Assessing carbon stocks within the peat of the Broads National Park

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Heppell CM, Bartlett A, Belyea L & Henshaw A

Commissioned by The Broads Authority

Project Manager Andrea Kelly (Broads Authority)

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School of Geography

Queen Mary University of London

Mile End Road

E1 4NS

Tel: +44 (0)207 882 2768

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1 Introduction

The Broads Authority commissioned this report as part of the CANAPE Interreg Project (https://northsearegion.eu/canape/about/) to assess current carbon stocks in the peat of the Broads National Park. The Broads Carbon Audit (2010) had previously estimated that earthy peat soils account for 66 % of the stored CO_2e in all the soils of the Broads National Park, highlighting the importance of organic soils for carbon storage in the Broads. The analysis in this report refines the previous estimate for earthy peat soils, by estimating carbon stocks in both peat soils (classified by Soil Survey as sub-group 10), and in peat buried at depth in mineral soils. To achieve this more detailed analysis, this report uses high resolution soils maps and auger data for the Broads National Park obtained from the Lowland Peatland Survey of England and Wales (1987) and the Broads Authority Peat Resource Survey (2010).

1.1 Aim and Objectives

The aim of this report is to provide a baseline analysis of existing peat carbon stocks for the Broads National Park using a combination of historical and current peat datasets. Objectives are to:

- Collate historical and current datasets describing location and depth distribution of peat in the Broads National Park.
- Identify the likely area and depths of the remaining peat.
- Estimate the carbon storage within the peat of the Broads National Park.

2 Study area and historical context

The Broads National Park comprises a landscape of inter-connected broads, rivers, fen and swamp, carr woodland and grazing marshes valued for its ecological biodiversity. The drained Broadland valleys are used extensively for improved permanent pasture with a smaller proportion of arable; and the wetter areas for extensive rough grazing and woodland with many areas under conservation management to protect fen and reedbed habitat.

Most of the extensive peat deposits in the Broads National Park are floodplain fens arising from repeated flooding by river water. A few narrow valley peats have formed from groundwater seeping from the valley sides. Peat in the upper valleys is banded with lacustrine clays whilst the lower reaches of valleys, which have been affected by fluctuating freshwater and estuarine conditions during Holocene sea level rise, comprise two wedges of estuarine clays sandwiched between three layers of peat. Burton and Hodgson (1987) provide a detailed account of the formation and structure of the peat on the basis of the augers taken for the Lowland Peatland Survey of England and Wales in the 1980s.

The wetter areas of floodplain fens have been cut for peat used as fuel for over 1000 years. The two-to-three metre deep basins of Broadland were excavated in the 13th century for peat, and became flooded during the period of sea level rise from the 14th century onwards. However, the practice of 'turbary' (cutting of shallow peat pits for fuel) started as early as 1st or 2nd century AD, and continued into the 19th century, and some cases 20th century, to supply local and domestic needs for fuel (Parmenter, 2016). Terrestrialisation of the extensive turbaries, which are believed to have covered much of the floodplain fen area (Parmenter, 2016), has led to loose fresh peat which contrasts with the firmer, humified peat of areas that have remained untouched by peat cutting (Burton and Hodgson, 1987).

Many peatlands in the Broads National Park have been drained for pasture, arable or horticultural use. This drainage leads to peat wastage and subsidence of the ground surface due to shrinkage, compression and oxidation of organic matter.

3 Methods

3.1 Peat soil classification

To accurately assess peat stocks in the Broads National Park we need to differentiate between peat soils, thin peat horizons at the soil surface and peat buried at depth.

Peat soils are a major soil group (10) in the soil classification system used by the Soil Survey of England and Wales. They must meet both of the following criteria (Avery, 1980):

- Either more than 40 cm of organic material within the upper 80 cm of the profile, or more than 30 cm of organic material resting on bedrock or skeletal material.
- No superficial non-humose mineral horizons with a colour value of 4 or more that extend below 30 cm depth.

So for a soil to be classified as soil group 10 the peat must be more than 40 cm in thickness, and not be buried by more than 30 cm of mineral material (Holman & Kechavarzi, 2011).

However, this classification does not take into account peat horizons within other soil series that do not meet the criteria of soil group 10. This will include areas where there are surface peat horizons which are less than 40 cm thick (referred to hereafter as 'remnant surface peat'); and areas where peat horizons, which could be of significant thickness, are buried at depth > 30 cm (referred to hereafter as 'peat at depth') (see Supplementary Information 1 for a flow chart summarising peat classification).

The peat datasets used in this report all consider peat auger datasets that extend beyond the conventional soil survey reference section of 1 m depth, so that total peat thickness could be estimated. Even then there are auger records that end before the maximum depth of peat was recorded and these are highlighted in the description of all auger records contained in the 'all-combined' spreadsheet.

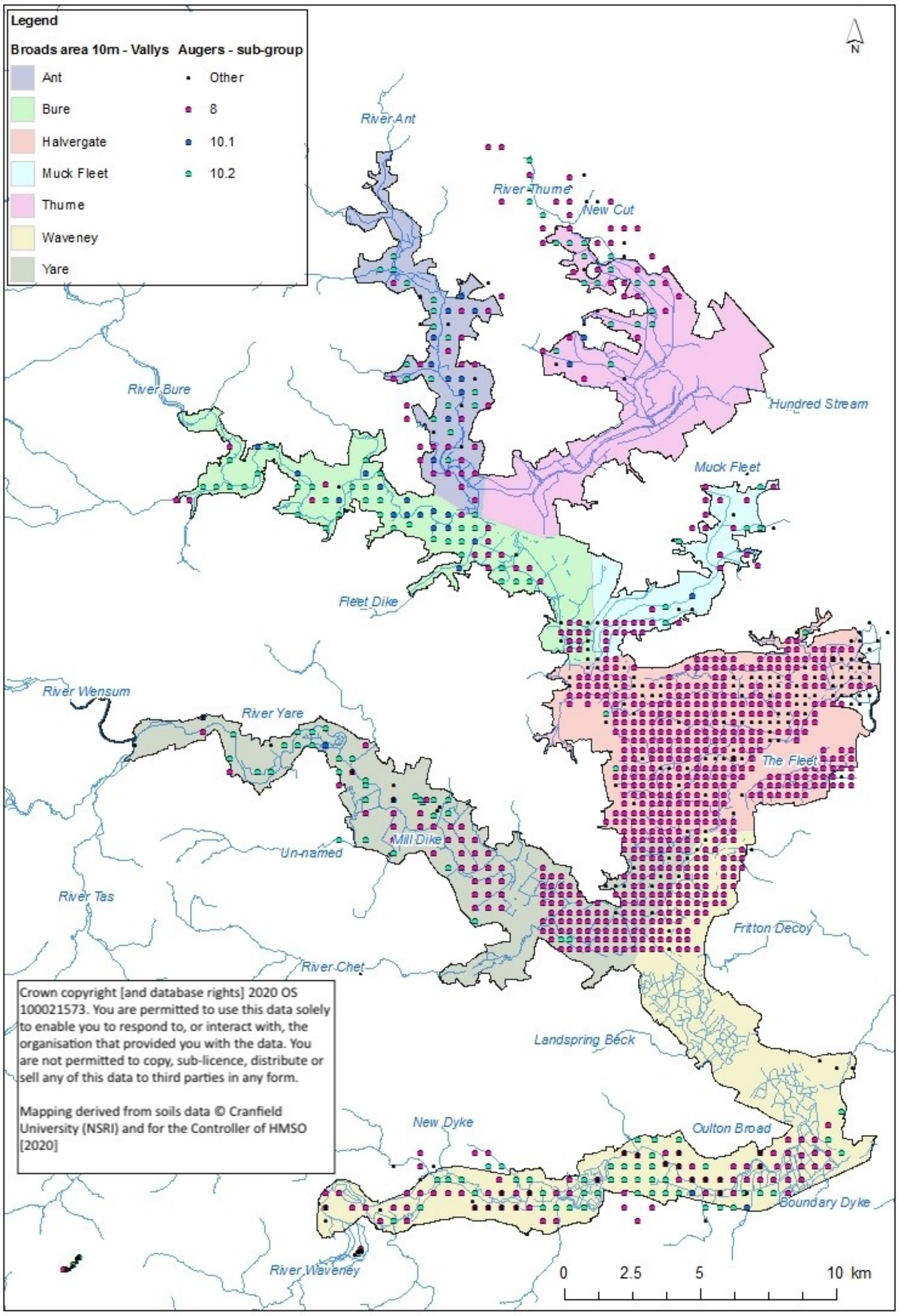
3.2 Secondary datasets used in this report

Secondary datasets were used to assess the carbon stock, and the key datasets are described in the section below. Additional datasets that could be used to improve the estimates in future are described in further recommendations (Section 4.3); and the transects of Joyce Lambert are described in Supplementary Information 2 as a potential dataset for future analysis.

3.2.1 Lowland Peatland Survey (Burton and Hodgson, 1987)

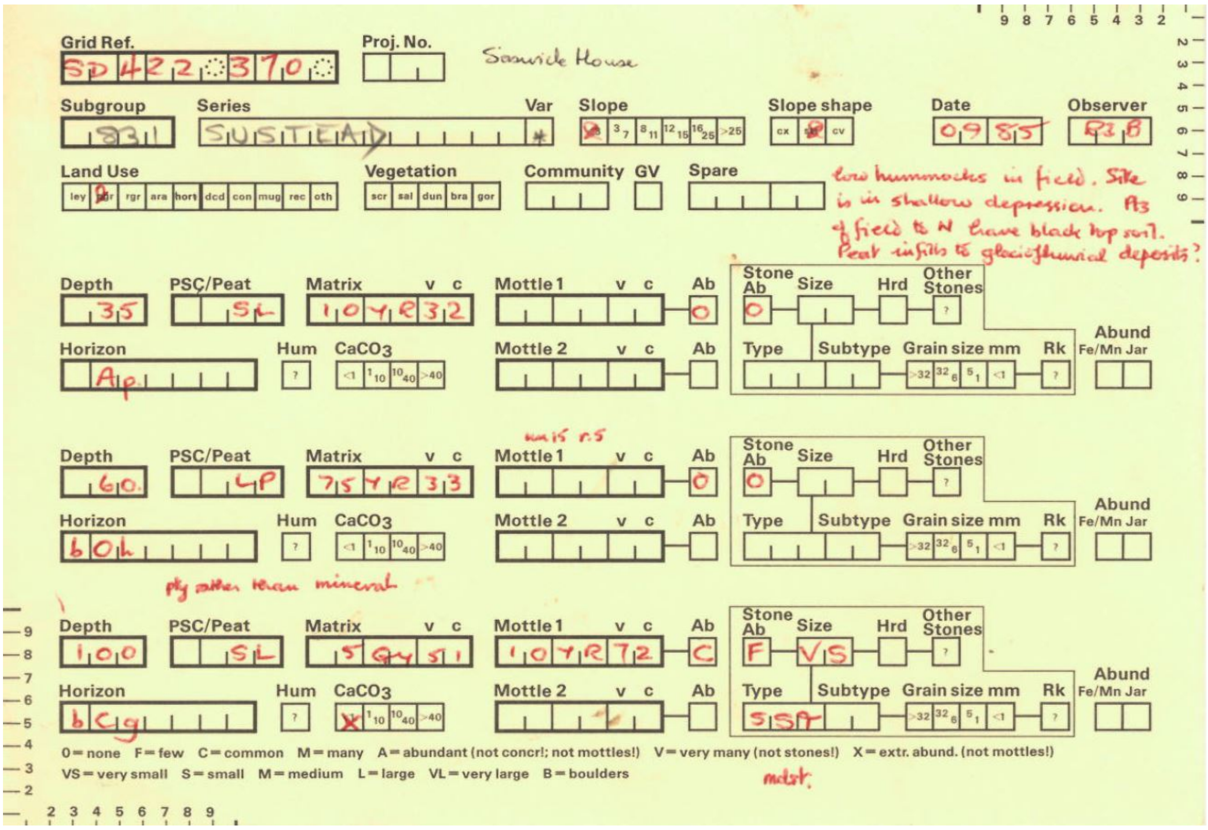
The Lowland Peatland Survey (LPS) of England and Wales (1987) surveyed peat by hand-auger borings at 500 m intersections of the National Grid located from 1:25 000 maps. Figure 1 shows the sites of borings within and surrounding the Broads National Park boundaries. For the purpose of the inventory, lowland peat was required to be at least 40 cm thick, covered by less than 30 cm of non-organic material and situated below 200 m O.D. Where possible borings were made through the peat profile to the underlying deposits. The site data indicated peat type following the modified Von Post humification assessment of Avery (1980).

Figure 1 Auger sites from Lowland Peatland Survey. Coloured polygons denote different valleys and auger points are colour-coded by soil sub-group (pink, blue and green indicating sub-groups 8, 10.1 and 10.2 respectively).



Horizon data was recorded on ‘RUFFS’ cards that at the time of the survey enabled input of peat data into the Soil Survey’s Land Information System (LandIS). Peat soil was recorded as humified (HP), fibrous (FP), mesic (semi-fibrous) (MP), loamy peat (LP) or sandy peat (SP). Peat loam (PL) and peaty sand (PS) were additional textures recorded on the cards (Figure 2). A full description of the classification of peat and explanation of the field and subsequent analysis carried out for the survey can be found in Burton & Hodgson (1987).

Figure 2 Example RUFFS card (from LandIS, viewed 26 August 2020, http://www.landis.org.uk/data/augerbore.cfm)


Grid Ref. SD 422 370 Proj. No. Sowick House
Subgroup 1831 Series SUSTEAD Var Slope Slope shape Date 0985 Observer RJB
Land Use ley gr rgr ara hort dcd con mug rec oth Vegetation scr sal dun bra gor Community GV Spare
Low hummocks in field. Site is in shallow depression. Pts of field to N have black top soil. Peat infills to glaciofluvial deposits?
Depth 35 PSC/Peat SL Matrix v c 10YR 3 2 Mottle 1 v c Ab O Stone Ab O Size Hrd Other Stones
Horizon Ap Hum CaCO3 Mottle 2 v c Ab Type Subtype Grain size mm Rk Abund Fe/Mn Jar
Depth 60 PSC/Peat LP Matrix 7.5YR 3 3 Mottle 1 v c Ab O Stone Ab O Size Hrd Other Stones
Horizon bOh Hum CaCO3 Mottle 2 v c Ab Type Subtype Grain size mm Rk Abund Fe/Mn Jar
Depth 100 PSC/Peat SL Matrix 5GY 5 1 Mottle 1 v c 10YR 7 2 Ab C Stone Ab F Size VS Hrd Other Stones
Horizon bCg Hum CaCO3 X Mottle 2 v c Ab Type SST Subtype Grain size mm Rk Abund Fe/Mn Jar
0=none F=few C=common M=many A=abundant (not concr!; not mottles!) V=very many (not stones!) X=extr. abund. (not mottles!)
VS=very small S=small M=medium L=large VL=very large B=boulders

On the basis of the horizons described in the auger bores the soil was classified into soil series. The Soil Survey of England and Wales uses a hierarchical soil description of ten major soil groups (Group 10 is Peat soils), soil group (10.1 Raw peat soils and 10.2 Earthy peat soils), soil subgroup and finally soil series. Table 1 summarizes the different peat soil series (Group 10) found within the Broads National Park boundaries. Note that there are other soil groups identified within the Park boundary that contain peat layers, even though they are not classified as a peat soil. Lowland Peat in England and Wales (1987) provides a brief characteristic description of the horizons in each soil series to 100 cm depth.

Peat depth in the Broads National Park frequently exceeds 100 cm depth. So, although the soil series classification can be used to identify peat to 100 cm depth, the original horizon data captured in the RUFFS cards is needed to assess peat depth and character at greater depths below the surface. Some, but not all, of these data have been captured in LANDIS as 'AUGERProfile' records. Similarly, locations of some (but not all) bores are captured in LANDIS as 'AUGERSite' records. Where auger records were captured on scanned RUFFs cards, but not in LANDIS, we added the records from the cards to the 'all_combined.xls' spreadsheet. Table 2 captures the total number of augers recorded by Lowland Peatland Survey in each valley of the Broads National Park along with the number of peat augers which recorded peat in each valley.

Table 1 Peat Soil Subgroups recorded within the Broads National Park by Lowland Peatland Survey of England and Wales.

Peat subgroup	Description
10.12	Raw eu-fibrous peat soil with a reference section of predominantly fibrous or semi-fibrous peat that does not contain remains of *Sphagnum*, *Eriophorum*, *Calluna* or *Trichophorum*, has a pH ($CaCl_2$ 1:2.5 undried) more than 4.0 in at least some part.
10.14	Raw eutro-amorphous peat soils with a reference section consisting predominantly of humified peat with a pH ($CaCl_2$ 1:2.5 undried) more than 4.0 in at least some part.
10.22	Earthy eu-fibrous peat lacking a sulphuric horizon within 80 cm depth and with a reference section of predominantly fibrous or semi-fibrous peat that does not contain remains of *Sphagnum*, *Eriophorum*, *Calluna* or *Trichophorum*, has a pH ($CaCl_2$ 1:2.5 undried) more than 4.0 in at least some part.
10.24	Raw eutro-amorphous peat soils lacking a sulphuric horizon within 80 cm depth with a reference section consisting predominantly of humified peat with a pH ($CaCl_2$ 1:2.5 undried) more than 4.0 in at least some part.
10.25	Earthy sulphuric peat soils with a sulphuric horizon starting within 80 cm depth.

Table 2 Peat augers recorded by Lowland Peatland Survey (LPS) by valley

Valley	No. Augers (No. augers with peat)
Ant	58 (45)
Bure	76 (51)
Halvergate	475 (50)
Muck Fleet	24 (11)
Thurne	41 (34)
Waveney	187 (94)
Yare	206 (80)

3.2.2 Detailed soil maps

Soil Survey of England and Wales provide a number of soil maps of the area. Complete coverage of the area was obtained from the National Soil Map of England and Wales (NSRI, 2019) at 1:250,000 scale. This was augmented by three scanned maps of TG40 Halvergate, TG31 Horning and TM49 Beccles at 1:25,000 scale each.

3.2.3 Broads Authority Peat Resource Survey (2010)

The consultancy firm, Ecology Land and People (ELP, a division of OHES Environmental), were commissioned by Broads Authority in 2009/2010 to complete peat auger surveys at 16 sites in the Ant, Bure, Thurne and Waveney Valleys (Table 3). Peat data from each hand-augered geo-located core were recorded in individual spreadsheets including peat classification and habitat. Each auger provides useful data to supplement the Lowland Peatland Survey database. However, in this case the surveyors did not always core to the base of the peat making total peat thickness impossible to calculate, and potentially leading to an under-estimation of peat stock in these areas.

Table 3 List of sites included in database from the Broads Authority Peat Resource Survey (2010)

Valley	Site	No. Cores (No. cores with peat)
Ant	Crostwright S	14 (13)
Ant	Crostwright M	15 (12)
Ant	Crostwright N	12 (10)
Ant	Dilham	26 (26)
Bure	Panxworth N	17 (7)
Bure	Panxworth S	13 (13)
Thurne	MHF Ingham N	21 (21)
Thurne	MHF Ingham S1	23 (23)
Thurne	MHF Ingham S2	24 (24)
Thurne	HF Ingham	25 (25)
Thurne	MF Hemsptead	14 (11)
Thurne	Bridge House	4 (2)
Thurne	Grange Farm	10 (7)
Waveney	Covehall Farm	45 (45)
Waveney	Marsh Lane Worl	19 (19)
Waveney	East Fen Carr Worl	3 (3)

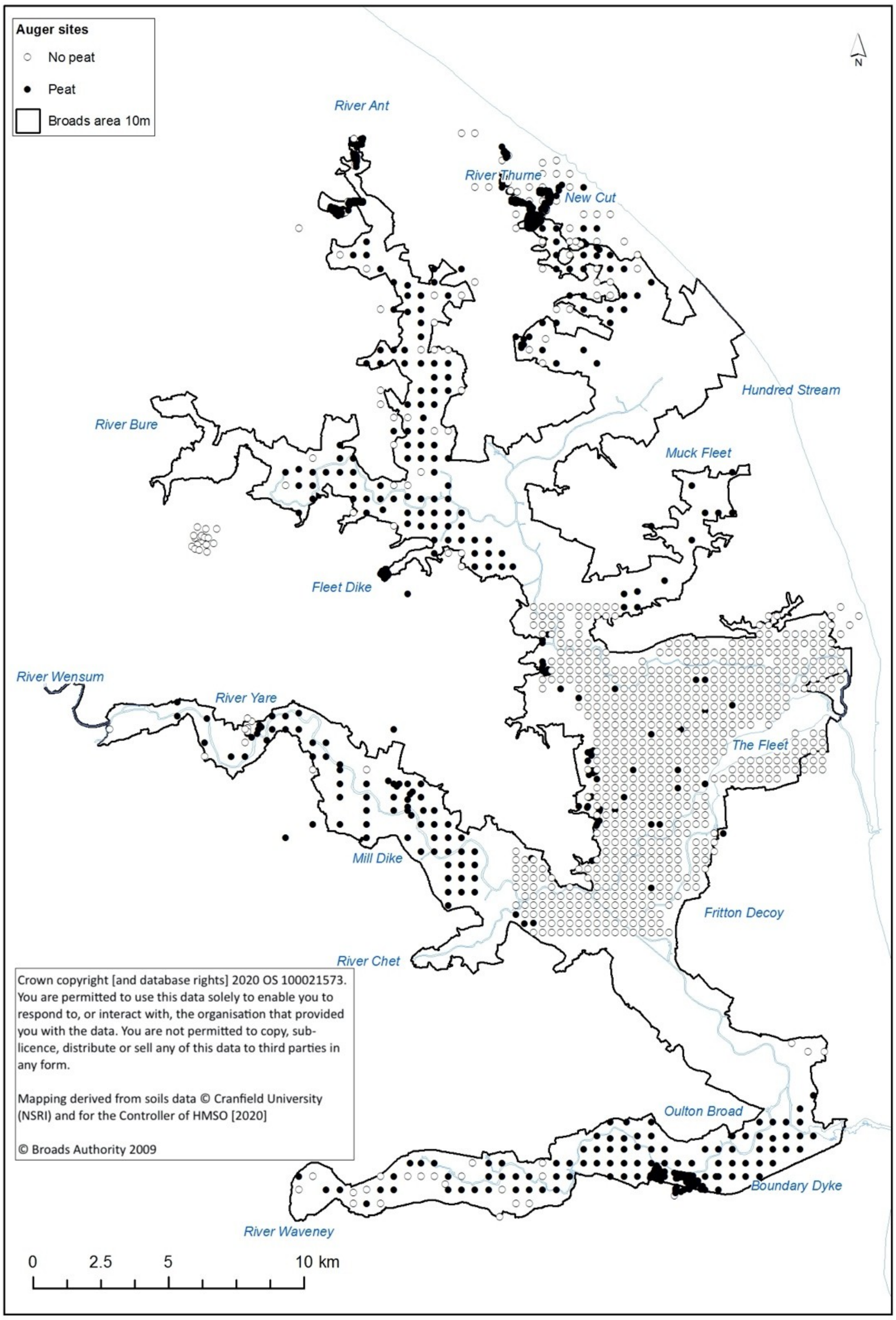
3.2.4 Land Cover

The UK Land Cover Map 2015 (LCM2015), released in 2017, was provided by the Broads Authority to identify current land cover based on the UK Biodiversity Action Plan Habitats classes. Land cover was defined using the Broad Habitat (bhab) attribute in the UK Land Cover Map 2015 (25m) vector dataset. This provides the dominant land cover at broad habitat level (e.g. improved grassland).

3.3 Calculations using peat auger datasets

The Lowland Peatland Survey (LPS) and the Ecology, Land and People (ELP) datasets were combined into one spreadsheet (All_combined.xls) to collate all geo-referenced auger data. Figure 3 illustrates the location of all the auger sites in the combined dataset with closed circles indicating sites with peat, and open circles indicating locations of sites without peat.

Figure 3 Auger sites in combined (LPS and ELP) dataset illustrating sites with and without peat.



Land use type at the time of the Lowland Peatland Survey (1980) and from the LCM (2015) dataset were added to the spreadsheet. Land use classes were simplified as indicated in Table 4 to enable cross-comparison between the two datasets. Each auger was given a unique bore ID on the basis of source data (LPS/ELP), OS grid square and number. According to LCM (2015) the Broads National Park contains improved and extensively managed grassland. For the purposes of estimating peat wastage rate (cm/yr) all grassland was characterized as one category because there are no peat wastage estimates available for extensively and intensively grazed scenarios. However, carbon density (g C cm^{-3}) calculations consider extensive and intensive grazing regimes using records of agri-environment schemes, and this is described in Section 3.3.2.

Table 4 Land use classification terms

Lowland Peatland Survey (LPS)		**LCM (2015)**
Other	oth ('Phrag', 'Juncus' & 'Carr' denoted by hand on RUFFs cards)	Fen, marsh and swamp
Deciduous woodland	dcd	Broadleaf woodland
Permanent grassland	pgr	Grassland
Ley grassland	ley	Grassland
Enclosed rough grassland	rgr	Grassland
Arable	ara	Arable and horticulture
Horticulture	hort	Arable and horticulture

For each auger the spreadsheet captures each soil/sediment layer described in the original dataset (upper and lower depth in relation to soil surface) and the peat texture. The original nomenclature from each dataset has been retained to ensure traceability and optimize future use of the dataset. Different surveyors used different abbreviations for peat texture and these are summarized in Table 5. Maximum recorded peat depth (cm) and peat thickness (cm, the sum of all layers containing peat) have been calculated for each auger record that contains peat. Peat thickness relates to augers collected in 1980 for the Lowland Peatland Survey data, and 2009/10 for the ELP dataset.

Table 5 Terms used to describe peat condition

Peat		**Loamy peat**		**Sandy Peat**	
HP	humified peat	LP	loamy peat	SP	sandy peat
MP	mesic (semi-fibrous) peat	HLP	humified loamy peat	HSP	humified sandy peat
FP	fibrous peat	FLP	fibrous loamy peat	FSP	fibrous sandy peat
P	peat	ALP	amorphous loamy peat	ASP	amorphous sandy peat
SFP	semi-fibrous peat	HALP	humified amorphous loamy peat		
CHP	Consolidated humified peat	MLP	mesic loamy peat		

UHP	Unconsolidated humified peat
AP	amorphous peat

The following variables have been calculated for each auger that contains peat and added to the all_combined.xls spreadsheet.

(i) Peat thickness as recorded in the 1980s (or 2010 for the ELP dataset)
(ii) Estimated peat thickness as of 2020
(iii) Carbon density assuming peat 'wastage' between 1980 to 2020 is due to compression (i.e. peat carbon has been retained) with upper and lower uncertainty (kg m^{-2})
(iv) Carbon density assuming peat 'wastage' between 1980 to 2020 is due to oxidation (i.e. peat carbon has been oxidized to carbon dioxide) with upper and lower uncertainty (kg m^{-2})

Section 3.3.1 and Section 3.3.2 explain the methods used to calculate the values above for each auger.

3.3.1 Peat thickness and peat wastage

In each case drainage of the land for improved pasture, arable or horticultural production may have occurred since the auger was recorded. Drainage generally leads to subsidence of the land surface, which is termed 'peat wastage'. Wastage involves a reduction in peat volume, occurring through one or more of the following processes: (i) consolidation of saturated peat due to the expulsion of water from soil pores, (ii) compaction of saturated or unsaturated peat due to expulsion of air from soil pores, (iii) oxidation of unsaturated peat due to aerobic decomposition and (iv) other mechanisms of peat loss, including wind erosion, peat harvesting and burning. Consolidation (i) and compaction (ii), along with deformation of soil solids, can together be termed 'compression'. Compression is caused by physical loading of the soil, such as by the passage of machinery, trampling by animals or soil sinking under its own weight. It leads to a reduction in soil volume but no loss of organic matter or carbon. Oxidation (iii) and soil loss (iv) result in both a reduction in soil volume and the loss of organic matter and carbon. In the analysis that follows, we contrast wastage due to 'compression' (i, ii) with that due to 'oxidation' (iii).

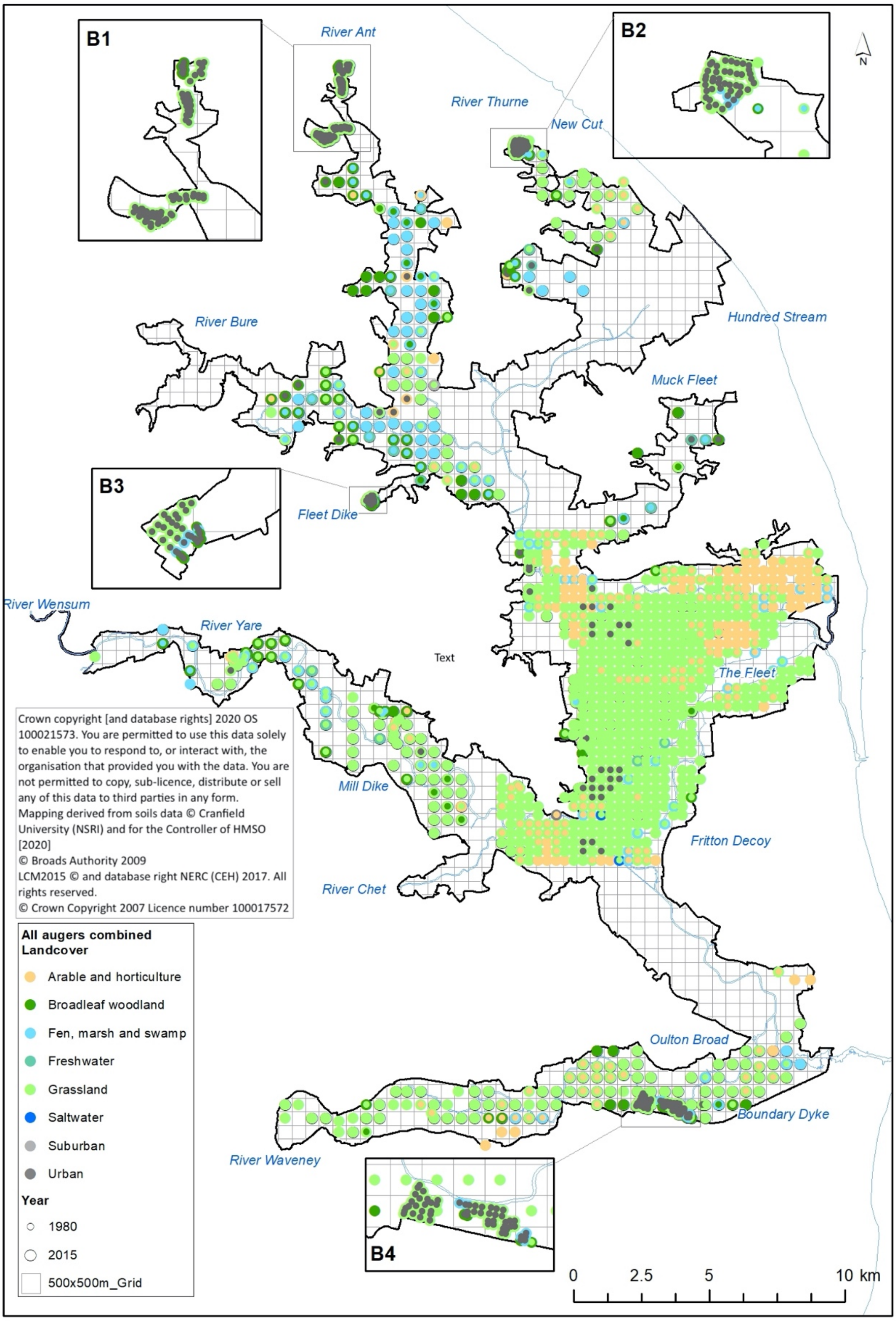
The rate of subsidence of the peat surface varies with land use and peat thickness so a measure of each was needed to estimate wastage. For each auger, peat depth was obtained from the auger record. The land use recorded for each auger site in 1980 (LPS dataset) or 2000 (ELP dataset) was compared to that recorded by LCM in 2015 (Figure 4). Where land use change appeared to have occurred, a combination of Google maps (satellite imagery) and Digimap (high resolution OS maps) were used to confirm the change in use. Maps and stacked bar charts of land use in 1980 and 2015 can be found in Supplementary Information 6.

Holman (2009) and Holman & Kechavarzi (2011) collated estimates of peat wastage for the Fens area from the literature. These peat wastage rates estimated by Holman & Kechavarzi (2011) were used to calculate wastage for arable and grassland sites in the Broads because agricultural practices are similar to the Fens (Table 6). These wastage rates are unlikely to be appropriate for areas of semi-natural land use (fens, marshes and swamps) within the Broads National Park, which may be gaining thickness through accretion. Webster (2016) estimated accretion rates of 0.27 cm/yr using Pb-210 and Cs-137 dated near-surface cores from three Phragmites-dominated reedbed sites under conservation management (Wheatfen, Strumpshaw and Woodbastwick). For the purposes of this study, we take a conservative approach and assume that neither peat wastage nor accretion has taken place across areas of semi-natural (fens, marshes and swamps) land use within the Broads National Park since the Lowland Peatland Survey (1987).

Table 6 Peat wastage rates (cm/yr) based on Holman & Kechavarzi (2011). Wastage, or subsidence of the land surface, may be due to physical compression of the soil, oxidation of soil organic matter or a combination of these processes.

Peat thickness	**Arable (drained and cultivated)**	**Grassland (drained)**	**Semi-natural (largely undrained)**
> 100 cm	2.1	0.8	0
< 100 cm	1.3	0.7	0

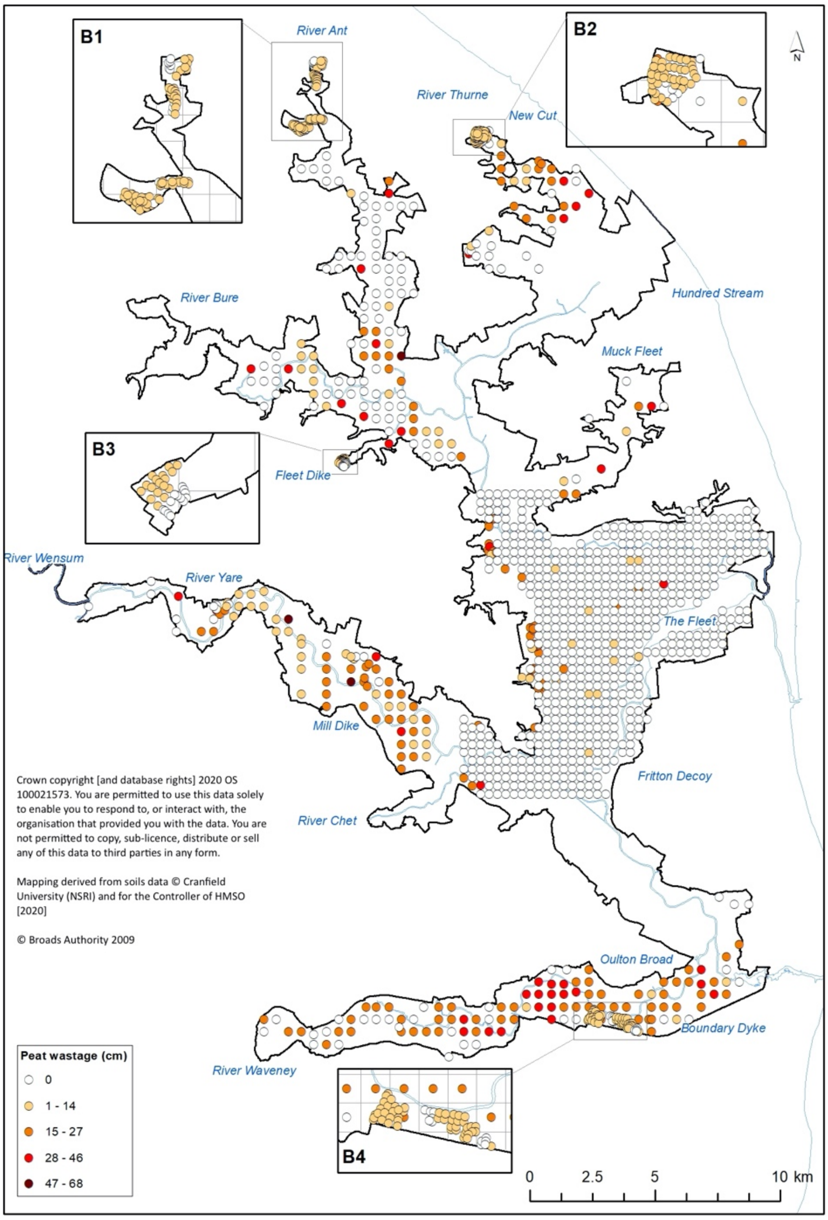
Figure 4 Land use change between 1980s and 2015 in the Broads National Park*.



* The 'grassland' category in the 1980s dataset includes permanent, ley and enclosed rough grassland. All the 'grassland' auger sites in 2015 are classified as 'improved grassland' by LCM (2015).

Peat wastage (cm) was calculated on an annual basis for each auger depending on land use and peat depth. If land use changed between 1980 and 2015 then the land use recorded by the lowland peatland survey was used from 1980 to 2002, and the LCM (2015) classification was used thereafter. Many cores in the Broads National Park contain clay lenses from marine transgressions, so overall peat wastage was reduced by 10% to account for this mineral material in line with the recommendations of Holman & Kechavarzi (2011). Figure 5 illustrates estimated peat wastage by auger (a) between 1980 and 2020 based on LPS augers, and (b 1-4) 2000 and 2020 based on the ELP survey augers.

Figure 5 Estimated peat wastage (cm) plotted by auger (A) between 1980 and 2020 based on LPS augers, and (B 1-4) 2000 and 2020 based on ELP augers. Wastage, or subsidence of the land surface,may be due to physical compression of the soil, oxidation of soil organic matter or a combination of these processes.



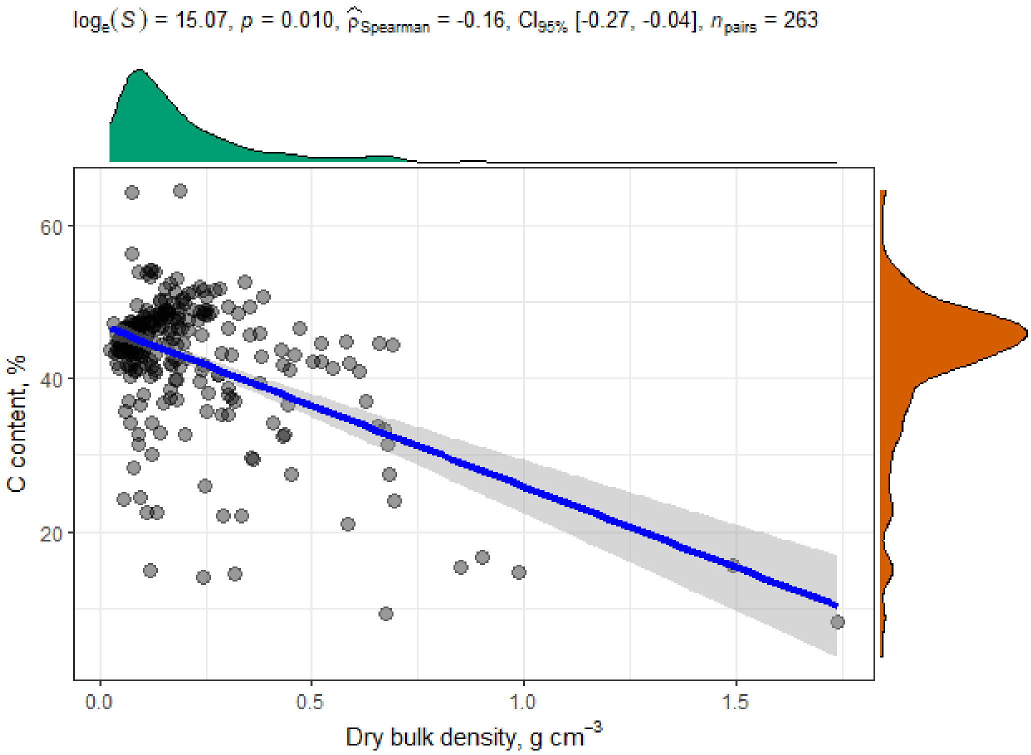
3.3.2 Carbon density

Whilst the Broads National Park has good spatial coverage of peat auger datasets describing peat horizons in great depth for most of the area, there is very little data available on bulk density and carbon content of the peat which are critical measurements needed to assess peat carbon stocks. The method in Holman (2009) describes the use of one estimated bulk density value to calculate carbon stock for the Fens. For this estimate of peat stock within the Broads National Park we take an alternative approach, using data collated as part of the Defra-funded SP1210 Lowland Peatland Systems project, along with a general linear modelling approach, to estimate carbon density for each geo-referenced auger site.

The general linear model was constructed using carbon content, dry bulk density and mineral content data collected from peat cores taken from lowland peatland sites across different land use regimes (as part of the Defra SP1210 Lowland Peatland Systems project). This approach was taken for several reasons:

- There is insufficient data on carbon content and dry bulk density across different land use types in the Broads National Park so data are needed from alternative geographical locations with lowland peat.
- The data from Defra SP1210 Lowland Peatland Systems project includes variation in peat characteristics by land use type, and also with depth and mineral content enabling these variables to be included in the model. This is important because peat in the Broads can be deep (over 8 m in places), and many areas contain peat that is either loamy or sandy in texture suggesting a significant mineral content.
- Two sites from the Broads National Park (Sutton and Strumpshaw fen) are included in the Defra SP1210 Lowland Peatland Systems dataset.
- Dry bulk density and carbon content are correlated (Figure 6) so errors are reduced on our carbon estimate by using one estimate of carbon density instead of separate estimates of bulk density and carbon content.

Figure 6 Correlation of bulk density and carbon content.

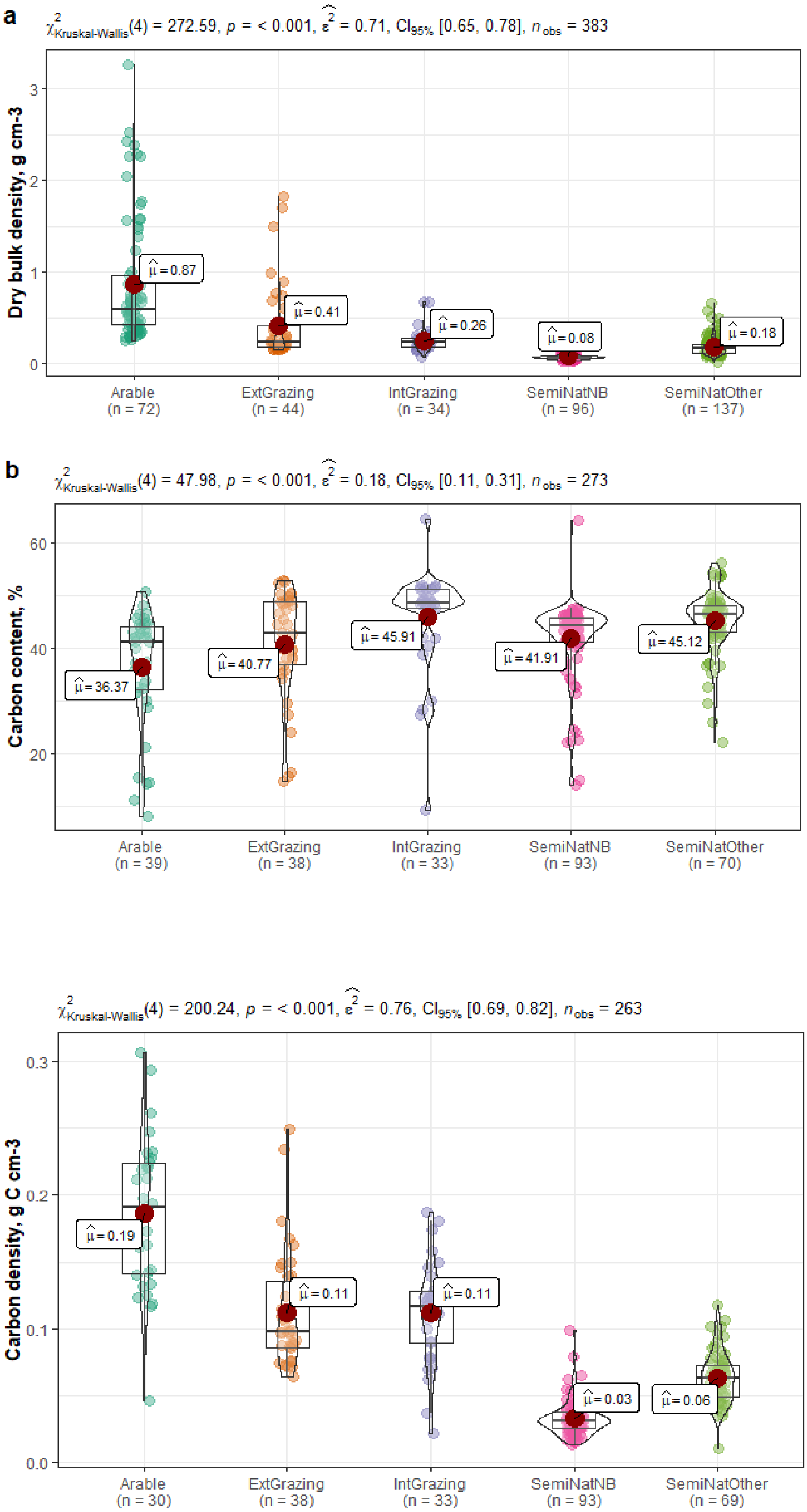


3.3.2.1 Variation in dry bulk density, carbon content and carbon density across different land use types

Violin plots are used to illustrate the differences in dry bulk density (Figure 7a), carbon content (Figure 7b) and carbon density (Figure 7c) by land use type in UK lowland peat.

- Arable sites have the highest bulk density and hence the highest mean carbon density (0.19 g C cm^{-3}).
- Extensively and intensively grazed peats have comparable carbon densities with a mean value of 0.11 g C cm^{-3}.
- Peat under semi-natural management regimes have the lowest carbon densities of all the land use types. Here peat under conservation management in the Broads National Park (SemiNatNB) has been separated from the other semi-natural sites in the database. This reveals a lower mean carbon density for the Broads of 0.03 g C cm^{-3} cf. 0.06 g C cm^{-3}, potentially due to past turf cutting activities.

Figure 7 Variation in (a) dry bulk density, (b) carbon content and (c) carbon density across land-use types using dataset from Defra SP1210 Lowland Peatland Systems project.

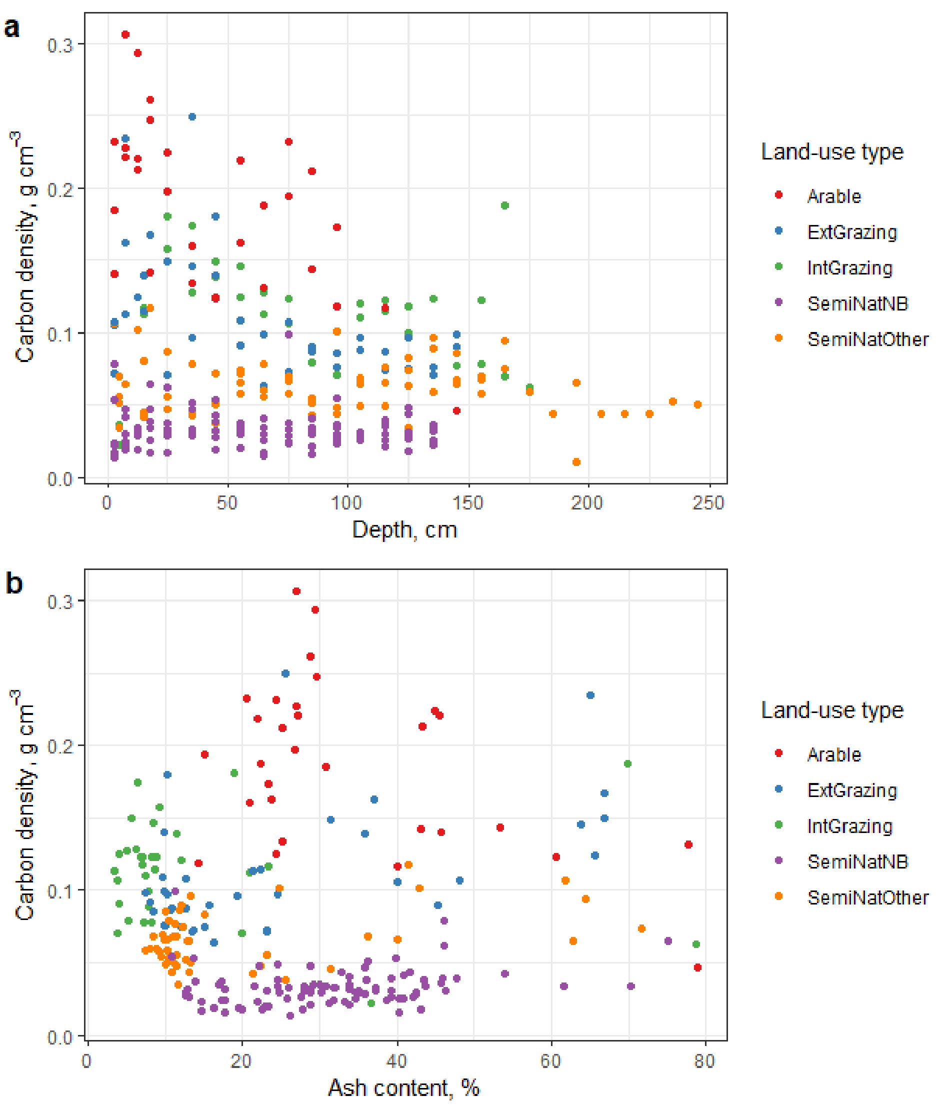


3.3.2.2 Variation in carbon density with depth and peat mineral content

The relationship between carbon density and peat depth varies by land use type; with arable and grazed sites showing a marked decline in carbon density with depth to c. 275 cm whilst semi-natural sites maintain a near-constant carbon density with depth (Figure 8a). Carbon density values from different land use types start to converge around 275 cm depth suggesting little impact of land use activity at greater peat depths. The shape and nature of the relationship between carbon density and mineral (ash) content also varies by land use type (Figure 8b).

Each auger site in the Lowland Peatland Survey of the Norfolk Broads provides details of changes in soil texture by depth, therefore this information has been incorporated into the model to improve the carbon stock estimate.

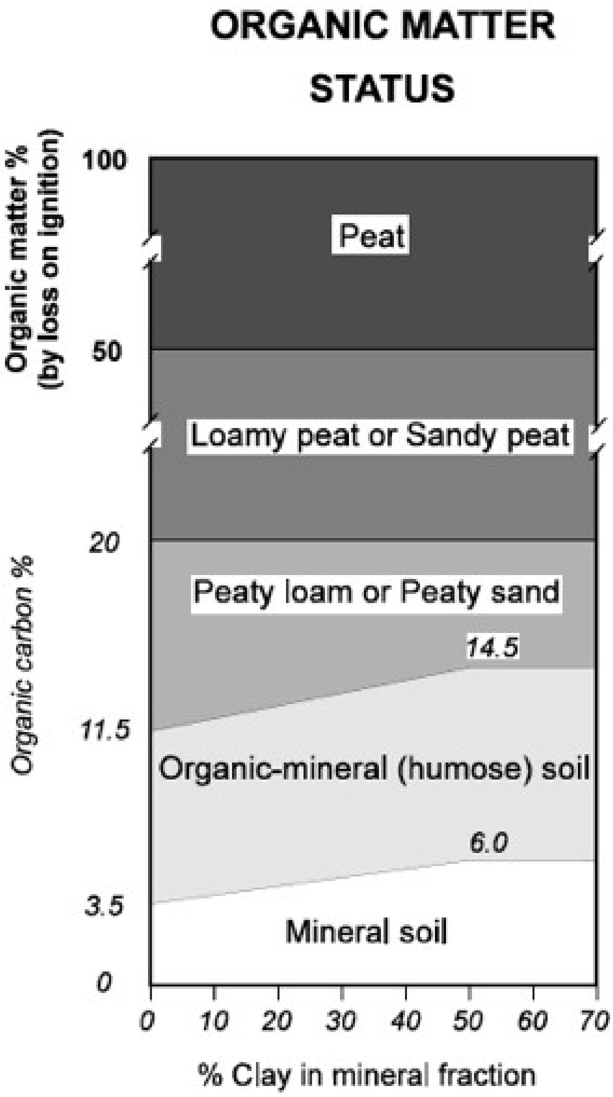
Figure 8 Correlation of carbon density with (a) depth and (b) ash content



3.3.2.3 Converting soil texture to ash content

Many sites in the Broads National Park have been classified by hand texturing as containing loamy or sandy peat. This corresponds to an organic matter content of 20 to 50 % according to the Soil Survey organic matter status diagram (Figure 9) and thus a mineral (ash) content of 50 to 80 %. Soil horizons classified as 'peat' only could comprise 0 to 50 % mineral content. Thus in the model a mineral content of 30% is used for peat, and 45% for loamy or sandy peat.

Figure 9 Organic matter diagram from RUFFS card manual of Soil Survey (SOURCE: Figure 1 in Burton & Hodgson, 1987).



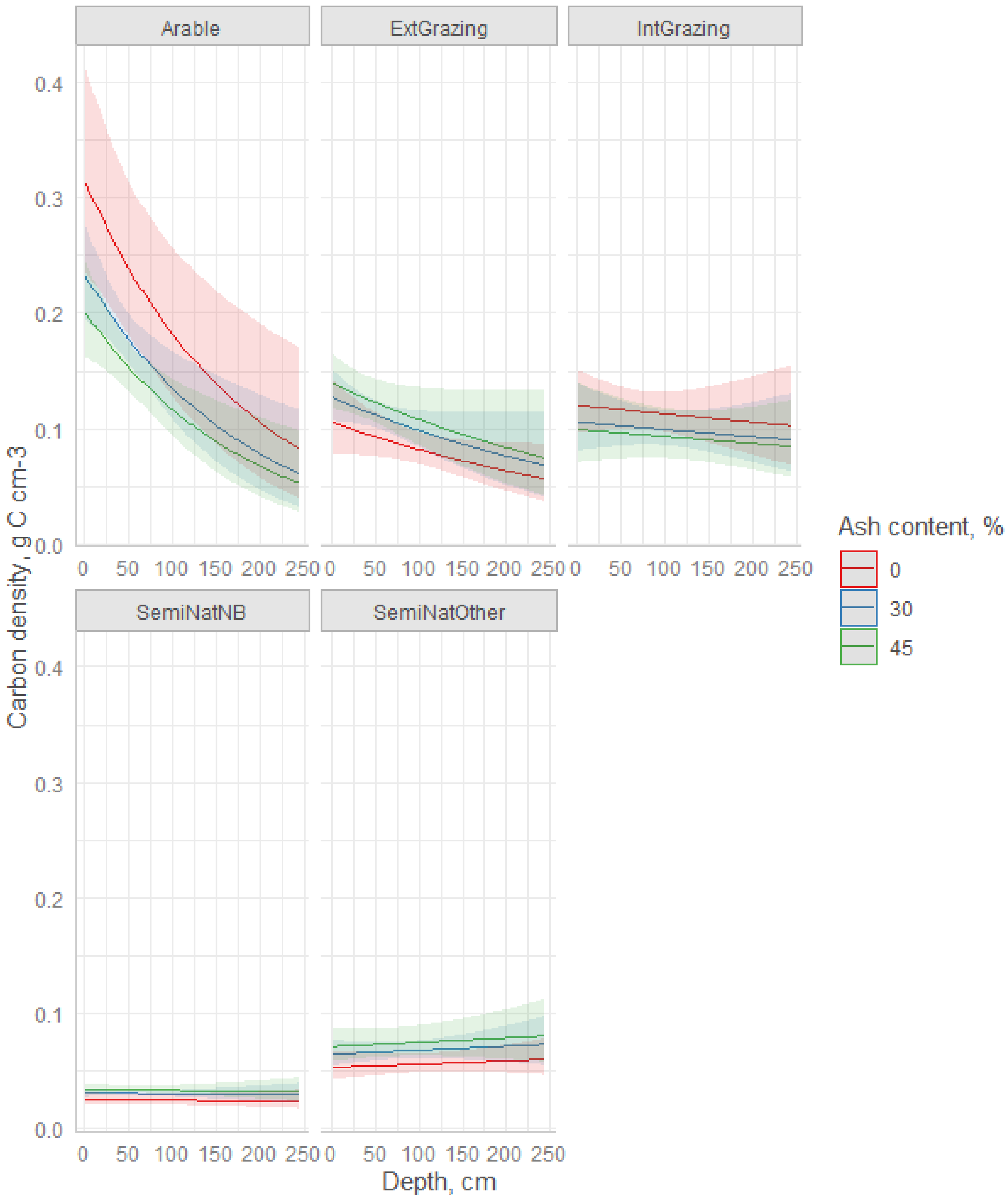
3.3.2.4 Modelling carbon density using general linear modelling approach.

The model which best explains the variation in carbon density includes soil horizon depth, mineral content and land use type as explanatory variables:

log(cd) = (b0) + (b1) * MidDepth_cm + (b2) * Ash_percent

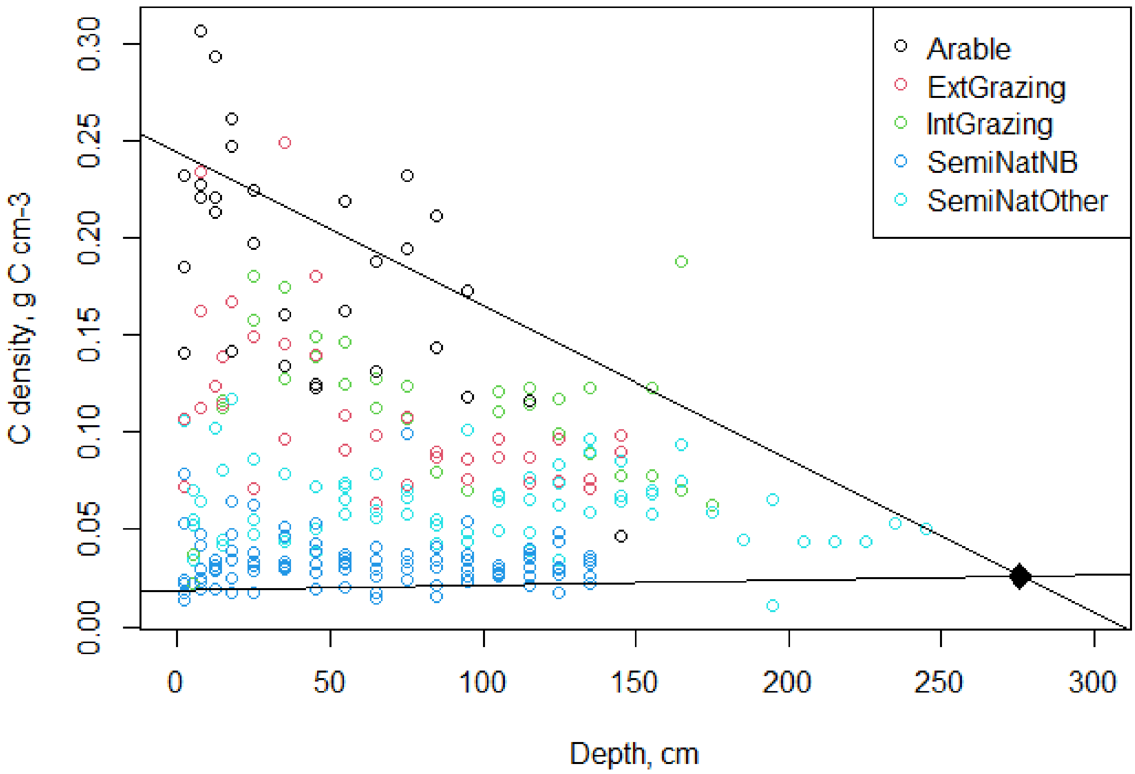
where MidDepth_cm is the mid-depth of the soil horizon under consideration, and Ash_percent is the mineral content of the soil. The three regression coefficients (b0, b1, b2) are specific to each land-use type (LUType3). Figure 10 shows that, for this study, accurate measurements of depth and mineral content are most important when calculating carbon density for peat under arable land use, of intermediate importance for grazed land and have least influence on peat under conservation management.

Figure 10 Predicted values of carbon density (back-transformed to units of g C cm^{-3}) for different land use types and mineral (ash) contents by depth (cm). Shading indicates 95% confidence intervals for each mineral content selected (not back-transformed).



The 'carbon density' spreadsheets calculate carbon density for each auger using the appropriate regression coefficients for each land use type (arable, extensive grazing, intensive grazing and semi-natural Norfolk Broads) for peat depths < 275 cm (see Supplementary Information 3). Quantile regression analysis of carbon density with depth only using the Defra-funded SP1210 Lowland Peatland Systems dataset showed that 5% and 95% quantiles intersect at a depth of 275.6 cm with a carbon density of 0.0261 g C cm^{-3}, therefore carbon density is set at 0.03 g C cm^{-3} for depths > 275 cm (Figure 11).

Figure 11 Quantile regression analysis of change in carbon density with depth.



Finally, the land use classification used in the Lowland Peatland Survey does not distinguish between intensive and extensive grazing. Here we have used an agri-environment designation; if a site falls under the Environmental Stewardship Scheme (ESS) or Countryside Stewardship (CS) Scheme it is considered to be extensively rather than intensively grazed.

3.3.2.5 Calculation of carbon density by area for peat wastage (compression and oxidation scenarios).

As discussed in Section 3.3.1, subsidence of the peat surface due to peat wastage can occur by physical compression of the soil and/or by oxidation of peat. In the former scenario peat volume is reduced and bulk density is increased but no peat carbon is lost. In the case of peat wastage by oxidation, organic carbon is lost from the soil layer as microbes consume the peat and respire carbon dioxide. There is insufficient literature both for the Broads National Park, and more widely for lowland peatlands, to enable us to determine the relative contribution of these two mechanisms to peat wastage. Therefore, we consider the two extremes:

(a) a 'best' case (since 1980s, all peat wastage has been due to compression; all peat carbon has been retained); and
(b) a 'worst' case scenario (since 1980s, all peat wastage has been due to oxidation; some peat carbon has been lost).

3.3.2.6 Calculation of carbon density on areal basis

Carbon density of each soil layer (g cm^{-3}) was multiplied by the thickness of the soil layer (cm) and then the multiple layers containing peat were summed to calculate total carbon density on an areal basis by core (g cm^{-2}). Finally, values were converted from g cm^{-2} to kg m^{-2}.

3.3.2.7 Propagation of uncertainties

The area-specific C stock for an individual peat layer, $z_{i,k}$, is given by the product of the layer's C density, $x_{i,k}$, and its thickness, $y_{i,k}$.

$$z_{i,k} = x_{i,k} \times y_{i,k} \qquad \text{[equation 1]}$$

These layer C stocks in auger *k* are summed to give C stock for the whole auger, C_k:

$$C_k = \sum_{i=0}^{n} z_{i,k} = \sum_{i=0}^{n} (x_{i,k} \times y_{i,k}) \qquad \text{[equation 2]}$$

The uncertainty in $z_{i,k}$ can be calculated by propagation of errors for a product:

$$\delta z_{i,k} = z_{i,k} \times \sqrt{\left(\frac{\delta x}{x_{i,k}}\right)^2 + \left(\frac{\delta y}{y_{i,k}}\right)^2} \qquad \text{[equation 3]}$$

The uncertainty in layer carbon density, δx, is the root-mean-square-error (RMSE) of the statistical model and is constant for all estimates (0.0286 g C cm^{-3}). The uncertainty in layer thickness, δy, is assumed to be 1 cm.

Since the relative uncertainty for layer thickness, $\delta y/y_{i,k}$ is very small compared with that for layer carbon density, $\delta x/x_{i,k}$, equation 3 can be approximated by

$$\delta z_{i,k} \cong z_{i,k} \times \frac{\delta x}{x_{i,k}} \qquad \text{[equation 4a]}$$

Substituting for $z_{i,k}$ according to equation 1, equation 4a simplifies to

$$\delta z_{i,k} \cong \delta x \times y_{i,k} \qquad \text{[equation 4b]}$$

In equation 4b, the relative error on measurements of layer thickness are considered trivial and are ignored when calculating the uncertainty on the layer C stock, $\delta z_{i,k}$. This uncertainty is approximated as the product of two terms: the RMSE in C density, δx, and the layer thickness, $y_{i,k}$. This means that the uncertainty on the C stock of an individual layer increases as the thickness of the layer increases.

The uncertainty in area-specific C stock for the whole auger, δC_k, can then be calculated by propagation of errors for a sum:

$$\delta C_k \cong \sqrt{\sum \delta z_{i,k}^2} \cong \delta x \times \sqrt{\sum {y_{i,k}}^2} \qquad \text{[equation 5]}$$

In equation 4, the uncertainty in auger C stock, δC_k, is the product of two terms: the RMSE in C density, δx, and the square-root of the sums of squares of layer thicknesses. This means that the uncertainty on the C stock of the whole auger tends to increase with peat thickness.

Figure 12 and Figure 13 illustrate area-specific auger C and its uncertainty as functions of land use (1980s) and total peat thickness of the auger. Error increases with peat thickness because of the way the uncertainty in carbon density is propagated (see equations 3 and 4).

Figure 12 Area specific auger C as a function of peat thickness plotted by land use recorded in 1980s.

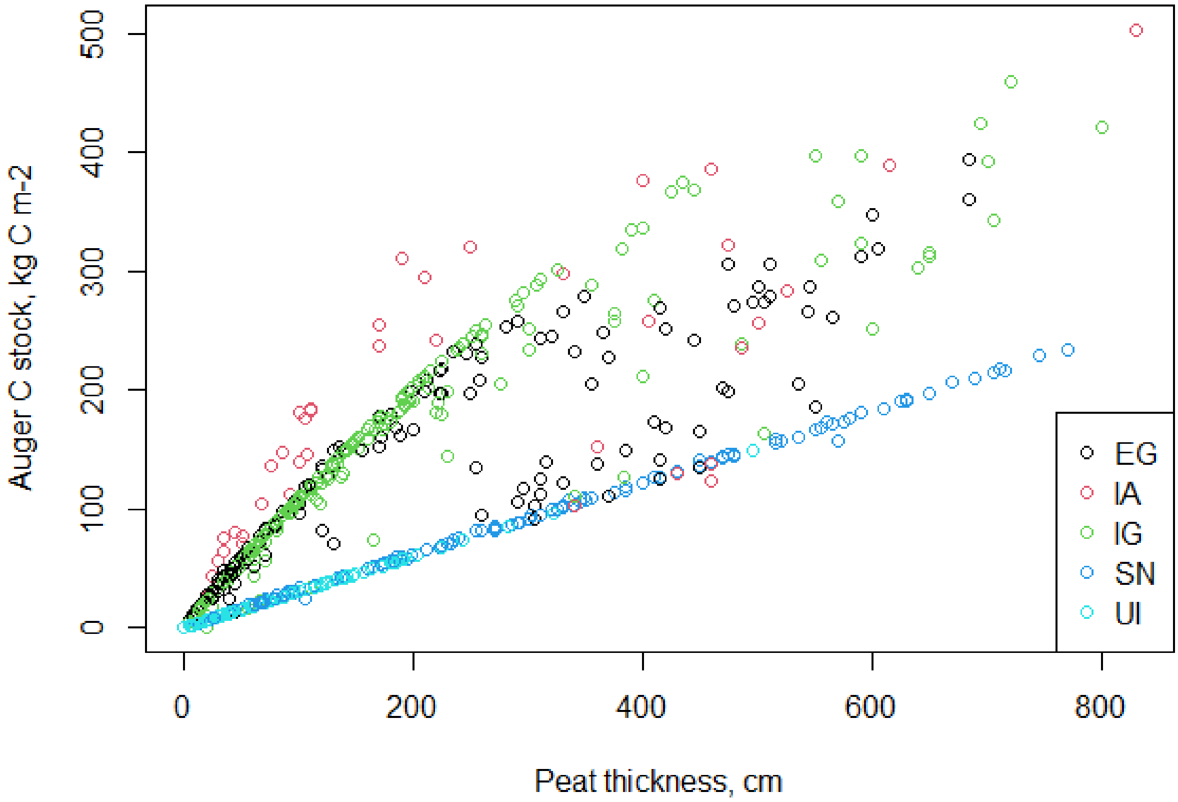
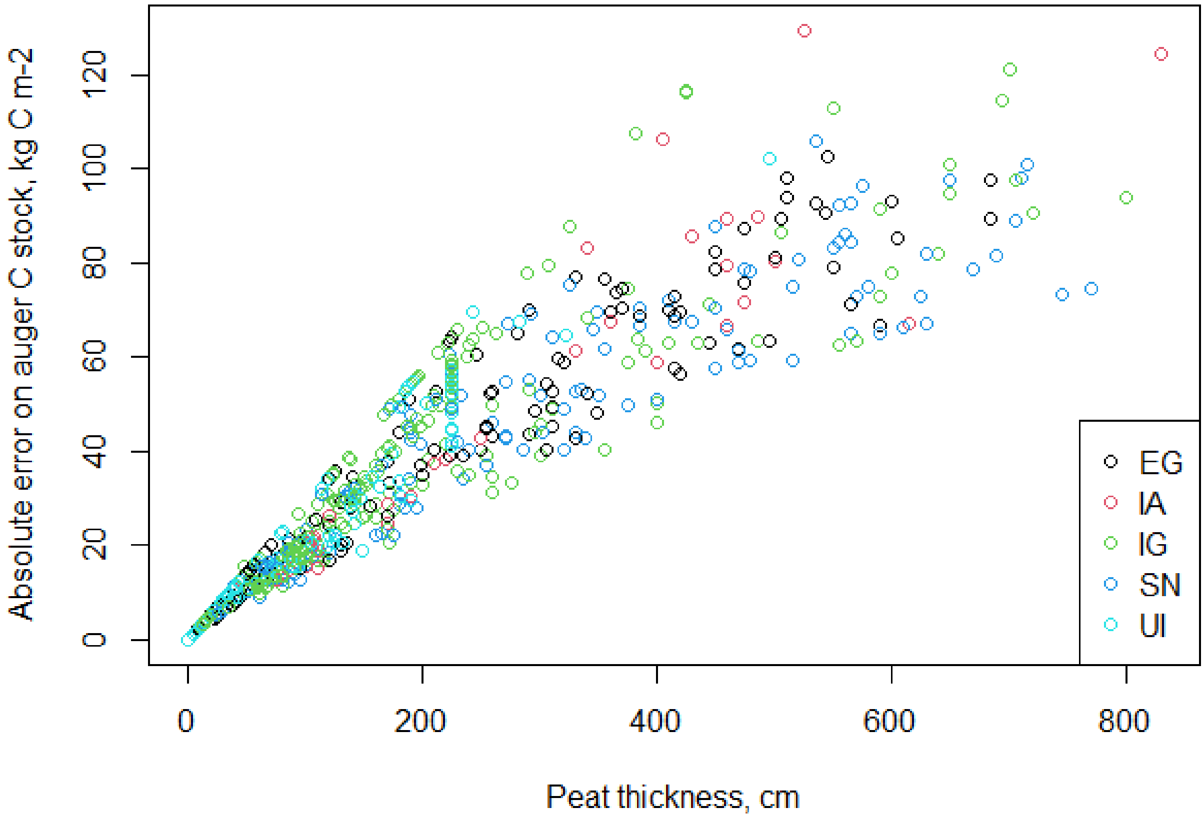


Figure 13 Absolute error in area specific auger C as a function of peat thickness plotted by land use recorded in 1980s.

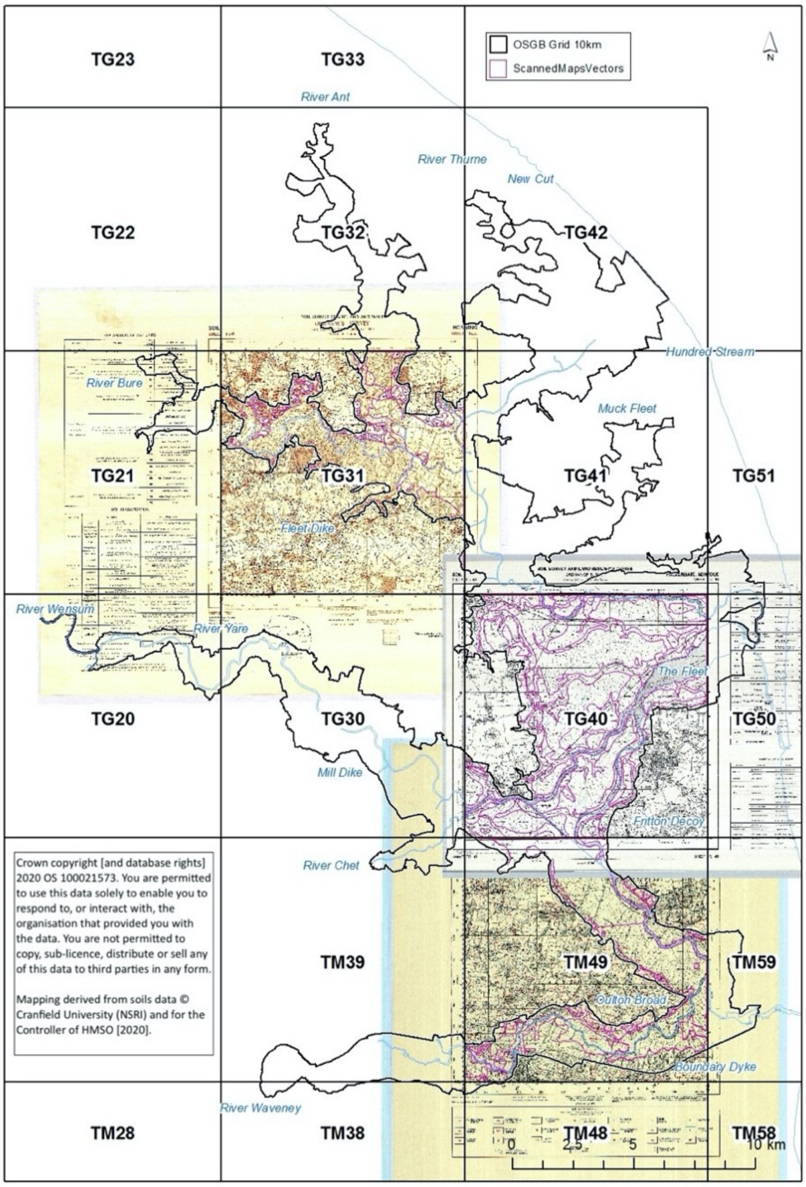


3.4 GIS methods for calculating peat stocks

All GIS analysis and mapping were performed using ESRI ArcMap v10.3.1. GIS vector layers and rasters cover the extent of the Broads National Park boundary, including a 10m buffer.

The Broads National Park area is covered by three detailed 1:25,000 resolution soil maps; TG31 Horning, TG40 Halvergate and TM49 Beccles (North) (Figure 14). The 1:25 000 soil maps were provided by Soil Survey as scanned maps and were added to ArcMap and georeferenced using Georeferencing tools. A polygon shapefile of the scanned 1:25,000 soils maps, called 'ScannedMapsVectors' was produced using ArcScan. The resulting 1:25,000, Soil Survey scanned maps polygon was combined with the 1:250,000k detailed soil map polygon (NSRI, 2019) to create the highest resolution spatial map of peat soil occurrence. GIS layers were combined using the Union tool in ArcMap.

Figure 14 Scanned 1:25,000k soil maps added to ArcMap and georeferenced. Scanned map vectors (polygon shapefile) generated with ArcScan are shown over the scanned maps.



Polygons in the Scanned Map vector polygons were assigned subgroup 10 where the soil series classification contained any of the following peat soil type classifications: Adventurers', Altcar, Bottisham, Floriston, Mendham, Ousby or Prickwillow. Subgroup attributes from the 1:250,000 detailed soil polygons and the 1:25,000 Soil Survey scanned maps were joined to the combined auger dataset using the Spatial Join tool in ArcMap.

Subgroup 10 was applied to peat observations using a hierarchy system where: (a) augers classified as subgroup 10 were classified as subgroup 10 (b) augers with no subgroup information were classified as subgroup 10 based on the 1:25,000, Soil Survey scanned maps, and (c) augers with no subgroup classification and no 1:25,000, Soil Survey scanned maps classification were classified as subgroup 10 based on the 1:250,000 detailed soil map. Remaining augers were assumed to not be subgroup 10.

Peat type classifications:

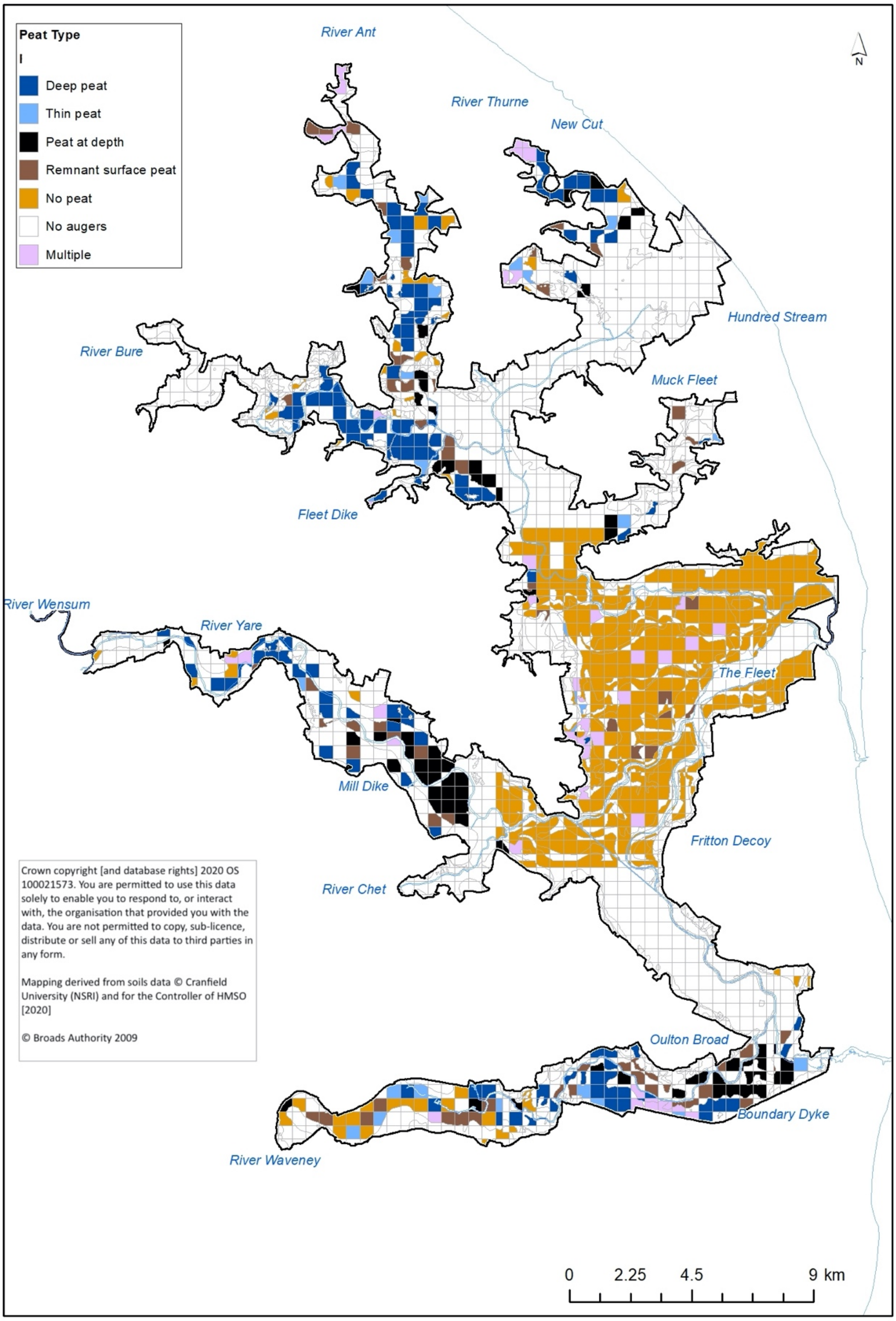
Peat type for each auger was defined based on the following criteria:

Deep peat soils - defined as peat soils (i.e. subgroup 10) with peat thickness > 100 cm
Thin peat soils - defined as peat soils (i.e. subgroup 10) with peat thickness < 100 cm
Peat at depth - defined as peat layers in soil covered by > 30 cm of mineral material at surface (i.e. no peat in soil layer 1, but the profile contains peat).
Remnant surface peat - defined as not a peat soil (i.e. not in subgroup 10) with peat in soil layer 1 (i.e. at surface)
No peat – defined as no peat in soil

Creating and classifying peat grid polygons:

Peat grid polygons were created by combining the 1:250,000 detailed soil polygons, the 1:25,000 Soil Survey scanned maps polygons, and a 500 by 500m grid (with LPS augers in the centre of grid squares), using the Union tool in ArcMap. Peat type assigned to augers was assigned to the peat grid polygons using the Spatial Join tool in ArcMap. The count augers with each peat type were attached to the attributes of each peat grid polygon. Where peat grid polygons contained augers with one assigned peat type (e.g. deep peat, thin peat, peat at depth, remnant surface peat, or no peat), that representative peat type was assigned to the peat grid polygon. Where multiple augers with more than one peat type were located within a peat grid polygon, a peat type named 'Multiple' was applied to the peat grid polygon. Where there were no augers in the peat grid polygon, a peat type named 'no augers' was applied to the peat grid polygon. Peat types assigned to peat grid polygons are shown in Figure 15.

Figure 15 Map showing peat type assigned to each peat grid polygon based on peat type assigned to augers within each peat grid polygon. Peat type ‘Multiple’ indicates peat grid polygons containing augers with more than one peat type assigned.



3.4.1 Peat thickness and peat wastage calculation

In addition to the peat grid polygons, two additional polygon shapefiles (1) peat polygons and (2) deep peat polygons, were produced to perform calculations for peat thickness and peat wastage. Methods for creating the additional polygon shapefiles are detailed below:

1. Peat polygons: Peat polygons were created by combining the 1:250,000 detailed soil polygons and the 1:25,000 'Scanned map vectors' polygon shapefile using the Union tool in ArcMap. Peat type assigned to augers was assigned to the peat polygons using the Spatial Join tool in ArcMap. The total number of augers for each peat type were attached to the attributes of each peat polygon. Where peat grid polygons contained augers with one assigned peat type (e.g. deep peat, thin peat, peat at depth, remnant surface peat, or no peat), that representative peat type was assigned to the peat polygon. Where multiple augers with more than one peat type were located within a peat grid polygon, peat type 'deep peat' was assigned where the peat polygon was subgroup 10. If a peat grid polygon was assigned 'multiple' peat type, was in subgroup 10, and had an average peat thickness of more than 100cm, calculations for deep peat were applied to the polygon.

2. Deep peat polygons: Deep peat polygons were created by extracting peat polygons assigned deep peat and remaining peat polygons which were subgroup 10 and did not contain any augers.

The peat thickness and peat wastage were calculated using the following method:

1) Each peat grid polygon classified as 'deep peat' was assigned an average peat thickness and wastage based on:

a. The average of all augers located within the peat grid polygon.
b. If there were no augers within the peat grid polygon, peat thickness and wastage were based upon the average of all augers located within the deep peat polygon that the peat grid polygon falls within.
c. If there were no augers within either the peat grid polygon or the peat polygon, the peat grid polygon was assigned the average peat thickness and wastage of all augers within all 'Deep peat' polygons.

2) Each peat grid polygon originally classified as 'peat at depth' was assigned a thickness based on:

a. The average of all augers located within the peat grid polygon.
b. If there were no augers within the peat grid polygon, peat thickness and wastage were based upon the average of all augers located within the peat at depth polygon that the peat grid polygon falls within.

3) For 'thin peat', 'remnant surface peat', 'no peat' peat types, the average of all augers within the peat grid polygon within the peat grid polygon was used to calculate peat thickness and wastage. Where peat grid polygons were assigned 'multiple', the average of all augers within the peat grid polygon was used regardless of peat type.

Calculation methods for each peat grid polygon are shown in Figure 16 and Figure 17. Figure 18 shows average peat wastage by peat grid polygon.

Figure 16 Summary of GIS method for Peat Grid Polygons

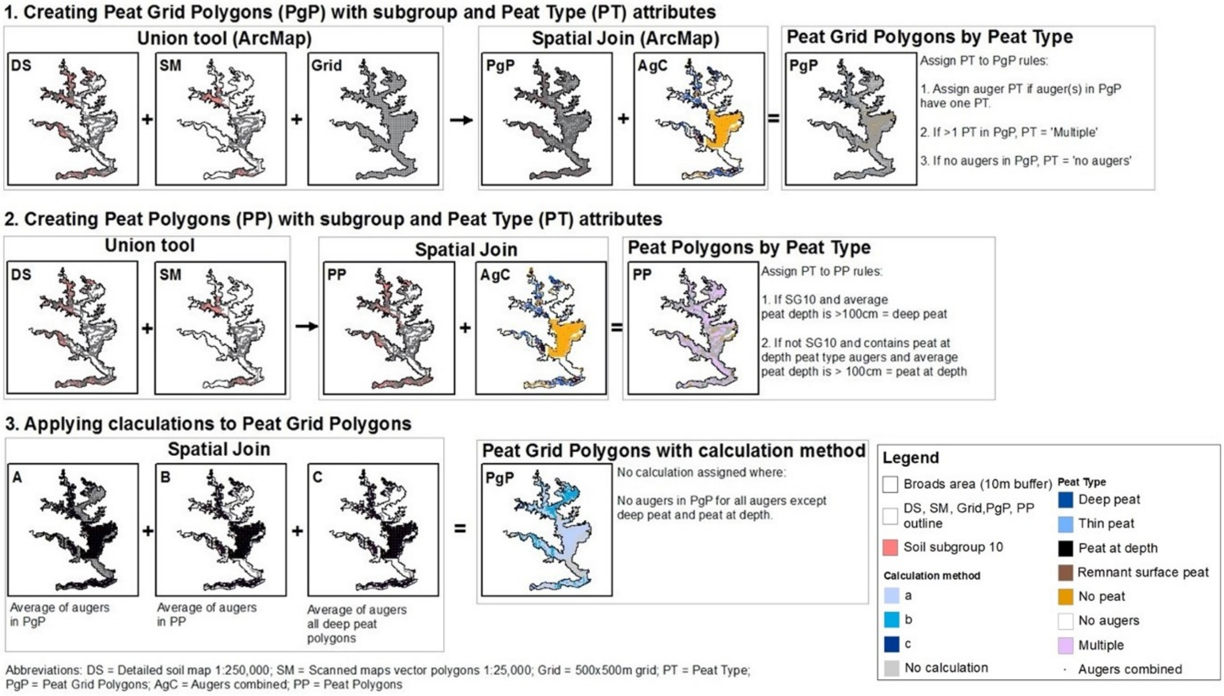


Figure 17 Calculation methods for each peat grid polygon.

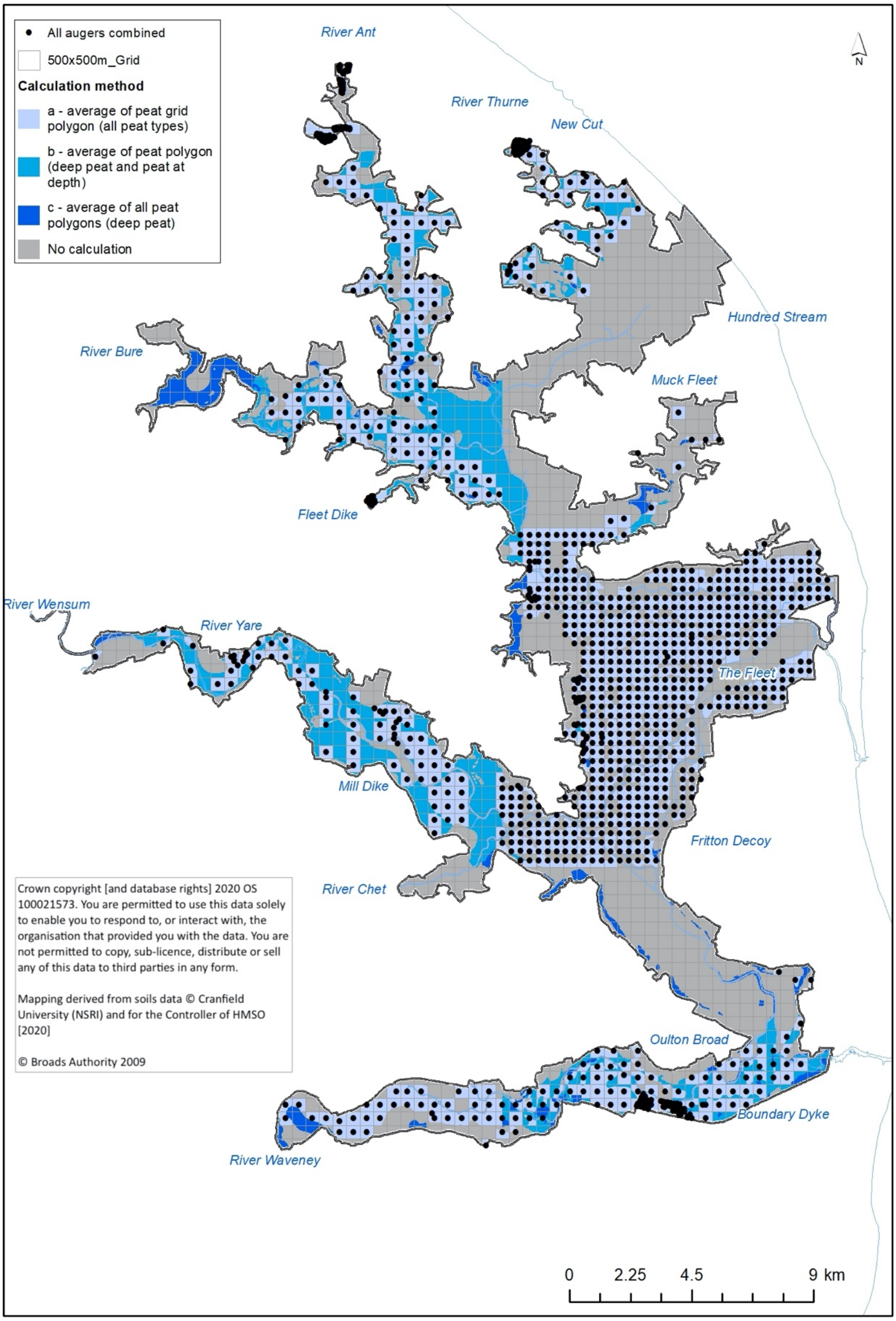


Figure 18 Average peat wastage between 1980 and 2020 calculated using method shown in Figures 15 and 16. Wastage, or subsidence of the land surface, may be due to physical compression of the soil, oxidation of soil organic matter or a combination of these processes.

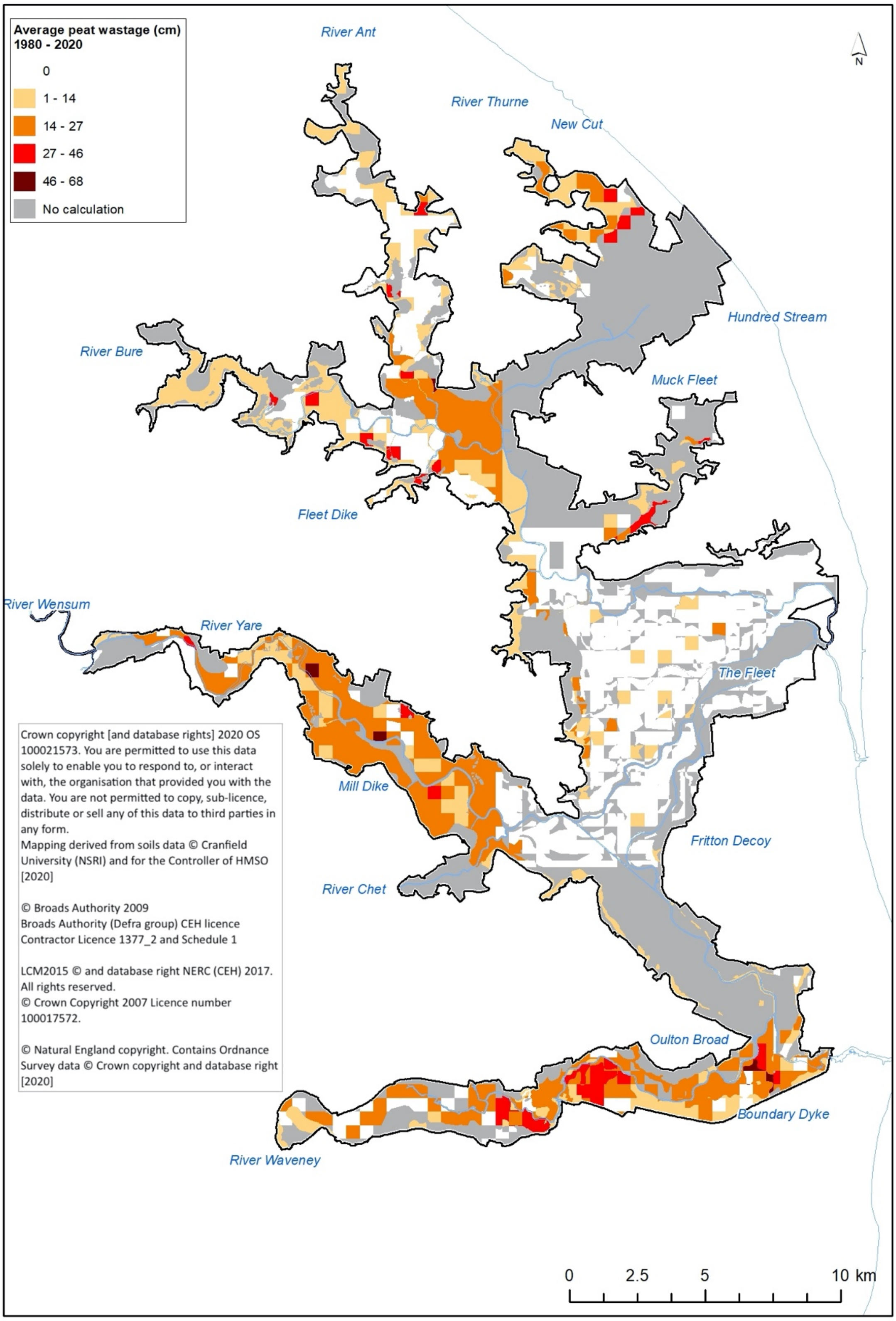


Table 7 describes all the layers created in ArcGIS.

Table 7 List of GIS layers produced. GIS analysis and mapping were performed using ArcGIS software. GIS vector layers and rasters cover the extent of the Broads National Park boundary, including a 10m buffer. Metadata with attribute descriptions are provided with GIS layers 1-4.

GIS layer name	Description	GIS layer type
1. Augers_combined	Combined ELP and LPS augers.	Shapefile (point)
2. PeatGridPolygons	Peat grid polygons with calculated average peat thickness and peat loss.	Shapefile (polygon)
3. PeatPolygons	Peat polygons with peat type and average peat thickness and peat loss for deep peat and peat at depth.	Shapefile (polygon)
4. ScannedMapVectors	Digitised polygons with soil type in the attributes based on scanned 1:25,000 soil maps.	Shapefile (polygon)
6. Lambert_Transects	Digitised polygons of the Lambert Transects with transect name and river valley in the attributes.	Shapefile (line)

4 Carbon storage within the peat of the Broads National Park.

4.1 Peat carbon stocks in the Broads National Park

The total amount of carbon stored in peat in the Broads National Park is estimated at 12 to 14 teragrams (or 12 to 14 million metric tonnes of carbon; Table 8, Fig. 19). For comparison, this is about the equivalent of 7% of the carbon stored in woodlands across the whole UK and double the carbon stored in UK coastal margin habitats (Office for National Statistics, 2016). On a per area basis, peat in the Broads stores 447 to 506 tonnes carbon per hectare, or four to six times that of 'high' above-ground biomass density (> 100 tonnes carbon per hectare) in tropical rainforests (Saatchi et al. 2011).

Table 8 Area-specific carbon stock (metric tonnes carbon per hectare) and total carbon stock (teragram or million metric tonnes carbon) in the Broads National Park*

Valley	Area (km^2)	Area-specific carbon stock, t C ha^{-1}		Total carbon stock, Tg C (uncertainty)			Confidence band
		Compression scenario	Oxidation scenario	Compression scenario	Mid-range scenario	Oxidation scenario	
Ant	22.7	623	589	1.41 (0.60)	1.37	1.33 (0.59)	Medium
Bure	33.0	821	771	2.71 (0.91)	2.63	2.54 (0.90)	Low
Halvergate	62.8	42	32	0.26 (0.07)	0.23	0.20 (0.06)	High
Muck Fleet	12.9	188	165	0.24 (0.08)	0.23	0.21 (0.08)	Low
**Thurne	18.9	631.9	536	1.20 (0.30)	1.11	1.02 (0.28)	Low
Waveney	69.5	586	500	4.07 (1.21)	3.77	3.47 (1.16)	Medium
Yare	52.6	814	715	4.28 (1.16)	4.02	3.76 (1.12)	Medium
Unassigned	11.3	159	113	0.18 (0.05)	0.15	0.13 (0.04)	-
****Total (Broads National Park)**	**283.6**	**506**	**447**	**14.36 (4.40)**	**13.52**	**12.67 (4.24)**	

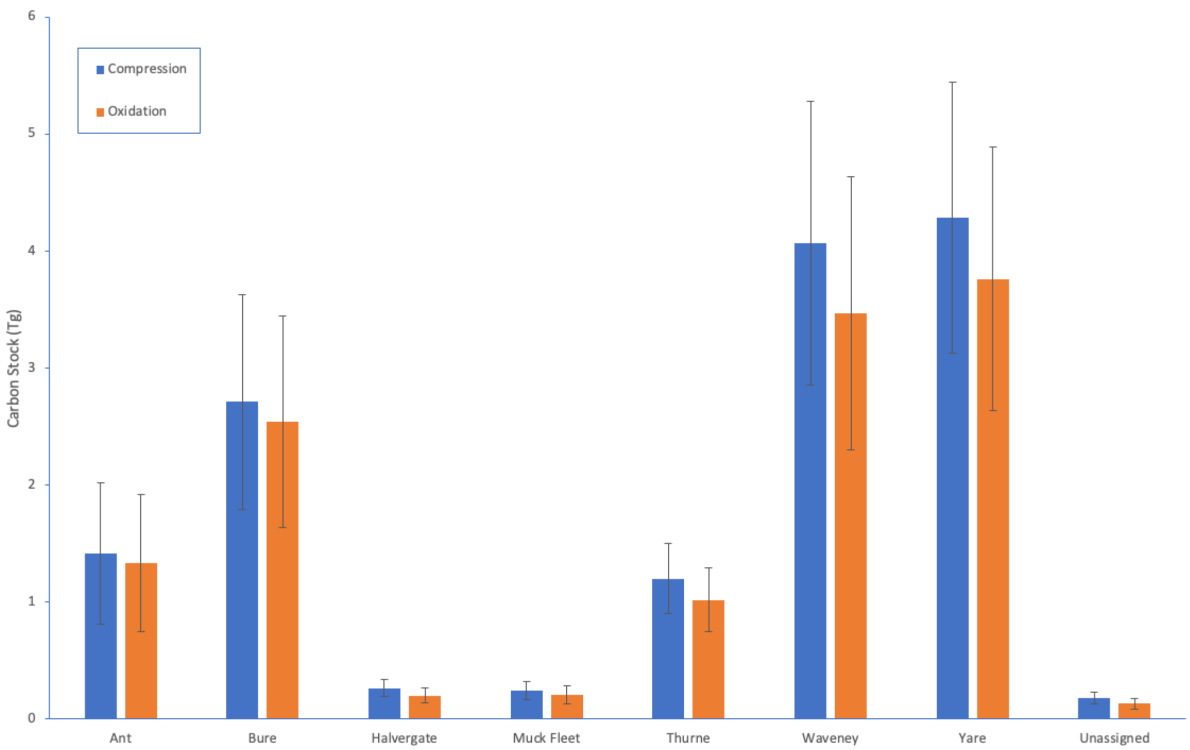
* The 'compression' scenario assumes that wastage since 1980 has reduced peat volume but has had no impact on carbon stock. The 'oxidation' scenario assumes that all wastage since 1980 was due to aerobic decomposition, resulting in some loss of peat carbon. Conversions: 1 km^2 = 100 ha; 1 Tg = 1 000 000 t = 1 Mt.

** See Supplementary Information 7 for additional information about the Thurne Valley peat stock estimate.

Estimates (Table 8) have been made without a large polygon in the Thurne Valley. Polygon 413 represents a large area (23 km^2 and 55% by area) of the Thurne Valley. Within this polygon the carbon stock estimate is based on only four augers in the most northern section, in which 'peat at depth' was recorded. Extrapolation of these limited data across 55% of the Thurne may considerably over-estimate peat carbon stock, and so further augers are required in this area to give a more reliable estimate.

Table 8 and Figure 19 provide the estimates by valley for two scenarios of peat wastage: a 'compression scenario', in which subsidence of the peat surface is entirely due to reduction in peat volume with no loss of peat carbon, and an 'oxidation scenario', in which subsidence is entirely due to oxidation of peat carbon. In both scenarios, rates of peat wastage were determined by land use and land-use changes, with areas under continuous conservation management assumed to have undergone no peat wastage. The 'compression scenario' estimate of 14 $\pm$ 4 Tg C assumes that peat measured during the Lowland Peatland Survey has reduced in volume over the years since the survey (1980 to 2020), but all peat carbon has been retained. This represents a 'best case' scenario for peat carbon stored in the National Park as at 2020. The 'worst case', or 'oxidation scenario' (12 $\pm$ 4 Tg C) assumes that some peat carbon has been lost via oxidation. It is likely that subsidence of the peat surface has resulted from some combination of both compression and oxidation (our mid-range estimate), but we were unable to find any supporting data to estimate the relative importance of these processes. Assuming 50% oxidation and 50% compression leads to a mid-range estimate of 13 Tg C currently stored in the Broads National Park. The difference between the mid-range and compression scenarios suggests that almost 1 million metric tonnes of peat carbon, c. 6% of the 1980s stock, may have been lost from the Broads National Park over the past forty years.

Figure 19 Estimate of carbon stock by valley (Tg) for the compression and oxidation scenarios with uncertainties derived only from field measurements and the general linear model for carbon density.



The uncertainties reported in Table 8 include those introduced by the field sampling and the statistical model for carbon density but do not include uncertainties around rates of peat wastage or spatial interpolation for areas without augers. Table 8 includes a confidence band for each valley that reflects the number of peat-grid-polygons in the valley that contain auger data. This confidence band should be used as a comparative tool only to identify valleys with the poorest spatial coverage of auger data.

4.2 Comparison with other estimates

The Broads Authority carbon audit (2010) estimated that earthy peat soils in the Broads executive area store a total of 25 million tonnes (Mt) of CO_2e, covering 9000 ha at a density of 2808 tonnes CO_2e ha^{-1}. Carbon dioxide equivalents (CO_2e) are normally used in relation to greenhouse gas fluxes, rather than carbon stocks. If the CO_2e estimate was obtained by a simple conversion of mass of carbon to carbon dioxide (carbon makes up 27% of the mass of carbon dioxide), then '25 Mt CO_2e' is equivalent to a carbon stock of 6.8 Tg of carbon (= 6.8 Mt of carbon) and '2808 t CO_2e ha^{-1}' is equivalent to an area-specific carbon stock of 766 t C ha^{-1}. The area covered by earthy peat soils (9000 ha or 90 km^2, according to the Broads Authority carbon audit, 2010) is less than a third of the area of the Broads National Park (307 km^2; Table 8). The area-specific carbon stock in earthy peat soils is higher than in all peat across the National Park (447 to 506 t C ha^{-1}; Table 8) because the latter includes peat layers buried in mineral soils.

Holman & Kechavarzi (2011) estimated a total carbon stock of 37 Tg for the peat in Fenland, covering 546 km^2 at a density of 678 t C ha^{-1}. The nearly two-fold greater carbon stock compared with that of peat in the Broads National Park is explained in part by the greater area covered by the Fens. In addition, the carbon stock in the Fens is greater on a per area basis potentially because of the higher estimates of bulk density used by Holman & Kechavarzi (2011). The lower bulk density recorded in the Broads National Park may arise from the extensive turbaries, but more measurements of bulk density are needed to confirm this suggestion (see section 4.3).

Natural England (2010) reported deep peaty soils in lowland fens and reedbeds across England covering a total area of 2880 km^2 and storing 330 megatonnes of carbon (1 Mt = 1 million tonnes = 1 Tg). About 67% of the area and 56% of the stored carbon was on 'wasted' peat, i.e., peat that has been substantially degraded by drainage and cultivation. Natural England's estimates suggest area-specific carbon stocks of 1503 t C ha^{-1} for deep peat and 970 t C ha^{-1} for wasted peat. These values are at least 1.5-fold higher than estimates of area-specific carbon stocks for the Broads National Park (this study) or the Fens (Holman & Kechavarzi 2011) and are almost certainly over-estimates. The data and methods used to obtain the Natural England (2010) estimates are not detailed in the report, but their maps indicate deposits of deep, carbon-dense peat throughout most of the valleys in the Broads. The present analysis suggests that some valleys of the Broads have thinner, less carbon-dense deposits, especially if oxidation of wasted peats has occurred.

We hope that these new estimates of peat carbon stocks in the Broads National Park will

(i) Provide a baseline analysis of existing carbon storage within the Broads to support future carbon offsetting activities (e.g. through schemes such as the IUCN Peatland Code)
(ii) Support the development of policy framework of spatial risk assessment and programmes where carbon mitigation options might have the greatest success in the long term
(iii) Support the development of programmes for reducing carbon losses from land and accumulating carbon within the Broads landscape;
(iv) Support the Broads Authority to contextualise, visualise and explain the rationale for climate change mitigation methods to stakeholders in line with their 'Response to

climate emergency' report of 27 Sept 2019 and Broads Test and Trial of Environmental Land Management 2020-21.

4.3 Recommendations to further improve the carbon stock estimates

We recommend that spatial coverage of sampling points in Bure, Muck Fleet and Thurne valleys is improved, with particular emphasis on the Thurne within polygon 413. A first assessment of pre-existing data should be made using datasets from Jacobs and British Geological Survey before extensive sampling is carried out.

Due to lack of bulk density measurements for different peat types in the Broads National Park we have used carbon density estimates from other lowland peatland sites obtained from the Defra-funded SP1210 study. We recommend sampling in the Broads be carried out to obtain carbon density values specific to the different peat types, under different land uses and at a range of depths.

There are multiple assumptions in the calculation of wastage that has occurred under different land use scenarios from the 1980s until now. We recommend either (i) installation of time-lapse cameras following the methods described in Evans et al. (in press) or (ii) installation of surface elevation tables and marker horizons (Lynch et al., 2015) to monitor peat wastage (both elevation changes and accretion or loss of peat) under different land use scenarios in the Broads area. The data obtained from such monitoring would help improve the accuracy of both estimates of past wastage from 1980s until now (by applying the rates retrospectively) as well as projections of future wastage, enabling the Broads Authority to assess what is happening to their peat resource.

Estimates of carbon dioxide and methane emissions from the peat stocks identified in this report could be made using the regression equations developed by Evans et al. (2017) that link mean annual water table depth to greenhouse gas balance for lowland peatland soils. Such an analysis would require a robust estimate of mean annual water level relative to ground surface in peat soils (sub-group 10) of the Broads National Park. Emissions from mineral soils that contain peat at depth could not be estimated using this method which was developed using data for peat soils. An estimate of mean annual water level could be made using land use classification to derive generalised water table regimes or by spatially modelling water table depth using high resolution digital elevation data (LiDAR), pump trigger levels for Broadland flood compartments, and areal extents of surface water bodies delineated using remotely sensed data products (aerial/satellite imagery). The latter approach would involve adaptation of methods used in other peatland environments (e.g. Rahman et al., 2017).

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Supplementary Information 1

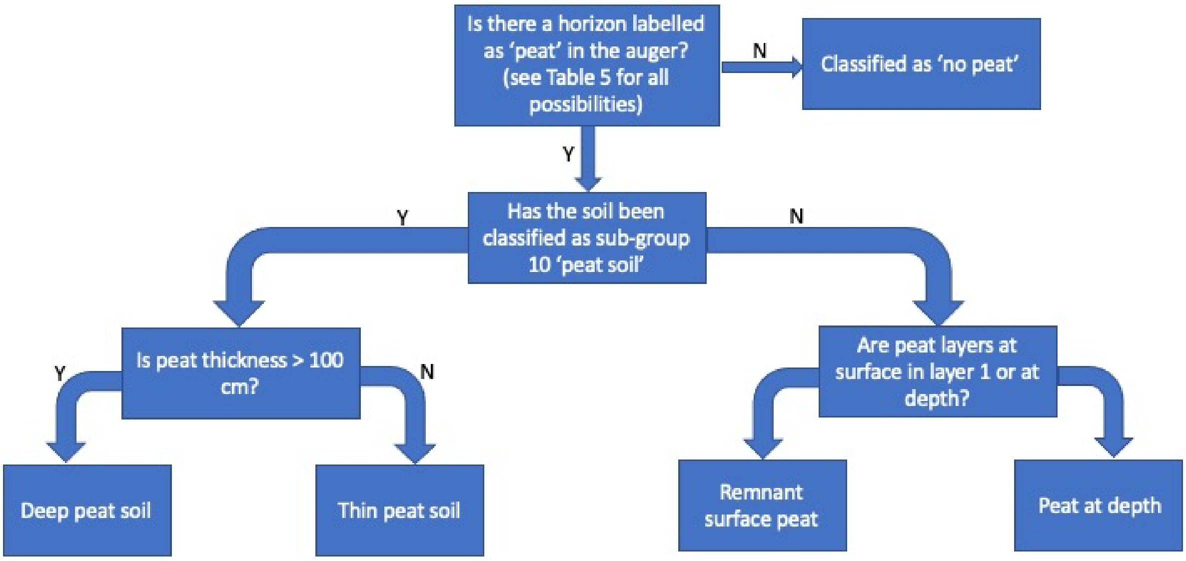


Figure SI1 A flow chart of peat classification used in this study.

Supplementary Information 2

Joyce Lambert published many research articles and one book (Lambert et al 1960) describing 2150 peat bores collected across the Broads area over > 10 years.

Table SI2.1 Approximate numbers of bores logged by Joyce Lambert by valley based on information in Lambert et al (1960).

Valley	No. boreholes
Yare	1120
Bure	440
Ant	260
Thurne	240
Waveney	90

The peat bores were taken in transects in order to understand the origin of the Broads themselves (whether natural or man-made) and so are focused around the open bodies of water in the different valleys. An advantage of these records is that Joyce Lambert cored to the full depth of peat in the valleys and the transects are extremely detailed (8 bores taken every 50 m in places) whereas many current auger records reach only a few meters in depth. A drawback is that Lambert used a botanical classification of peat which is difficult to cross-compare with those based on the degree to which peat is humified. For our purposes the Lambert dataset offers a unique opportunity to cross-check the overall depth of peat to the Lowland Peatland Survey records, to assess the cross-sectional area of peat across each valley and identify the depth of and cross-sectional area of clay arising from each marine transgression.

Geo-referencing of Lambert transects

Lambert et al (1960) post-dates the research articles and draws together Joyce Lambert's original body of research with some additional detail. For this reason we have chosen to geo-reference transects described in the book using the original nomenclature for transect identification (Table SI2). For the Bure Valley Lambert et al (1960) describes transects that have been reproduced in Jennings & Lambert (1951) so in this instance we have geo-referenced the transects using diagrams from this latter research article.

Transects were scanned as JPGs at 600 x 600 dpi (Figure SI1). The National Grid was used to georeference transects in ArcMap with Georeferencing tool. A polyline shapefile of the transects called 'Lambert_Transects', was produced by manual creation of polylines in ArcMap. Start x,y and End x,y in the attributes table give the co-ordinates for the start and end of each transect line.

Figure SI2. Lambert transects within the Broads National Park boundary. Scanned and georeferenced Lambert Transect maps are shown, with generated Lambert Transect vector polylines.

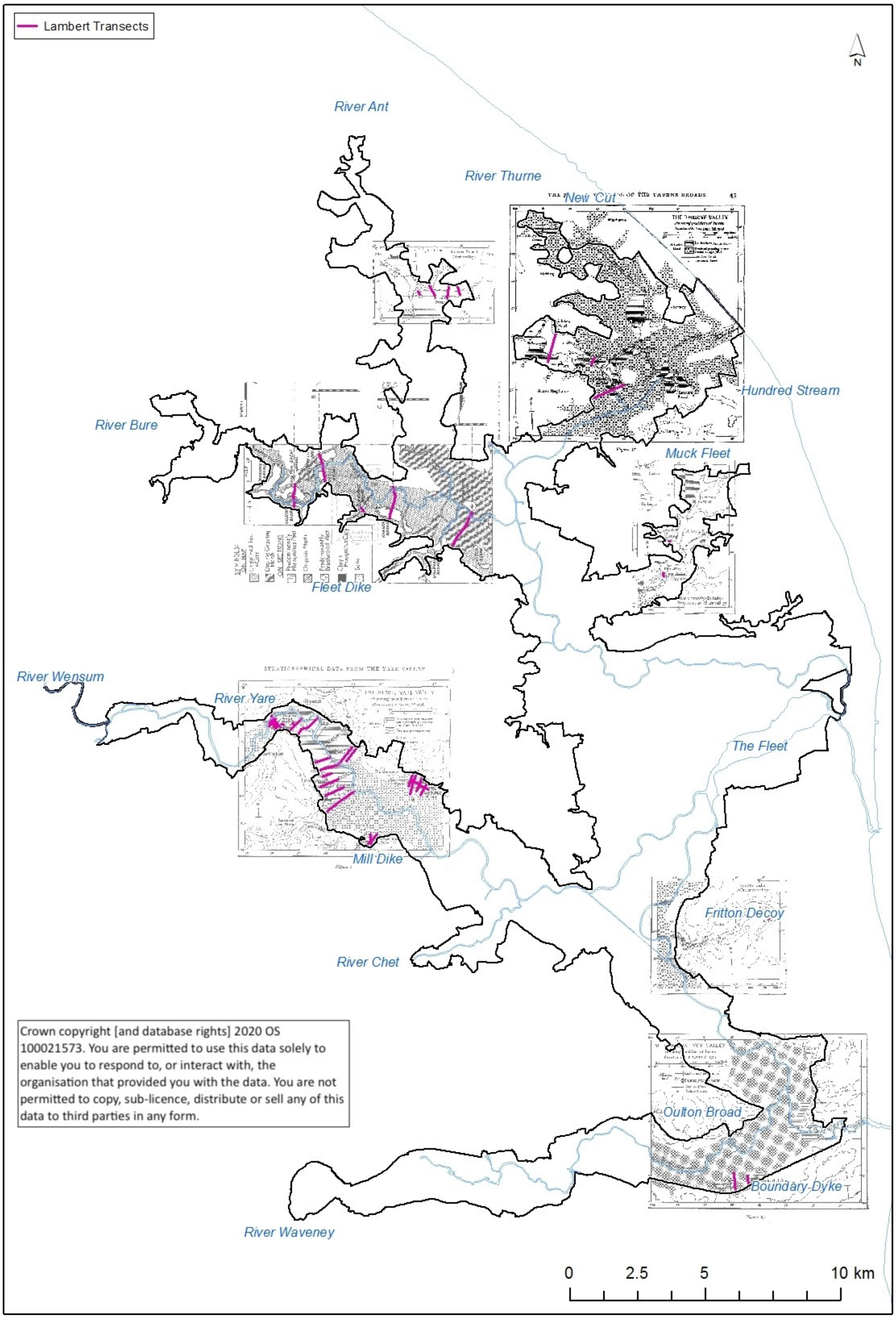


Table SI2.2 Transects described by Joyce Lambert in Lambert et al (1960)

Transect	Location	Transect schematic?	Reference containing drawn transect
Yare Valley (Location of transects in Fig 1 – N.B. SI/AC crosses whole valley)			
SI/SO	Strumpshaw Broad	Yes (Fig 8,9)	RGS Research Series 3
SF/SB/SC/SG/BR/NT/SP	Surlingham Broad	Yes (Fig 2,3,4,5,6,7)	RGS Research Series 3
C/AC	Wheatfen	Yes (Fig 10,11)	RGS Research Series 3
HD/PM	Wheatfen	No – described not drawn	RGS Research Series 3
RL	Rockland Broad	Yes (Fig 12)	RGS Research Series 3
RK	Rockland Broad	No – described not drawn	RGS Research Series 3
CN/CL	Carleton Broad	Yes (Fig 13,14)	RGS Research Series 3
BW/BK/WC/HS/HBA	Buckenham & Hassingham Broad	Yes (Fig 15,16, 17,18,19)	RGS Research Series 3
Bure Valley (no useful overview of transect locations in RGS Research Series 3)			
H	Hoveton Great Broad	Yes (Fig 20)	RGS Research Series 3
LC/L	Hoveton Great Broad	No – described not shown	RGS Research Series 3
A in Jennings & Lambert 1951a	Salhouse Broad and across Bure Valley	Yes (Fig 3)	Transect A in Fig 3 of Jennings & Lambert 1951a (also includes Hoveton Great Broad)
B in Jennings & Lambert 1951a	Decoy Broad and across Bure Valley	Yes (Fig 3)	Transect B in Fig 3 of Jennings & Lambert 1951a (also includes Hoveton Little Broad)
B in Jennings & Lambert 1951a	Hoveton Little Broad and across Bure Valley	Yes (Fig 3)	Transect B in Fig 3 of Jennings & Lambert 1951a (also includes Decoy Broad)
C in Jennings & Lambert 1951a	Ranworth Broad and across Bure valley	Yes (Fig 3)	Transect C in Fig 3 of Jennings & Lambert 1951a
R	Ranworth Broad	Yes (Fig 21)	RGS Research Series 3
U	Upton Broad	Yes (Fig 22)	RGS Research Series 3
No data	Hedney's Bottom	No – described not shown	
KS/K/KN	Cockshoot	No – described not shown	
FB1-15/LB1-7/RB1	Ormesby-Rollesby-Filby	Individual boreholes marked on map but no log (Fig 27)	RGS Research Series 3
D in Jennings & Lambert 1951a	S of South Walsham Broads across Bure Valley	Yes	Transect D in Fig 3 of Jennings & Lambert 1951a

Waveney Valley (Location of transects in Figure 23, p32)			
BN	Barnby	Yes (Fig 25)	RGS Research Series 3
WV	Waveney	Yes (Fig 24)	RGS Research Series 3
FL1-4/AD1-5	Fritton Lake	Individual boreholes marked on map but no log (Fig 27)	RGS Research Series 3
Ant Valley (Location of transects in Figure 27, p38)			
CE/CC/CW	Sutton Broad	Yes (Fig 28,29,30)	RGS Research Series 3
Thurne Valley (Location of transects in Figure 31, p43)			
HK	Hickling Broad	Yes (Fig 32)	RGS Research Series 3
WS	Whiteslea	Yes (Fig 33)	RGS Research Series 3
CD	Heigham Sound	Yes (Fig 34)	RGS Research Series 3

Supplementary Information 3: Analysis of covariance, model with ash content

log(cd) = MidDepth_cm * LUType3 + Ash_percent * LUType3

```
Call:
lm(formula = log(cd) ~ MidDepth_cm * LUType3 + Ash_percent *
    LUType3, x = TRUE, y = TRUE)

Residuals:
     Min       1Q   Median       3Q      Max
-1.53777 -0.18775 -0.00114  0.15193  1.29683

Coefficients:
                                 Estimate Std. Error t value Pr(>|t|)
(Intercept)                     -1.155613   0.143449  -8.056 4.66e-14 ***
MidDepth_cm                     -0.005474   0.001591  -3.441 0.000692 ***
LUType3ExtGrazing               -1.087210   0.211464  -5.141 5.94e-07 ***
LUType3IntGrazing               -0.959528   0.184888  -5.190 4.71e-07 ***
LUType3SemiNatNB                -2.514711   0.177181 -14.193  < 2e-16 ***
LUType3SemiNatOther             -1.770670   0.185064  -9.568  < 2e-16 ***
Ash_percent                     -0.009916   0.003683  -2.692 0.007631 **
MidDepth_cm:LUType3ExtGrazing    0.002908   0.002088   1.393 0.165039
MidDepth_cm:LUType3IntGrazing    0.004823   0.001976   2.440 0.015465 *
MidDepth_cm:LUType3SemiNatNB     0.005294   0.001775   2.983 0.003171 **
MidDepth_cm:LUType3SemiNatOther  0.005978   0.001789   3.342 0.000974 ***
LUType3ExtGrazing:Ash_percent    0.016051   0.004934   3.253 0.001317 **
LUType3IntGrazing:Ash_percent    0.005672   0.005016   1.131 0.259340
LUType3SemiNatNB:Ash_percent     0.016566   0.004562   3.631 0.000350 ***
LUType3SemiNatOther:Ash_percent  0.016340   0.004707   3.471 0.000622 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3193 on 224 degrees of freedom
Multiple R-squared:  0.8184,  Adjusted R-squared:  0.807
F-statistic: 72.09 on 14 and 224 DF,  p-value: < 2.2e-16
```

Based on 5-fold cross-validation, the RMSE of this model is 0.0286 +/- 0.0060 g C cm-3 (NOTE: RMSE has already been back-transformed to original units).

Boot-strapped estimates for coefficients (more reliable than those above):

```
                              term     original      BootMed      BootSE
1                      (Intercept) -1.155613401 -1.171998329 0.130049321
2                      MidDepth_cm -0.005474206 -0.005288043 0.001363286
3                LUType3ExtGrazing -1.087210260 -1.060049631 0.199511411
4                LUType3IntGrazing -0.959527653 -0.860869628 0.270528109
5                 LUType3SemiNatNB -2.514710646 -2.495496435 0.188719086
6              LUType3SemiNatOther -1.770670374 -1.758322420 0.156388530
7                      Ash_percent -0.009916479 -0.009390643 0.003311873
8    MidDepth_cm:LUType3ExtGrazing  0.002907705  0.002646981 0.001779542
9    MidDepth_cm:LUType3IntGrazing  0.004822542  0.003833370 0.002707416
10    MidDepth_cm:LUType3SemiNatNB  0.005293687  0.005144086 0.001608039
11 MidDepth_cm:LUType3SemiNatOther  0.005978435  0.005869699 0.001503674
12   LUType3ExtGrazing:Ash_percent  0.016051137  0.015542408 0.004209425
13   LUType3IntGrazing:Ash_percent  0.005672080  0.005699288 0.013527338
14    LUType3SemiNatNB:Ash_percent  0.016565544  0.016036070 0.004860616
15 LUType3SemiNatOther:Ash_percent  0.016339670  0.015825146 0.004140722
```

Note: predicted values estimated by these coefficients need to be back-transformed, i.e., exp(predicted value). Estimates for the Arable land-use type are given by 'Intercept', 'MidDepth_cm' and 'Ash_percent'. The coefficients for other land-use types should be added to these values.

Supplementary Information 4: Analysis of covariance, model without ash content

log(cd) = MidDepth_cm * LUType3

```
Call:
lm(formula = log(cd) ~ MidDepth_cm * LUType3, x = TRUE, y = TRUE)

Residuals:
    Min      1Q  Median      3Q     Max 
-1.6027 -0.1829  0.0182  0.1939  1.1635 

Coefficients:
                                 Estimate Std. Error t value Pr(>|t|)    
(Intercept)                     -1.454602   0.098993 -14.694  < 2e-16 ***
MidDepth_cm                     -0.006335   0.001699  -3.728 0.000238 ***
LUType3ExtGrazing               -0.547606   0.137060  -3.995 8.48e-05 ***
LUType3IntGrazing               -0.813834   0.154271  -5.275 2.85e-07 ***
LUType3SemiNatNB                -2.003803   0.117921 -16.993  < 2e-16 ***
LUType3SemiNatOther             -1.272343   0.124430 -10.225  < 2e-16 ***
MidDepth_cm:LUType3ExtGrazing    0.002368   0.002095   1.130 0.259485    
MidDepth_cm:LUType3IntGrazing    0.006392   0.002073   3.084 0.002272 ** 
MidDepth_cm:LUType3SemiNatNB     0.006102   0.001903   3.207 0.001514 ** 
MidDepth_cm:LUType3SemiNatOther  0.005379   0.001820   2.956 0.003406 ** 
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.3481 on 253 degrees of freedom
Multiple R-squared:  0.7655,	Adjusted R-squared:  0.7572 
F-statistic: 91.77 on 9 and 253 DF,  p-value: < 2.2e-16
```

Based on 5-fold cross-validation, the RMSE of this model is 0.0293 +/- 0.0050 g C cm-3 (NOTE: RMSE has already been back-transformed to original units).

Boot-strapped estimates for coefficients (more reliable than those above):

```
                              term     original      BootMed      BootSE
1                      (Intercept) -1.454601770 -1.465538713 0.086348797
2                      MidDepth_cm -0.006335240 -0.006116479 0.002008677
3                LUType3ExtGrazing -0.547605625 -0.538504735 0.127680068
4                LUType3IntGrazing -0.813834116 -0.792559591 0.248882418
5                 LUType3SemiNatNB -2.003803484 -1.987760532 0.113148252
6              LUType3SemiNatOther -1.272343422 -1.261226691 0.113981734
7    MidDepth_cm:LUType3ExtGrazing  0.002367950  0.002083918 0.002201151
8    MidDepth_cm:LUType3IntGrazing  0.006391663  0.006015036 0.002943711
9     MidDepth_cm:LUType3SemiNatNB  0.006102496  0.005771956 0.002195997
10 MidDepth_cm:LUType3SemiNatOther  0.005379336  0.005162102 0.002135721
```

Note: predicted values estimated by these coefficients need to be back-transformed, i.e., exp(predicted value). Estimates for the Arable land-use type are given by ‘Intercept’ and ‘MidDepth_cm’. The coefficients for other land-use types should be added to these values.

Supplementary Information 5: A list of spreadsheets used in this analysis

Spreadsheet Name	Description
All_combined.xls	All data obtained for each auger by row (Lowland Peatland Survey of England and Wales (1987) and the Broads Authority Peat Resource Survey (2010))
Peat Wastage calculations.xls	Calculations of peat wastage for each auger as described in Section 3.3.1
carbon density calculations.xls	Calculations of carbon density for each auger as described in Section 3.3.2
Uncertainty analysis.xls	Calculation of uncertainty for each auger under both consolidated and oxidized scenarios.
All scenarios summary.xls	Output of carbon stock from GIS analysis for each peat-grid-polygon

Supplementary Information 6

Figure SI6.1 Stacked bar chart of land cover in Broads National Park using auger data from Lowland Peatland Survey of England and Wales (1987).

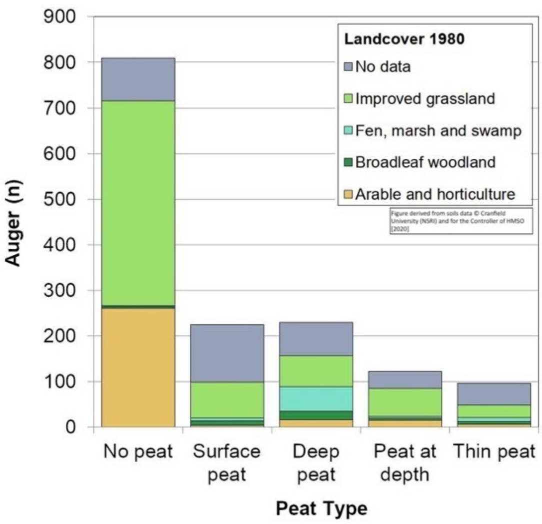


Figure SI6.2 Stacked bar chart of land cover in Broads National Park using data from UK Land Cover Map (2015).

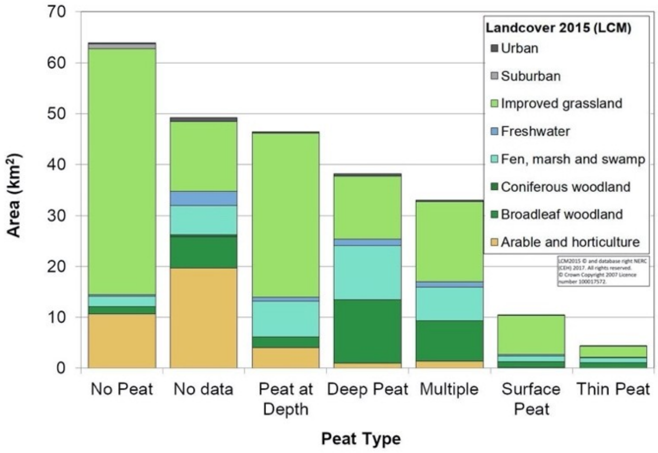


Figure SI6.3 Land cover by auger in Broads National Park at the time of the Lowland Peatland Survey (1980s).

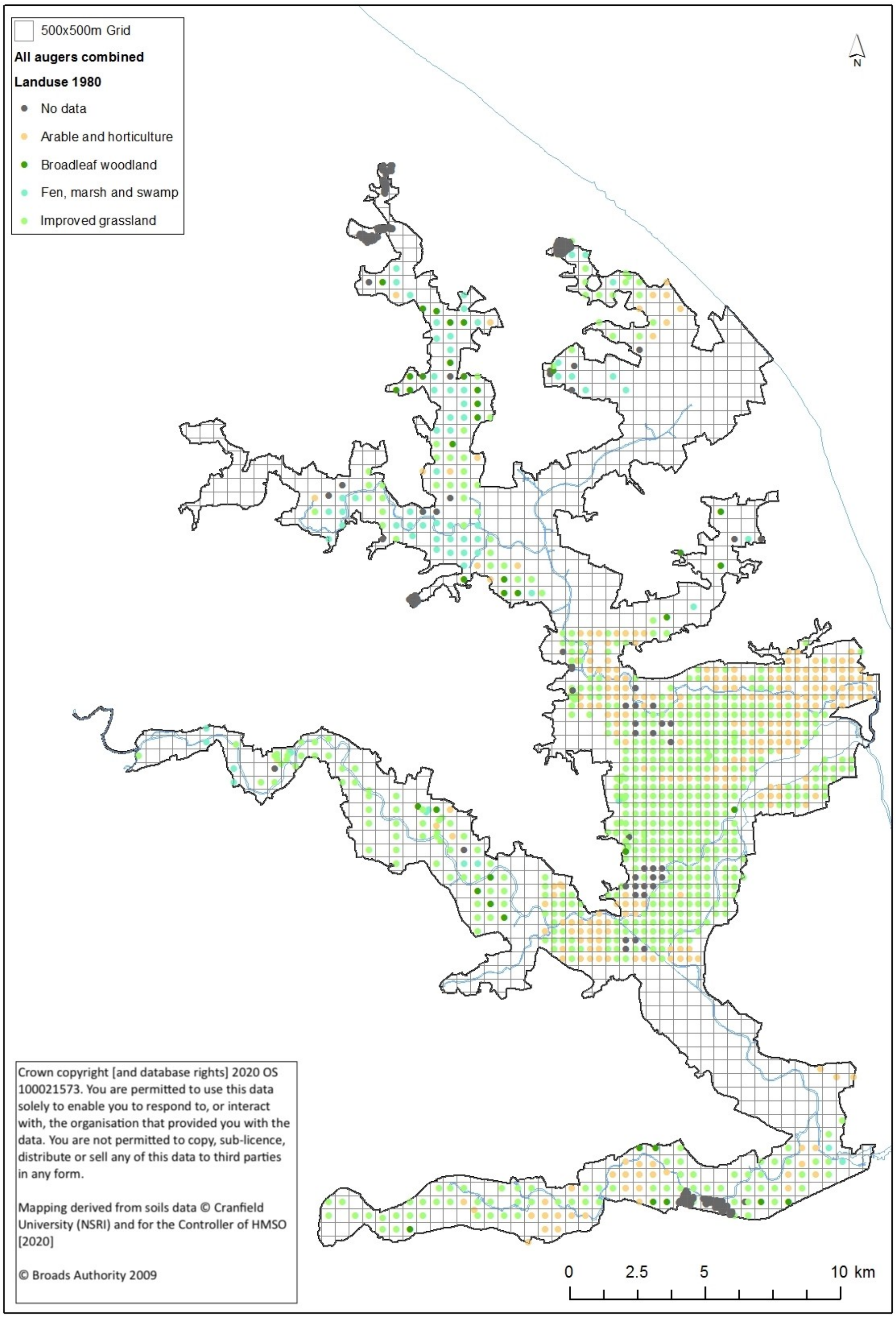
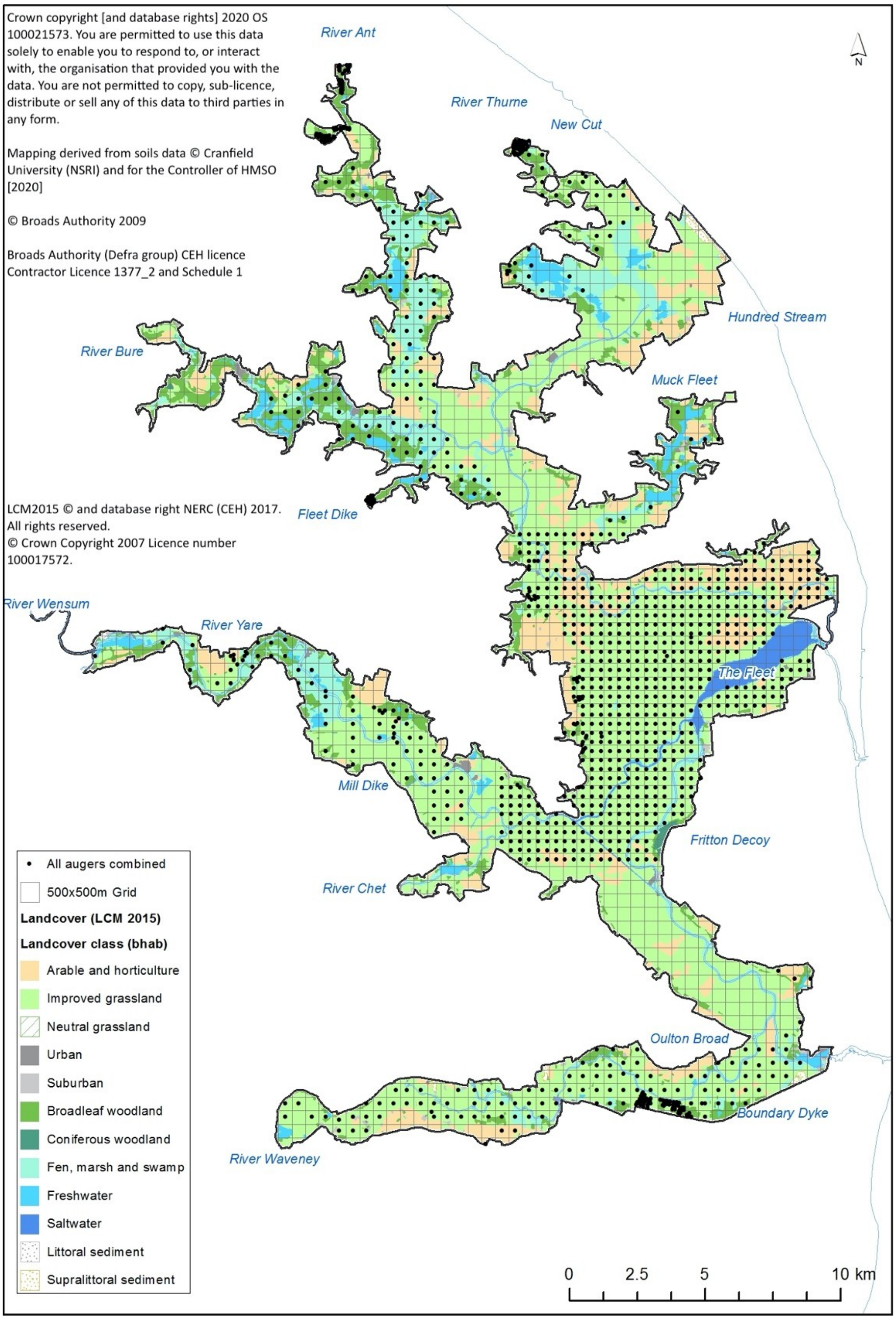


Figure SI6.4 Land cover by polygon in Broads National Park using data from UK Land Cover Map (2015).



Supplementary Information 7

Auger data for the Thurne Valley is concentrated in the upstream northern sections of the valley with very little data in the middle and downstream sections of the Thurne. The middle and downstream sections are dominated by one large polygon (ID 413) in the GIS. There are four augers in the northern portion of the peat polygon. One auger shows deep peat, and the other three show peat at depth (see Figure SI6.1 and SI6.2). This means that the average of the three 'peat at depth' augers was used to calculate peat stock for the entire polygon (which covers a large area). Local expert knowledge of the Thurne suggests that there is little peat at surface in the valley, and that the initial value may be an over-estimate of the peat stock. So in this case we have removed estimates of peat stock from the peat-grid-polygons in polygon 413 that do not have any auger data. Until additional data can be analyzed to determine whether peat occurs at depth throughout the valley, this may cause an under-estimate for the peat stock.

Figure SI7.1 Thurne Valley peat and peat-grid-polygons to describe method of calculating peat stock

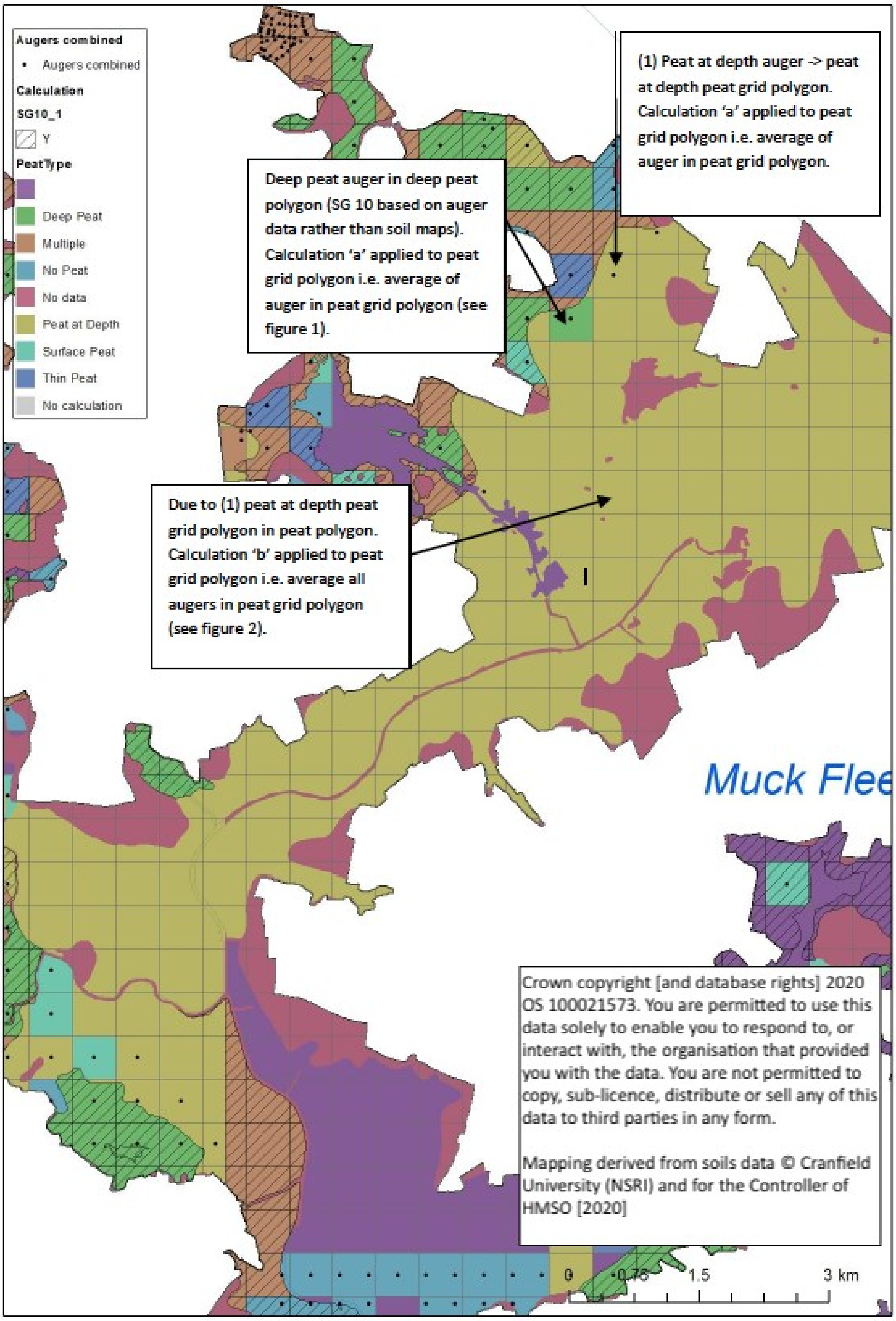


Figure SI7.2 Landcover (2015) in Thurne Valley with peat polygon 413.