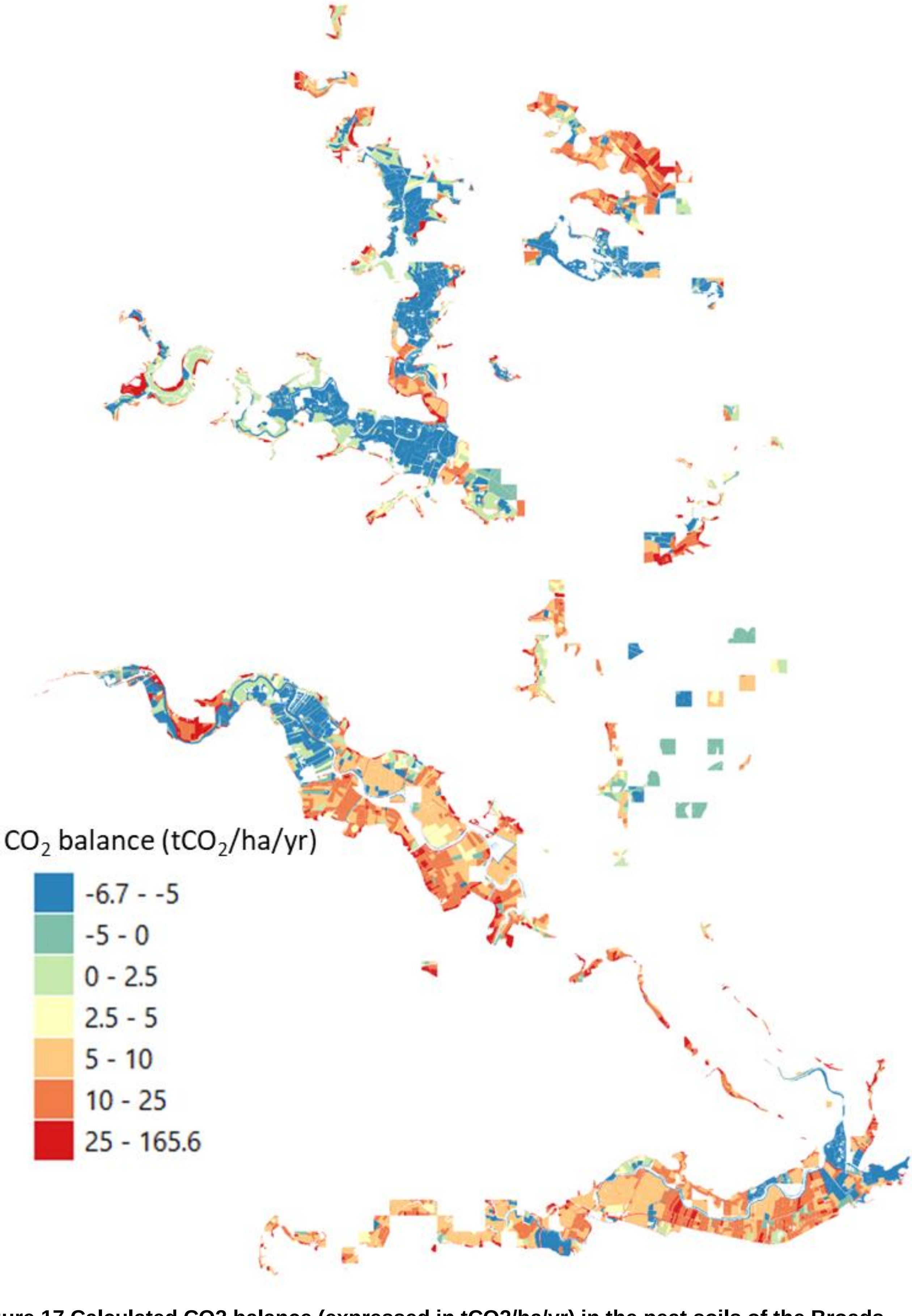


Figure 17 Calculated CO2 balance (expressed in tCO2/ha/yr) in the peat soils of the Broads (Ordnance Survey data © Crown copyright [and database rights] 2023 OS 100021573; Lidar data © Environment Agency copyright and/or database right 2015. All rights reserved. LCM2021 ©UKCEH 2022; peat soils ©Broads Authority 2020, modelled using data licenced by Cranfield University)

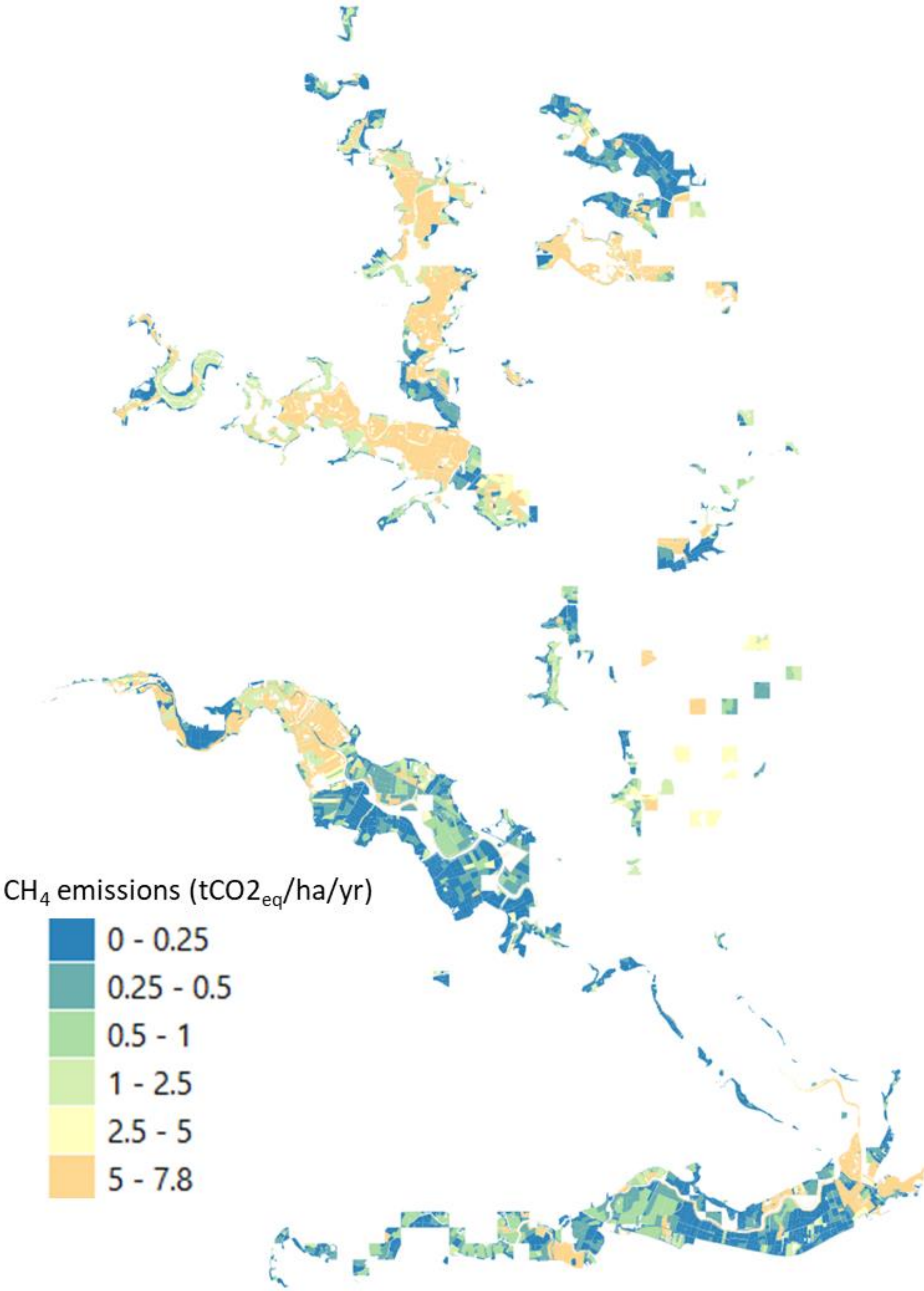


Figure 18 Calculated CH4 emissions (expressed as tCO2eq/ha/yr) from the peat soils of the Broads (Ordnance Survey data © Crown copyright [and database rights] 2023 OS 100021573; Lidar data © Environment Agency copyright and/or database right 2015. All rights reserved. LCM2021 ©UKCEH 2022; peat soils ©Broads Authority 2020, modelled using data licenced by Cranfield University)

4. Discussion and Conclusions

This report has, for the first time, provided a high resolution spatial assessment of estimated greenhouse gas emissions from the peats in The Broads, that takes account of land cover, watertable depth and weather. It suggests that the peats of the Broads are associated with highly spatially varying carbon emissions in the form of CO_2 from both drained areas and CO_2 and CH_4 from semi-natural areas (Figure 19).

The simulated Fen fields are generally associated with low and sometimes negative CO_2 balance (although with a few high outliers) and relatively high CH_4 fluxes (expressed as CO_{2eq}) reflecting their high mean effective watertable depth. The improved grassland fields (which also included the few arable landcover fields) are associated with generally positive CO_2 balance (representing net emissions) and low CH_4 reflecting their lower, but variable, average effective watertable depth. Finally, the woodland fields are intermediate between the simulated Fen and improved grassland fields reflecting their range of hydrological conditions from wet to dry woodland.

However, when the radiative forcing of the CO_2 and CH_4 are combined, it can be seen that the Fen sites are generally associated with the lowest values.

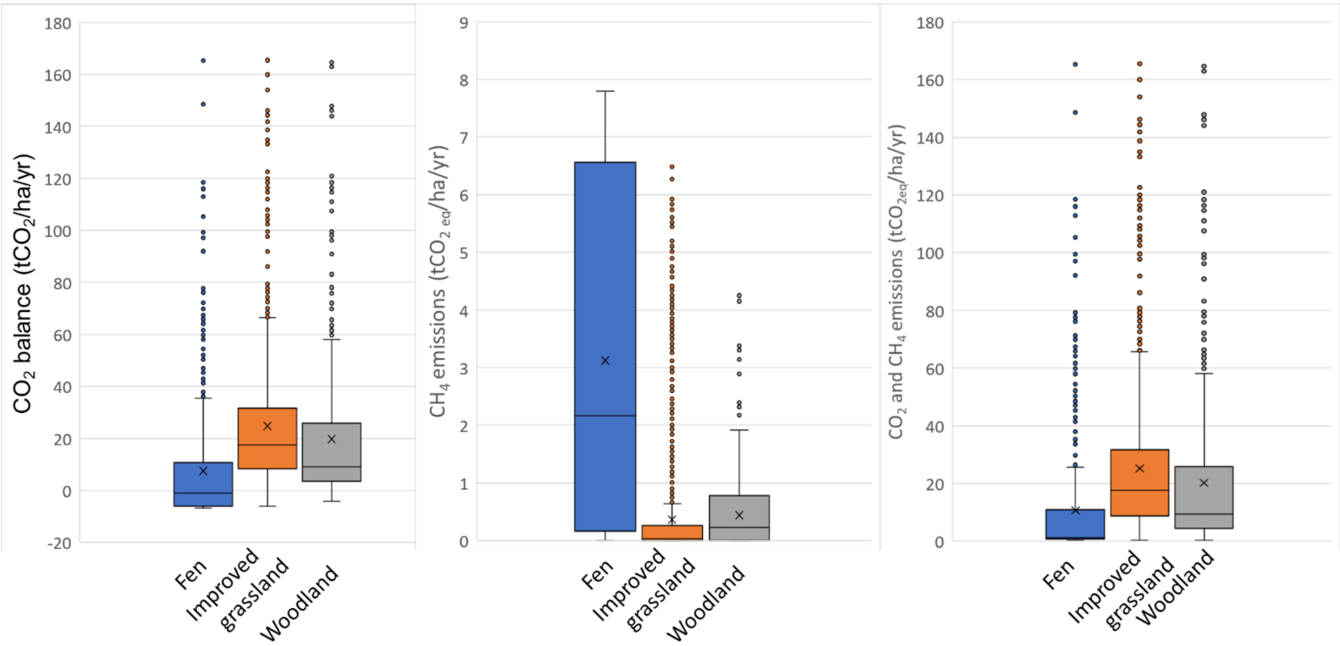


Figure 19 Distribution of (left) CO2 balance, (centre) CH4 emissions and (right) combined CO2 and CH4 emissions, all expressed in tCO2eq/ha/yr, by modelled landcover class [Note that the y axis of the CO2 graph is 10 times higher than the CH4 graph]

However, it must be recognised that there are uncertainties in the estimates which must be taken into consideration:

- Unlike Holman and Kecharvarzi (2011), the original peat soil dataset of Heppell et al. (2020) made no differentiation between soils where peat is at the surface and where peat is or may be buried below significant mineral layers. Consequently, the modifications made to the peat map of Heppell et al. (2020) by the Broads Authority have included adding additional peat observations but also removing the area of Newchurch Association (marine alluvium soils) within the Thurne catchment which may include areas of buried peats. The spatial extent and importance of emissions from buried peats remains uncertain;
- The estimates of the GHG emissions from the peats of the Broads is limited to CO_2 and CH_4 and does not consider emissions of N_2O which can be significant from agricultural peat soils (Evans et al., 2017)
- This assessment used the UK regression equations of Evans et al. (2021) to estimate emissions from mean effective watertable depth (WTDe):
    - The estimated effective watertable depth in each field is affected by uncertainties in the estimated drain water levels, peat properties, drain spacing and groundwater seepage.

Nevertheless the evaluation against available data on drain water levels and watertable depth suggests that the results are plausible;

  - The CO_2 balance (or Net Ecosystem Production) was estimated using Equation 1 of Evans et al. (2021) which was based on CO_2 flux measurements from16 eddy covariance flux towers on peatland located across the UK and Ireland. If the uncertainty ranges in UK regression Equation 1 of Evans et al. (2021) was used, the uncertainty range in the estimated CO_2 balance for the peat soils of the Broads would range from 3302 tC/yr to 32522 tC/yr;
  - The CH_4 flux regression (Equation 3 in Evans et al. 2021) was derived from 41 measurements of annual mean CH_4 flux from peatlands in the United Kingdom and Ireland made using static chamber methods. The uncertainty in CH_4 flux was assumed by Evans et al. (2021) to be $\pm$50% giving higher uncertainties when WTDe was low. Consequently, the uncertainty range in the estimate of CH_4 from the peat soils of the Broads is 347 – 1,041 tC/yr.

- Due to these uncertainties in emissions, the total radiative forcing of carbon emissions from peat soils in the Broads could range from 25,049 – 158,068 t CO_{2eq}/yr.

The non-linear relationship between the greenhouse gas balance and effective watertable depth from Evans et al. (2021) suggests that the optimal mean watertable depth is around 4 cm which is typical of relatively pristine sites (Turetsky et al., 2014). Any decrease in watertable depth up to this depth would be expected to have a net beneficial impact in terms of climate forcing. Examination of Figure 16 suggests that the greatest potential climate forcing benefits from land management and drainage change (associated with higher drain water levels) would be afforded in the improved grassland (and arable) fields in the lower Yare, middle Waveney and Upper Thurne.

5. References

Conservation Engineering Division (1986). Urban Hydrology for Small Watersheds. Natural Resources Conservation Service Technical Release-55, USDA, Washington DC, USA.

Dutta A (2022). Quantifying Greenhouse gas emissions from wetlands in Broads National Park. Unpublished MSc thesis, Cranfield University

Evans CD, Peacock M, Baird AJ et al. (2021). Overriding water table control on managed peatland greenhouse gas emissions. Nature 593, 548-552. Doi: 10.1038/s41586-021-03523-1

Evans, C., Artz, R., Moxley, J., Smyth, M-A., Taylor, E., Archer, N., Burden, A., Williamson, J., Donnelly, D., Thomson, A., Buys, G., Malcolm, H., Wilson, D., Renou-Wilson, F., Potts J. (2017). Implementation of an emission inventory for UK peatlands. Report to the Department for Business, Energy and Industrial Strategy, Centre for Ecology and Hydrology, Bangor.88pp.

Heppell CM, Bartlett A, Belyea L & Henshaw A (2020). Assessing carbon stocks within the peat of the Broads National Park. Unpublished report for the Broads Authority

Hess TM and Counsell C (2010). A water balance simulation model for teaching and learning – WaSim, Paper presented at the ICID British Section Irrigation and Drainage Research Day, 29 March 2000, HR Wallingford. Available from http://dspace.lib.cranfield.ac.uk/handle/1826/2455

Hess T.M., Holman I.P., Rose S.C., Rosolova Z. and Parrott A. (2010). Estimating the impact of rural land management changes on catchment runoff generation in England and Wales. Hydrological Processes 24(10), 1357-1368

Holman IP & Kechavarzi C (2011). A revised estimate of peat reserves and loss in the East Anglian Fens, commissioned by the RSPB, Department of Natural Resources, Cranfield University, pp.31.

Holman I.P., Hess T.M., Rose S.C. (2011). A broad-scale assessment of the effect of improved soil management on catchment Baseflow Index. Hydrological Processes 25(16), 2563-2572

Lindsay R, Clough J, Clutterbuck B, Bain C, Goodyer E (2019). Eyes on the Bog: Long-term monitoring network for UK peatlands. IUCN Peatland programme. Available from https://www.iucn-uk-peatlandprogramme.org/get-involved/eyes-bog

Robinson, E.L.; Blyth, E.M.; Clark, D.B.; Comyn-Platt, E.; Rudd, A.C. (2020a). Climate hydrology and ecology research support system meteorology dataset for Great Britain (1961-2017) [CHESS-met]. NERC Environmental Information Data Centre. https://doi.org/10.5285/2ab15bf0-ad08-415c-ba64-831168be7293

Robinson, E.L.; Blyth, E.M.; Clark, D.B.; Comyn-Platt, E.; Rudd, A.C. (2020b). Climate hydrology and ecology research support system potential evapotranspiration dataset for Great Britain (1961-2017) [CHESS-PE]. NERC Environmental Information Data Centre. https://doi.org/10.5285/9116e565-2c0a-455b-9c68-558fdd9179ad

Smith, C., Z.R.J. Nicholls, K. Armour, W. Collins, P. Forster, M. Meinshausen, M.D. Palmer, and M. Watanabe (2021). The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Available from https://www.ipcc.ch/ .

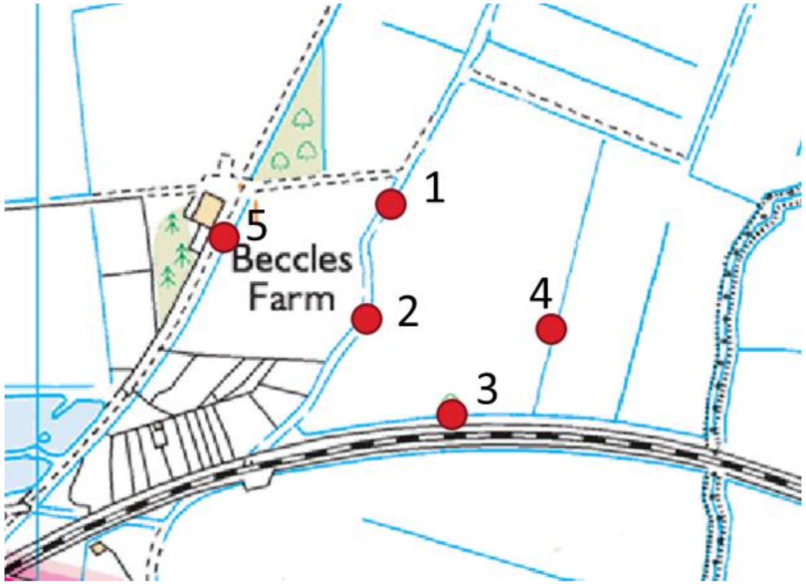
Turetsky, M.R., Kotowska A, Bubier J et al. (2014). A synthesis of methane emissions from 71 northern, temperate, and subtropical wetlands. Global Change Biol. 20, 2183–2197.

Youngs, E. G., Leeds-Harrison, P.B. and Chapman, J.M. (1989). Modelling water-table movement in flat low-lying lands. Hydrological Processes 3: 301-315.

Appendix 1

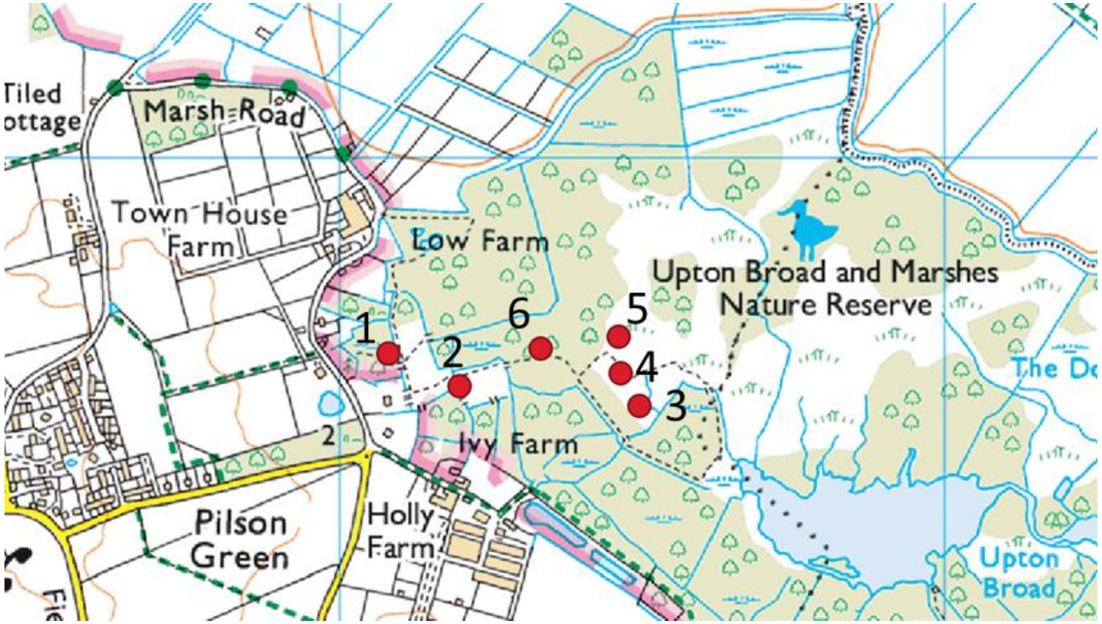
Beccles Farm

Site	East	North	Habitat	Site typology	Peat starting depth	Peat thickness
Beccles1	643455.7681	291589.8585	Rushy grassland	Grassland - medium water level	66	50
Beccles2	643423.7704	291442.8588	Rushy grassland	Grassland - medium water level	0	112
Beccles3	643532.9629	291321.4361	Rushy grassland	Grassland - medium water level	0	115
Beccles4	643660.2222	291430.9568	Rushy grassland	Grassland - medium water level	0	103
Beccles5	643241.2002	291547.5739	Rushy grassland	Grassland - medium water level	0	152



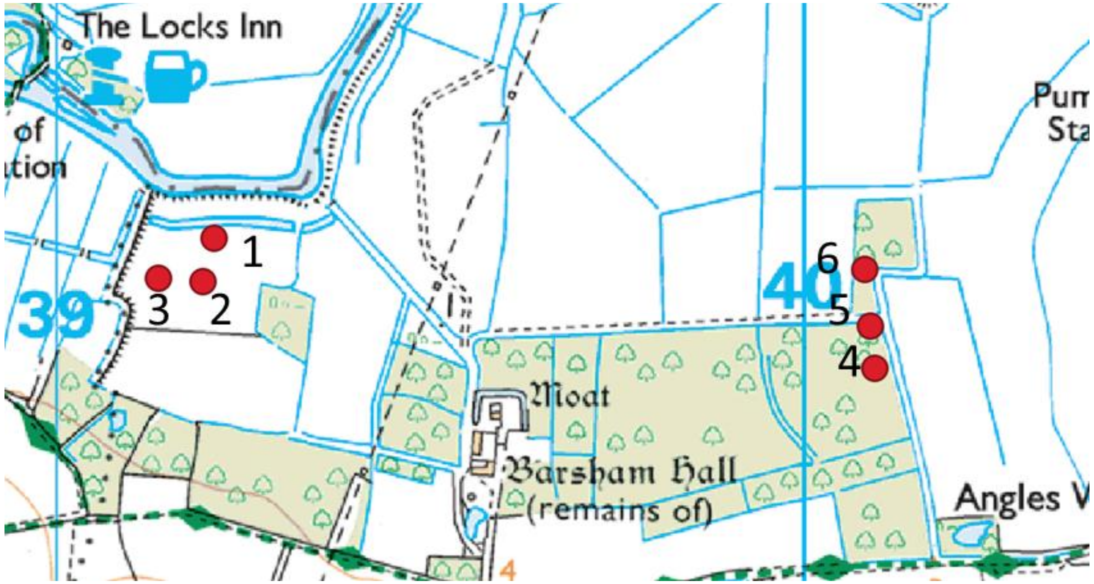
Upton Broad

Site	East	North	Habitat	Site typology	Peat starting depth	Peat thickness
Upton1	638082.0322	313677.8675	Reedbed	Fen - high water level	0	81
Upton2	638199.0501	313622.5602	Typha / phragmites	Fen - high water level	0	270
Upton3	638497.1184	313591.1294	Fen (sphagnum)	Fen - high water level	0	353
Upton4	638465.2295	313644.3082	Fen (sphagnum)	Fen - high water level	0	355
Upton5	638462.0607	313705.1176	Fen (sphagnum)	Fen - high water level	0	452
Upton6	638333.678	313685.5664	Typha / phragmites in woodland	Fen - high water level	0	525



Whitehouse Farm

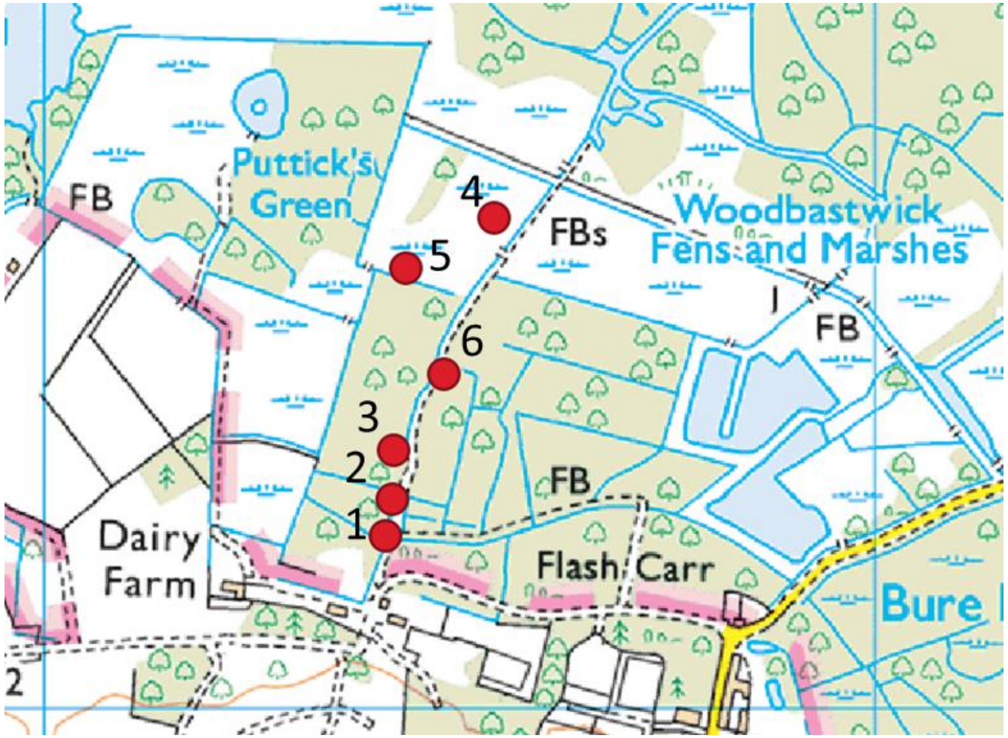
Site	Easting	Northing	Habitat	Site typology	Peat starting depth	Peat thickness
WhiteHouse1	639211.1266	290637.586	Permanent grassland (with rushes)	Grassland - medium water level	28	222
WhiteHouse2	639195.8725	290579.8694	Permanent grassland (with rushes)	Grassland - medium water level	100	110
WhiteHouse3	639137.3463	290584.6917	Permanent grassland (with rushes)	Grassland - medium water level	45	165
WhiteHouse4	640094.8884	290464.0306	Woodland (dry)	Woodland - medium water level	20	120
WhiteHouse5	640087.9716	290520.4134	Woodland (dry)	Woodland - medium water level	0	180
WhiteHouse6	640081.7922	290595.9921	Woodland (dry)	Woodland - medium water level	53	202



(Ordnance Survey data © Crown copyright [and database rights] 2023 OS 100021573)

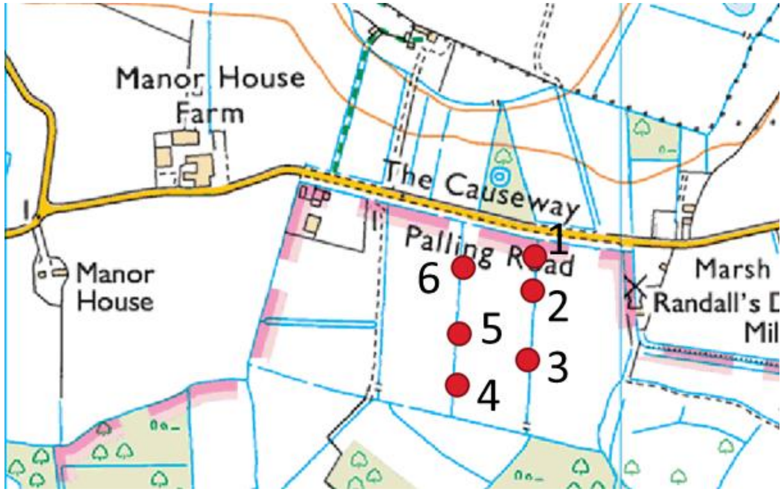
Woodbastwick

Site	East	North	Habitat	Site typology	Peat starting depth	Peat thickness
Woodbastwick1	633410.8709	316206.442	Fen (open, sedge)	Fen - high water level	20	130
Woodbastwick2	633418.6007	316251.8187	Wet woodland	Fen - high water level	0	165
Woodbastwick3	633420.0276	316309.9726	Reedbed	Fen - high water level	0	110
Woodbastwick4	633541.7021	316589.7318	Fen (open, sedge, rushes)	Fen - high water level	0	340
Woodbastwick5	633435.0858	316528.8686	Fen boundary (phrgamites/open fen)	Fen - high water level	0	220
Woodbastwick6	633481.7854	316401.892	Wet woodland	Fen - high water level	0	235



Manor House Farm

Site	East	North	Habitat	Site typology	Peat starting depth	Peat thickness
ManorHouse1	640860.4784	326474.7585	Ley grassland	Grassland- low ditch level	0	148
ManorHouse2	640857.4333	326419.5207	Ley grassland	Grassland- low ditch level	0	142
ManorHouse3	640849.8616	326305.8264	Ley grassland	Grassland- low ditch level	0	177
ManorHouse4	640734.4629	326265.5917	Ley grassland	Grassland- low ditch level	0	245
ManorHouse5	640738.5554	326349.3527	Ley grassland	Grassland- low ditch level	0	216
ManorHouse6	640744.9652	326456.2995	Ley grassland	Grassland- low ditch level	0	232



(Ordnance Survey data © Crown copyright [and database rights] 2023 OS 100021573)

Leist's Farm

Site	East	North	Habitat	Site typology	Peat starting depth	Peat thickness
Leists2a	636688.553	314729.3849	Rushy grassland	Grassland - high water level	0	305
Leists2b	636689.1517	314730.2575	Rushy grassland	Grassland - high water level		
Leists3a	636747.5486	314725.2016	Rushy grassland	Grassland - high water level	0	380
Leists3b	636747.8163	314726.106	Rushy grassland	Grassland - high water level		
Leists4a	636720.9899	314720.3492	Rushy grassland	Grassland - high water level	0	268
Leists4b	636721.0788	314721.1248	Rushy grassland	Grassland - high water level