Using peat surface motion to map peatland condition

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Report details

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NCEA Natural Capital and Ecosystem Assessment

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Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

This joint report was commissioned by Natural England to create an evidence base and build knowledge of how peatland surface motion characteristics relate to peatland condition.

The England Peat Action Plan published in 2021 set out the Government's plans to *'work to ensure all our peatlands, not just deep or protected peat, are responsibly managed, or, in good hydrological condition or under restoration management'*. As part of the plan a more detailed and up to date England Peat Map was commissioned to provide baseline evidence of peat extent, depth and condition across England. Upon review during the planning stages, peat surface motion was deemed not yet ready to be operationalised into the England Peat Map. Prior research did show promise, however, that satellite derived surface motion could be used to infer peatland condition. Therefore, this report was commissioned to create an evidence base of ground measured surface motion and better understand if this motion could be used to infer peatland condition across a range of English peatlands.

1. Executive summary

1.1 Background

Recent developments in the use of satellite derived datasets have included the use of Interferometric Synthetic Aperture Radar (InSAR) to monitor peatland surface motion in both time and space. Examples include multiannual subsidence or uplift, and annual oscillation of the peat surface level in response to groundwater level variation (e.g., Alshammari et al. 2020; Alshammari et al. 2018; Hrysiewicz et al. 2023; Hrysiewicz et al. 2024; Tampuu et al. 2023). Since open-access satellite radar data covering the entirety of the United Kingdom are available from the European Union's Copernicus Earth Observation program, the focus of this work was to determine the feasibility of using InSAR data to map and monitor peatland ecohydrological behavior on a nation-wide scale.

Recent work (Bradley et al., 2022; Marshall et al., 2022) has shown that the intra and inter-annual fluctuations in peat surface can be linked to semi-natural peatland functioning. Peatlands have the capacity to regulate their surface to an extent in response to changes in wetness, in a phenomenon known as "bog breathing". One of the aims of this work is to determine to what extent low-cost measures of peat surface movement can be used as a proxy for 'hard to measure' aspects of peatland function including GHG balance and long-term soil carbon gain or loss.

In this work we developed a standardised method of automatically monitoring peat surface motion and water table depth continuously in the field so that we could determine how these measurements differed between regions and between peatland land use. The methodology for monitoring peat motion is based on a platform that moves with the surface of the peat, and on that platform is fixed a camera, which takes photos of a vertical ruler fixed through the peat into the underlying geology. When the images are analysed the output is a time-series of vertical motion that corresponds to the movement of the peat surface, providing the first England wide report of peat surface motion.

This report describes the work carried out by UKCEH, University College Dublin and Terramotion for Natural England to investigate the extent to which satellite data can be used to map peat condition at scale across England. The work covered all the main peatland types and regions in England, with the exception of Dartmoor.

1.2 Key Findings

The cameras have shown that it is possible to continuously monitor peat surface motion and water table dynamics, at scale, using comparatively low-cost sensors and materials. These results have provided the first England wide dataset of peat motion dynamics and water levels across the full range of peatland types found in England. We have shown that the interplay between water availability and peat surface motion can, in the short term, over-ride the long-term surface motion trend (i.e. subsidence or uplift in the peat), which in turn will affect the use of surface motion as a metric from which carbon sequestration or emission at these peatlands can be calculated. It is, therefore, important that when comparing the metrics calculated from peat surface measurements to peat condition multiple years of measurements are used to minimise the effects of short-term variability. It is worth noting as well that some of this variability in annual motion could prove to be an important metric when comparing peatland condition within and between land use categories.

When comparing the measured surface motion to InSAR derived surface motion models there is a clear trade-off between spatial coverage and accurate quantification of the amplitude and timing of surface motion. None of the methods tested provide a ready to operate solution to national mapping of peatland surface motion. IPTA InSAR showed a good relationship with surface motion characteristics measured at raised and blanket bogs with moderate spatial data coverage. This suggests that InSAR mapping of peat surface motion could provide a partial solution to mapping peat condition across raised and blanket bogs. However, we also demonstrated that open source InSAR maps do not provide sufficient spatial coverage to form part of a national peatland monitoring strategy at present so a proprietary methodology would be needed to take this solution forwards.

Finally, we showed that SAR backscatter data can be used to model water table across a restored blanket bog and that published relationships between water table depth and greenhouse gas emissions from peatlands could be used as the basis of a future satellite derived methodology for monitoring, reporting and verifying restoration efforts to raise water levels in peatlands.

1.3 Implications

Results to date suggest that a InSAR derived approach to mapping peat surface motion is not yet at a stage where it could be operationalised for England peatland monitoring. However, it seems that for peat bogs in semi-natural condition (both raised and blanket bogs) InSAR could be used alongside other remote sensing methods.

The peat cameras provide a large-scale ground data resource, and their importance as a baseline dataset will increase over time as the long-term trends and inter-annual variability can be established from the overall data.

This joint approach has demonstrated the importance of method testing in a range of peatland types across England. Having sufficient ground data to calibrate and validate remote sensing datasets is crucial for a tool to be used for national monitoring, reporting and verification of peatland condition, in support of the England Peat Action Plan.

Contents

2. Introduction

Peatlands hold the largest carbon stock of any UK ecosystem, are a major source of drinking water, and include globally rare habitats such as upland blanket bog, which support a range of specialised species. However historic and ongoing degradation of peatlands has converted them from long-term carbon sinks into a nationally important emissions hotspot, responsible for an estimated 3-4% of UK greenhouse gas (GHG) emissions. English peatlands make a disproportionately large contribution to these emissions as a result of a range of factors including drainage, grazing, fire and air pollution in blanket bogs, mining of lowland raised bogs for peat extraction, and the widespread conversion of lowland fen and some raised bog areas into high-value agricultural land. They are important havens of biodiversity, a key component of England's natural capital, and a source of both ecosystem services and (as a result of degradation) disservices.

Despite their importance, our knowledge of both the extent and condition of English peatlands is surprisingly limited. The peat mapping that forms the basis of current assessments, including emissions inventory reporting and agricultural payment schemes, was largely undertaken prior to the 1980s, often at a coarse resolution. In deeply drained agricultural areas continuing peat wastage in the region of 1 cm yr^{-1} means that some areas currently mapped as true peat (i.e. > 40 cm deep) are now likely to be thin 'wasted' peat, while in other areas peat may have been completely lost. Information on peat condition is also often limited, with emissions inventory and natural capital reporting based on a combination of relatively crude satellite-based classifications and air photograph analyses undertaken around a decade ago. Restoration activities have increased dramatically in recent years but have not been comprehensively mapped, and where information is available this is often limited to recording the intervention (e.g. whether ditches have been blocked) rather than the outcome (e.g. whether water tables have been raised, or a peat-forming *Sphagnum* cover re-established).

The England Peat Map will address these evidence gaps by greatly enhancing baseline evidence on the extent, depth, and condition of England's peatlands. This will inform the England Peat Action Plan, improve the calculation of GHG emissions reporting and the targeting of future restoration. Existing and new survey tools will be employed and complemented by Earth Observation (EO) and modelling. Reliable and robust ground data are required to enable the development of earth observation-based modelling approaches for peat condition in England, and to re-orientate restoration monitoring from an intervention-based approach to an outcome-based approach.

While most methods to monitor peat condition over time are either expensive (e.g. flux towers for GHG emissions measurement, commercial pressure transducers for water table monitoring) or provide very limited temporal resolution information (e.g. peat stock change monitoring, vegetation surveys), the UK Centre for Ecology & Hydrology (UKCEH) have recently developed a novel, low-cost approach to peat condition monitoring that uses time-lapse cameras to monitor small (sub-mm to cm scale) changes in peat surface elevation and water table depth (Evans et al., 2021a). Conceptually, this approach relies on the fact that peatlands have the capacity to regulate their surface elevation (sometimes referred to as ‘bog breathing’) in response to changes in wetness, such that a wet peat will expand, whereas a dry peat will contract. This behaviour is evident in response to individual rain events or droughts, seasonally, and over multiple years as the peatland either subsides (indicating carbon loss) or grows (indicating hydrological recovery and ultimately peat formation and carbon sequestration). The UKCEH peat camera system has been developed and tested in the UK, Sweden, the Falkland Islands, Brunei, Indonesia and Malaysia, demonstrating a high degree of resilience over an extreme range of temperatures and humidities, and generating novel, high-resolution information at low cost. Recent work (Bradley et al., 2022; Marshall et al., 2022) has shown that the intra and inter-annual fluctuations in peat surface can be linked to semi-natural peatland functioning, and one of the aims of this work is to determine to what extent low cost measures of peat surface movement can be used as a proxy for ‘hard to measure’ aspects of peatland function including GHG balance, long-term soil carbon gain or loss, and changes in hydrological behaviour following interventions such as restoration or changes in agricultural water management.

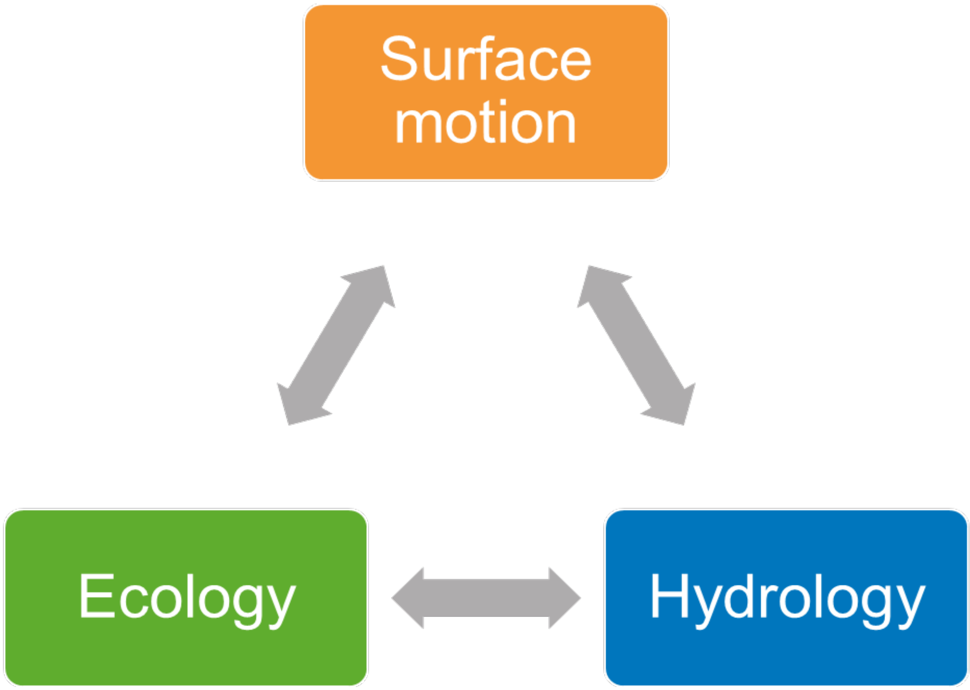


Figure 2-1. Links between peatland ecology, hydrology and the visible surface motion in peatland areas (see also Marshall et al., 2022).

Peat elevation is highly dynamic on short-term (e.g. rain event, dry period), seasonal and inter-annual timescales. These dynamics are closely related to peat condition, with hydrologically intact sites tending to show a more gradual, seasonal fluctuation in elevation (‘bog breathing’) whereas drainage-impacted sites tend to rise and fall rapidly in response to individual rain events as the capacity of the system to store water has been disrupted. Over the longer term, drained peatlands undergo subsidence (sometimes at rates of a cm or more per year), which the cameras are easily able to detect, whereas wet peat-forming systems may show slow vertical growth. In general, deeper peat sites tend to exhibit a higher amplitude of vertical fluctuations compared to shallow, mineral-enriched peats, which may be valuable for peatland mapping.

Synthetic aperture radar interferometry (InSAR) has the potential to enable large-scale measurement of peat surface motion on timescales ranging from weeks to years, based on freely available data (Sentinel-1 C-band SAR). There is growing evidence to indicate that this approach is suitable for peat condition assessment, but it has not yet been fully tested against the high-frequency surface motion data generated by the peat cameras. This work assesses the extent to which InSAR analysis of peat surface motion matches the peat surface motion detected by the peat cameras. If the two methods prove comparable then the InSAR data could provide a national-scale monitoring method of peat surface movement, and hence peat condition.

A further aspect of peat condition is the land cover overlaying the substrate. At present, land cover on peat is determined through the intersection of existing peat maps with national scale land cover mapping. This land cover mapping is not primarily aimed at detecting differences in semi-natural habitats found on peat soils, despite land cover being a major factor in our understanding of peatland condition (See Figure 2-1), though previous work has demonstrated that both spectral satellite data (e.g. Williamson et al., 2018, Dąbrowska-Zielińska et al., 2022) and SAR backscatter data (Williamson et al., 2021) can be used within a supervised classification methodology to discriminate between semi-natural peatland land covers.

This report covers work to test the following research hypotheses:

1. The dynamics of peat surface motion, as measured in the field using time lapse photography of a fixed datum, can be used (alongside other metrics such as vegetation and land management) to determine peatland condition.
2. Peat surface motion is linked to water table dynamics, and water table depth is a key driver of GHG flux from peatlands. The peat surface motion can be used to predict annual carbon dioxide and methane emissions.
3. Peat surface motion measured by the cameras can be detected using conventional and APSIS InSAR. APSIS InSAR is likely to provide more coverage in low coherent areas.
4. SAR data can be used alongside topographic information to model water table depth across a raised bog.
5. Remotely sensed radar and spectral data can form the basis of a national peatland monitoring strategy, alongside low-cost ground sensors that are spatially distributed across the range of the England peat condition categories.

3. Ground measurement of surface motion

3.1 Peat cameras

Ground measurement of surface motion has previously either been recorded infrequently (e.g. monthly/quarterly measurements of subsidence poles) or at higher temporal resolution for short periods of time, usually via labour intensive levelling approaches. Automated approaches have been trialled (Fritz et al., 2008; Zanello et al., 2011) but have experienced challenges such as mechanical breakdown and human/animal disturbance. UKCEH have developed a novel, high-resolution camera system to monitor small (sub-mm to cm scale) changes in peat surface elevation and water table depth (Evans et al., 2021a).

The peat camera consists of a time-lapse camera housed within a waterproof box attached to a metal stool (Figure 3-1 and Figure 3-2). Next to the stool a metal rod is placed vertically and anchored into the underlying substrate, onto which a ruler is attached. The stool is pressed 20cm into the peat surface, meaning it moves up and down with the peat surface whereas the rod is anchored and stationary. The ruler attached to the metal rod is printed with ArUco markers allowing automation of peat surface measurement from the camera photos. The camera takes a photo every 2 hours and automatically transfers this via mobile signal to cloud storage. A flash allows imagery to be taken both day and night. Automated water table depth measurements are taken every two hours using a pressure transducer housed within a dip well.

An early version of the peat cameras was compared against manual measurements via subsidence poles in tropical peatlands (Evans et al., 2021a). Results showed a very strong relationship between the manual and peat camera measurements (R^2 of 0.97), although camera derived data did overestimate peat motion slightly (a coefficient of 1.129). Significant development of the cameras has taken place over the last three years with a focus on improving reliability. Improvements have included the use of a Raspberry Pi, custom-designed printed circuit board, high-endurance micro-SD cards, solar panel, 4G LTE modem and a multi-network sim cards, allowing data to be transferred over multiple phone network providers. In addition, all data is stored locally in the camera in a removable USB drive. Cameras installed at sites with low insolation, such as wet woodlands, have also been equipped with an extra solar panel in parallel (50 W of power in total) to allow the cameras to run continuously during the winter months.

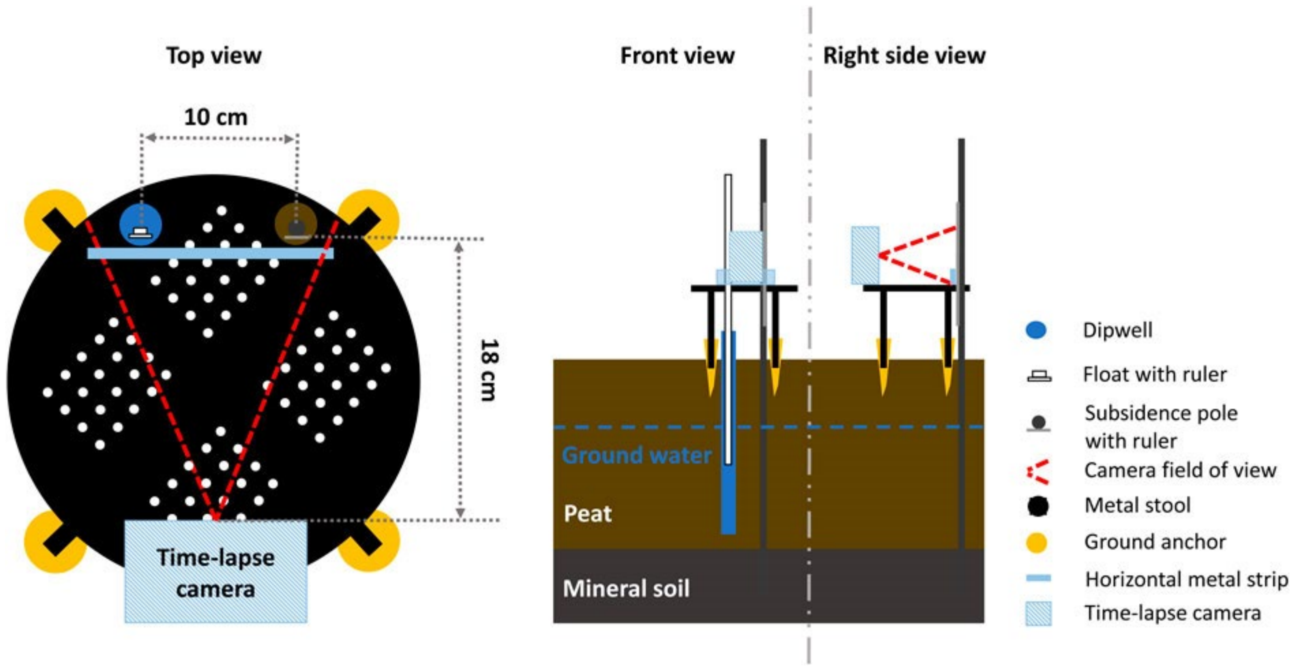


Figure 3-1 Schematic diagram of peat camera design (Evans et al., 2021a) republished under CC - BY licence https://creativecommons.org/licenses/by/4.0/

Figure 3-2 Photographs of peat cameras in situ (credit: John Spill, left photo, and Jonay Jovani, right photo © UKCEH)

3.2 Site selection

This project aimed to cover the main peatland landscapes across England, while ensuring that there was sufficient coverage by peatland condition category planned for incorporation in the UK greenhouse gas inventory (Figure 3-3). Site selection also had to account for installation and maintenance efficiency, with cameras 'clustered' to reduce travel time and therefore maintenance costs. This approach also helped to identify differences in behaviour associated with management (i.e. between sites located within one peatland area) from those associated with differences in other factors such as peat depth and climate that are more likely to arise between regions. In addition, sites with existing funded infrastructure, such as flux towers and experimental plots for greenhouse gas flux measurements, were also prioritised during the site selection. In total, 52 cameras have been installed by this project, with one (camera 9) no longer operational. Figure 3-4 shows the geographic spread of cameras across England, while Appendix 1: Installed cameras lists the cameras installed and their respective condition categories. All categories in Figure 3-3 are covered except for shallow drained plantation and extraction. Shallow drained grassland as well as *Molinia* and *Calluna* dominated semi-natural bog have the greatest number of cameras, with seven each. Since the beginning of this project, a further 41 peat cameras have been installed in England, through other projects and funding schemes. The peat camera network has expanded to 92 units in total and 26 cameras have been installed adjacent to flux towers.

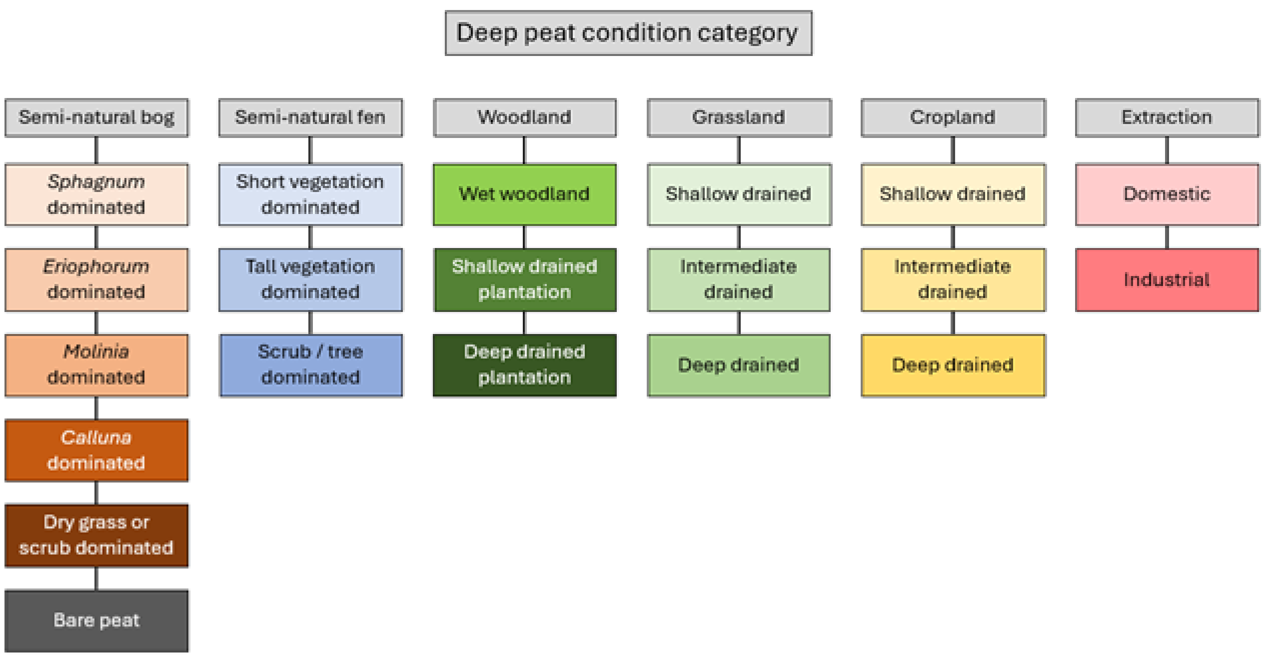


Figure 3-3 Peat condition categories used in the assessment of peat greenhouse gas emissions

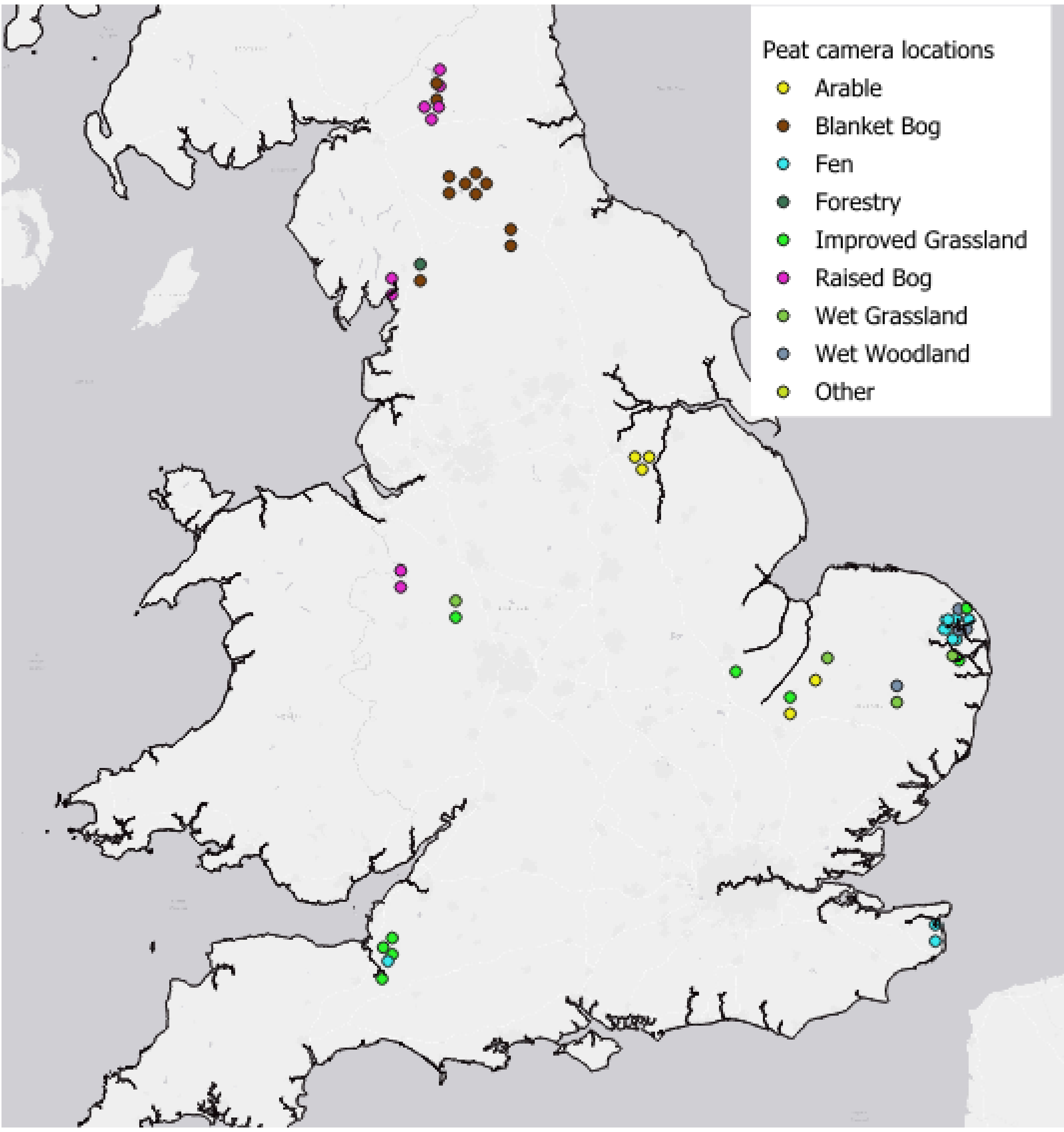


Figure 3-4 Map of approximate peat camera locations and their peatland types

3.3 Data availability

The first peat cameras for the project were installed in March 2022. Most cameras (43) were installed by March 2023 and all cameras were installed by September 2023. The month of first data collection for each peat camera is shown in Appendix 1: Installed cameras. A full timeline of data availability is provided in Appendix 2: Data coverage for peat cameras in 2024 for 2024, Appendix 3: Data coverage for peat cameras in 2023 for 2023 and Appendix 4: Data coverage for peat cameras in 2022for 2022.

3.4 Automated data publication online

A pipeline to automate the process, from data capture to data dissemination, was implemented as part of this project.

Figure 3-5 shows the workflows, highlighted in different colours, that were implemented. First, the peat camera obtains the image and data and Python and Bash scripts then upload the acquired data to a cloud storage service. The second workflow, highlighted in light green, retrieve the data from cloud storage and save it into the UKCEH internal server. Once data from all web Apps has been downloaded, another script produces a summary report, which is sent by email. This report contains information regarding the location of the data, the number of images and data files downloaded and some metadata about the files.

Once the data has been securely stored in the server, the pipeline executes two independent workflows to process the images (in green), and the environmental data (in light blue). Computer vision (OpenCV package) is used to detect each ArUco marker and measure the distance of each marker to a reference point within the image. The method detects all fully visible ArUco markers, measures the distance between the top of the ArUco markers and the watermark at the bottom of the image (the fixed reference point) and finally converts that value (in pixels) to a total vertical motion (in mm) based on the known position of the detected ArUco markers on the ruler (Figure 3-6). This method can process each image in isolation with no need to detect the change in movement from a previous image. Images are processed daily, and the script generates daily data files with the peat motion results. Once this workflow has finalised, it generates a summary report, sent by email, indicating the number of images processed for each camera.

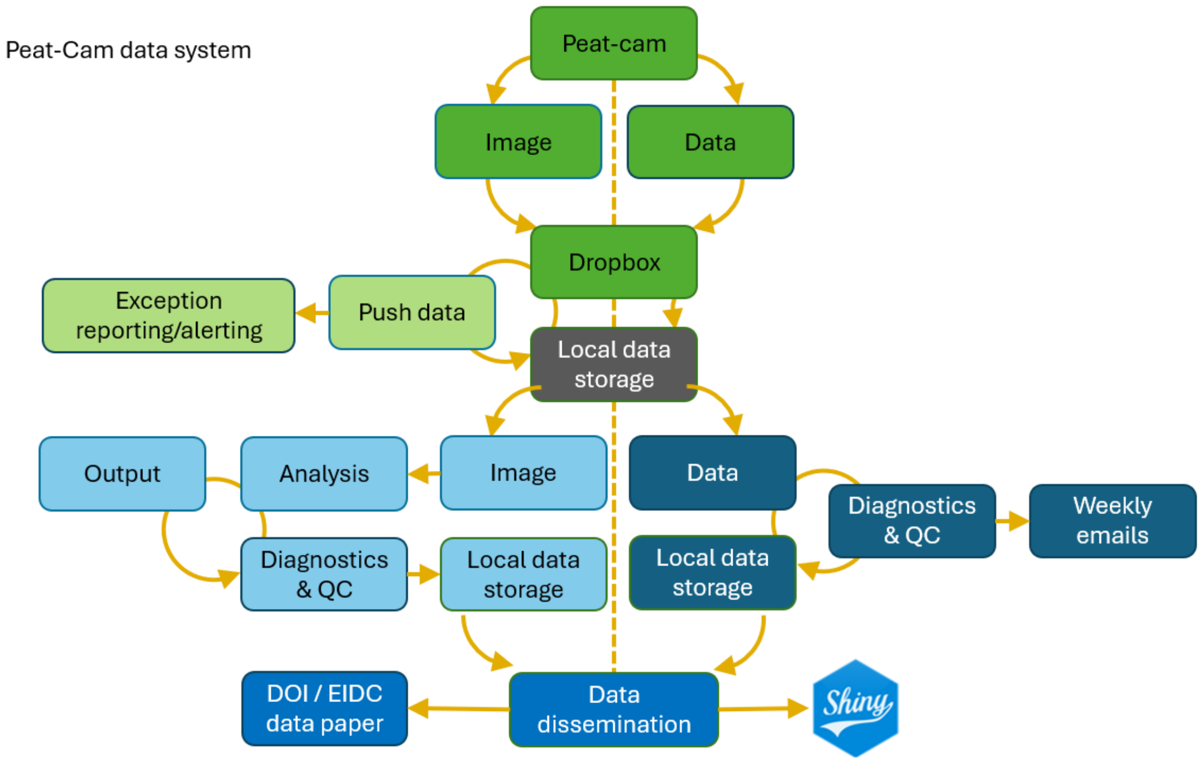


Figure 3-5 Pipeline for automation of data processing and quality control (QC). Different colours highlight independent workflows

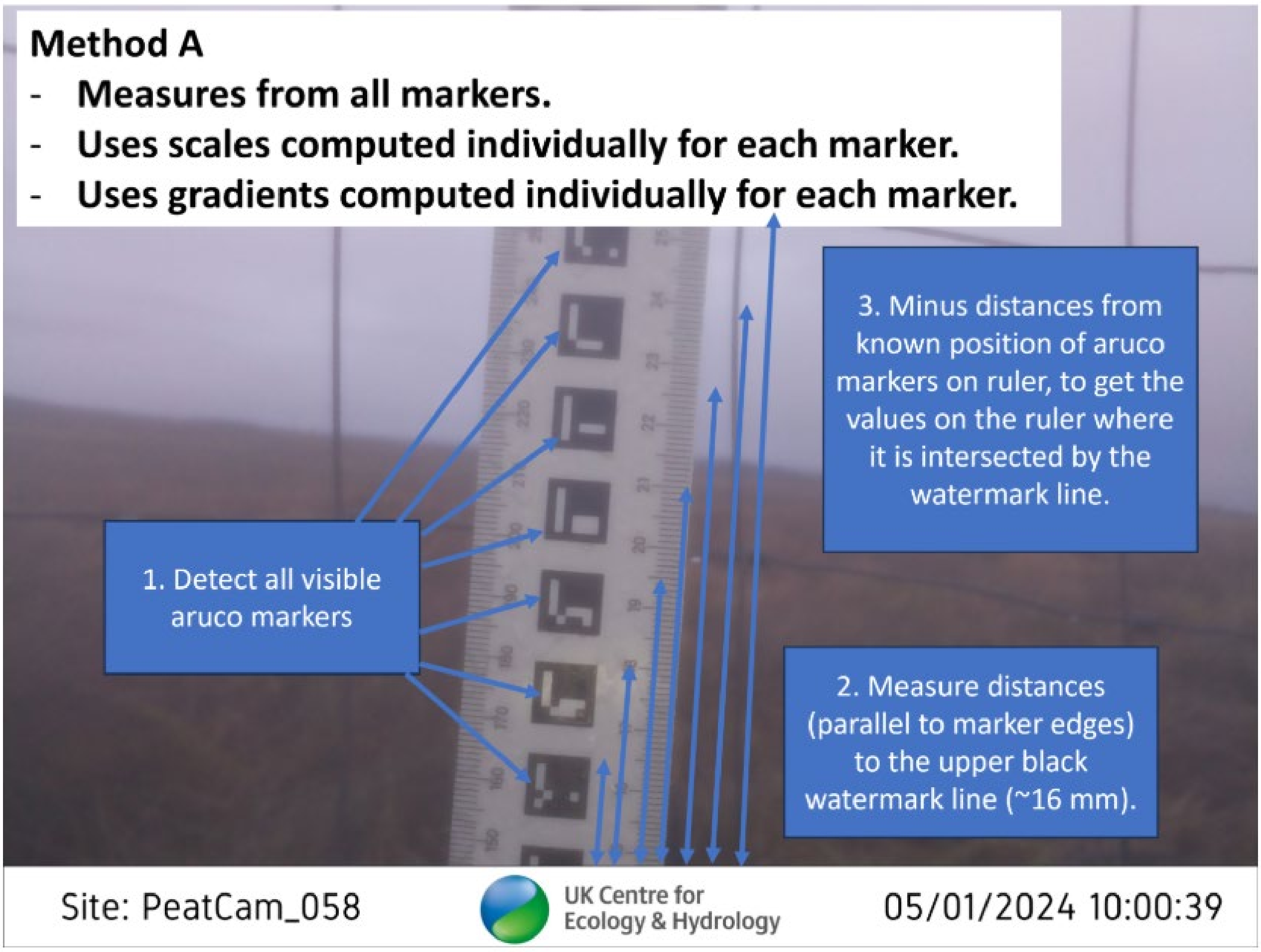


Figure 3-6 Visual description of the image analysis process steps for each image

The next workflow of the pipeline, highlighted in light blue in Figure 3-5, reads the data files uploaded each day by each camera and adds new data to the master file. After compiling the new data, the scripts perform a series of quality control checks to identify and remove any outliers and detect any battery issues. The script then generates a summary status report identifying battery levels, warnings and the timestamps of the last processed file. Diagnostic plots are generated daily. In addition, once a week, the workflow sends plots, containing data from the last seven days, by email to the users that have signed up to receive these alerts. The last step of the pipeline is the data dissemination workflow (dark blue in Figure 3-5) which consists of uploading all the data into web Shiny App containing semi-real time data. The Shiny App allows users to download and visualise data (hourly and daily averages) though dynamic plots.

3.5 Future network uses and needs

The peat camera network is providing water table depth and peat motion data across different peatland condition classes. In addition to this report, the outputs are being used by private owners, not-for profit organisations, public organisations and private companies. Cameras installed in the Broads are already assisting a private farmer in monitoring water level across the farm to make sure that the measured values are within those required in the SW18 countryside stewardship scheme. Furthermore, the co-location of peat cameras with eddy covariance flux towers, will help in developing more accurate empirical functions relating peat subsidence rates and CO_2 emissions. During the second part of 2024, 26 peat cameras have been installed adjacent to 13 flux towers. These will provide valuable data for the development of a monitoring, reporting and verification tool based on remote sensing methods.

The main challenge of the peat camera network is that they require regular maintenance (once every three months on average). To maximise efficiency and keep the network well maintained, it is important that a local point of contact exists. This contact could carry out easily regular maintenance activities (e.g. trimming grass around the ruler, clean solar panel and download data from the USB drive), significantly reducing the ongoing maintenance costs. In order to assist our local partners, we have produced field guides and maintenance logs. This facilitates the field work activity and the quality control of the data. Further improvement of these guides and documents is planned by UKCEH.

4. Peat condition metrics from ground data

4.1 Introduction

There is general recognition that the surface motion dynamics of peatlands can provide valuable diagnostic information about their ecohydrological functioning. These include the effects of natural variations at a range of scales from hummock-hollow microtopography in natural bogs (e.g., Marshall et al., 2022) through position within large peatland units (e.g., bog centre, bog edge; Fritz et al., 2008; Howie and Hebda, 2018; Marshall et al., 2022) to broad scale differences such as those between bogs and fens. In addition, it is clear that peatland surface motion dynamics can be profoundly altered by human disturbances including direct or indirect drainage (Bradley et al., 2022), afforestation (Bradley et al., 2022), agriculture (Evans et al., 2021), peat extraction (Howie and Hebda, 2018), management-related vegetation change (Morton and Heinemeyer, 2019; Bradley et al., 2022), and loss or re-establishment of the peat-forming acrotelm layer (Howie and Hebda, 2018). Over the long-term, natural peatlands can be expected to exhibit slow growth, in the region of 1 mm yr^{-1}, whereas drawdown of the water table leads to long-term peat subsidence. In UK fen peat drained for agriculture the long-term rate of subsidence is around 0.5-2 cm yr^{-1}, while in recently drained tropical peatlands it can exceed 5 cm yr^{-1} (Hooijer et al., 2024; Evans et al., 2019). Subsidence rates may be significantly higher in drought years versus wet years (Evans et al., 2022).

Although there is now a substantial body of published research on long-term peat subsidence, and a modest body of research on shorter-term peat surface oscillation, a large part of this work has been essentially exploratory, and/or limited to a particular peatland type, most often near-natural bogs in the case of shorter-term oscillation, and tropical and temperate agricultural peatlands in the case of long-term subsidence. As a result, there are few – if any – generalisable metrics currently available that can systematically predict peat condition from peat surface motion data.

In the following section we briefly describe and evaluate a range of different potential metrics, and the inferences that can be drawn from them. We then evaluate the more promising metrics using the available data from the peat camera network.

4.2 Metrics and Inferences to Peat Condition

Table 4-1 summarises a range of metrics that relate peat elevation data, over a range of timescales, to aspects of peat condition. These metrics form the basis of the following section. Each metric is outlined in greater detail followed by an investigation of the extent to which the currently available ground data supports the use of the metric to assess peatland condition across the range of peatland habitat found across England. It is important to note the limited, and in some cases incomplete, timeseries (see Section 3.3) used in this analysis does limit the conclusions that can be drawn from the dataset at this stage.

Table 4-1 Peat condition metrics obtained from surface elevation data

Metric	Interpretation	Notes/references
Annual change	Positive change: Indicative of peat growth and carbon accumulation; or swelling following a sustained rise in water table. Negative change: Indicative of peat compaction and carbon loss due to drainage or other hydrological disturbance	Subsidence widely used as a metric of long-term peat loss but may vary from year to year in response to climatic variation (e.g. Evans et al., 2022) and as a function of climate zone, current land-use and land-use history.
Seasonal amplitude	Low amplitude: 1) a good condition peatland with stable WT; or 2) a highly degraded thin peat subject to continuous WT drawdown. High amplitude: High WT variability, e.g. due to active drainage or perturbation of peat hydrological function via degradation processes such as erosion.	Howie and Hebda (2018), but note that some good-condition bogs had high amplitude despite relatively stable water levels due to greater elasticity of acrotelm peat (see below) Preferably calculated using detrended data, multi-year data.
Small spatial scale variability in seasonal amplitude	High: 1) good condition bog with hummock-hollow microtopography, or 2) highly topographically modified bog e.g. with peat haggs and erosion gullies Low: Modified bog with loss of microtopography but not major erosion	Marshall et al. (2022), developed and tested in good condition Flow Country bogs. Wider inferences are uncertain. Not possible to test this metric based on current density of cameras
Ratio of elevation change to water table change	Extremely high: Floating peat High: Low bulk density and high elasticity of peat, associated with natural condition or restoration (e.g. presence of a *Sphagnum* acrotelm) Low: Higher bulk density and lower elasticity ('stiffer') peat as a result of degradation, compaction and the presence of roots (e.g. loss of acrotelm, shrub-dominance)	Fritz et al. (2008); Howie and Hebda (2018); Mahdiyasa et al. (2023). Tested for bogs but not fens.
Seasonal elevation peak	Autumn maxima: Presence of 'stiffer' peat associated with more degraded bog, steeper hydraulic gradients and shrub dominance Winter maxima: Presence of 'softer' peat, associated with better condition bog, lower hydraulic gradients and Sphagnum dominance Irregular maxima: Heavily managed or disturbed areas such as agricultural peatlands or erosion complexes	Bradley et al. (2022). Developed and tested for bogs. Dynamics of semi-natural fens may differ, e.g. in response to seasonal variations in groundwater input.

Metric	Interpretation	Notes/references
Lag between water table change and surface elevation change (hysteresis)	High (longer lags, greater hysteresis): Wetter, 'softer' peat (undrained). Low (shorter lags, less/no hysteresis): Drier, 'stiffer' peat (drained).	Howie and Hebda (2018); Mahdiyasa et al. (2023). Hysteresis can occur due to both short-term (event) or longer-term (seasonal) dry-wet cycles. Linked to previous metric.

Annual Change in surface elevation

Annual rates of elevation change have been most widely used to quantify rates of peat shrinkage (i.e. subsidence) due to long-term drainage. Subsidence occurs as a result of both compaction and organic matter oxidation under aerobic conditions. Most studies of subsidence have focused on lowland peat drained for agriculture, in both high-latitude (temperate and boreal) and tropical regions. A previous collation of published subsidence values by Evans et al. (2019) gave typical subsidence rates of 0.5 to 2 cm yr^{-1} for drained high-latitude peatlands, and 1 to 5 cm yr^{-1} for tropical peatlands. Within each climate region, there was a significant relationship between mean subsidence and mean annual water table depth, although with considerable scatter in both cases. For high-latitude peatlands, the relationship was:

Equation 1

$$subsidence\ (cm) = (-0.0212 * water\ table\ depth) + 0.43$$

Where annual subsidence is expressed in cm yr^{-1} (with a negative value indicating downward movement of the peat surface), and Water Table Depth (WTD) represents annual mean water table depth in cm (expressed 'positive downwards', i.e. as depth relative to the peat surface). Where the water table falls below the base of the peat the peat depth is used, i.e. the whole peat column is considered to be dry and is termed effective water table depth. This relationship implies that the peat will be stable or growing if the water table is within 20 cm of the peat surface, with the rate of subsidence increasing by approximately 0.2 cm yr^{-1} for every 10 cm of drainage below that depth. Scatter in the relationship reflects a range of factors, including time since drainage. This is because compaction tends to slow down over time unless ground water levels are continuously lowered as the peat subsides (Hutchinson, 1980). In UK blanket bogs, in which drainage typically only occurred once and where drains are rarely maintained, there is evidence that the peat surface near ditches has subsided down to the new lower water table, effectively re-wetting much of the peat (Williamson et al., 2017). As peat wastage progresses, the remaining peat layer becomes increasingly dense (increasing bulk density) and intermixed with underlying mineral soils (e.g. as a result of ploughing) so subsidence rates can be expected to slow further. Other factors may include differences in climate, peat type, seasonal hydrology and peat depth.

The peat cameras provide a new opportunity to assess the annual subsidence dynamics across the range of peat types included in this national monitoring. The initial analyses are limited to one year of subsidence due to data availability. Annual subsidence was calculated as the total change in the monthly mean peat surface level between winter months. For example, the difference in mean monthly peat level in January 2023 and January 2024. A specific month could not be assigned in advance as the month to use for all sites as the selection was limited by available data. Winter months were defined for this work as being between November and March, where water levels are generally high in semi-natural systems and water levels are less tightly managed in grassland and arable locations. Months were included in the analysis where more than 25% of potential surface measurement data was available.

Once annual subsidence values were calculated the mean annual water table was calculated for the same time period. For this analysis sites were included if there was less than 1 month water table data missing. This is because a large period of missing data can skew the annual mean water table depth value, particularly if the missing period is particularly wet or dry.

Figure 4-1 shows the relationship between the annual effective water table depth and subsidence across all locations and land use types where sufficient data are available (24 sites). There is a relationship ($P = 0.015$) between annual subsidence and water table depth (Equation 2), though the slope of the regression is less than that seen in Evans et al. (2019) and only 24% of the variation in the annual subsidence can be explained by the mean annual water level. One aspect that is especially noticeable is the significant uplift in surface level seen at a number of sites, and across the range of land use types explored in this work. This uplift is greater than the understood rate of peat formation in temperate peatlands of ~ 1 mm per year, meaning that it is unlikely to be the result of the accumulation of “new” peat material, but rather that the winter water levels were higher in the second winter of measurement compared to the first. This implies that our subsidence values calculated from a single year of records are primarily reporting the impacts of inter-annual changes in winter water levels. It should be noted that Year 2 for most calculations covered December – March 2024 and this time period was especially wet across many of the sites, particularly in the Norfolk Broads and Somerset Levels, where cameras installed 50 cm above ground level were flooded for weeks.

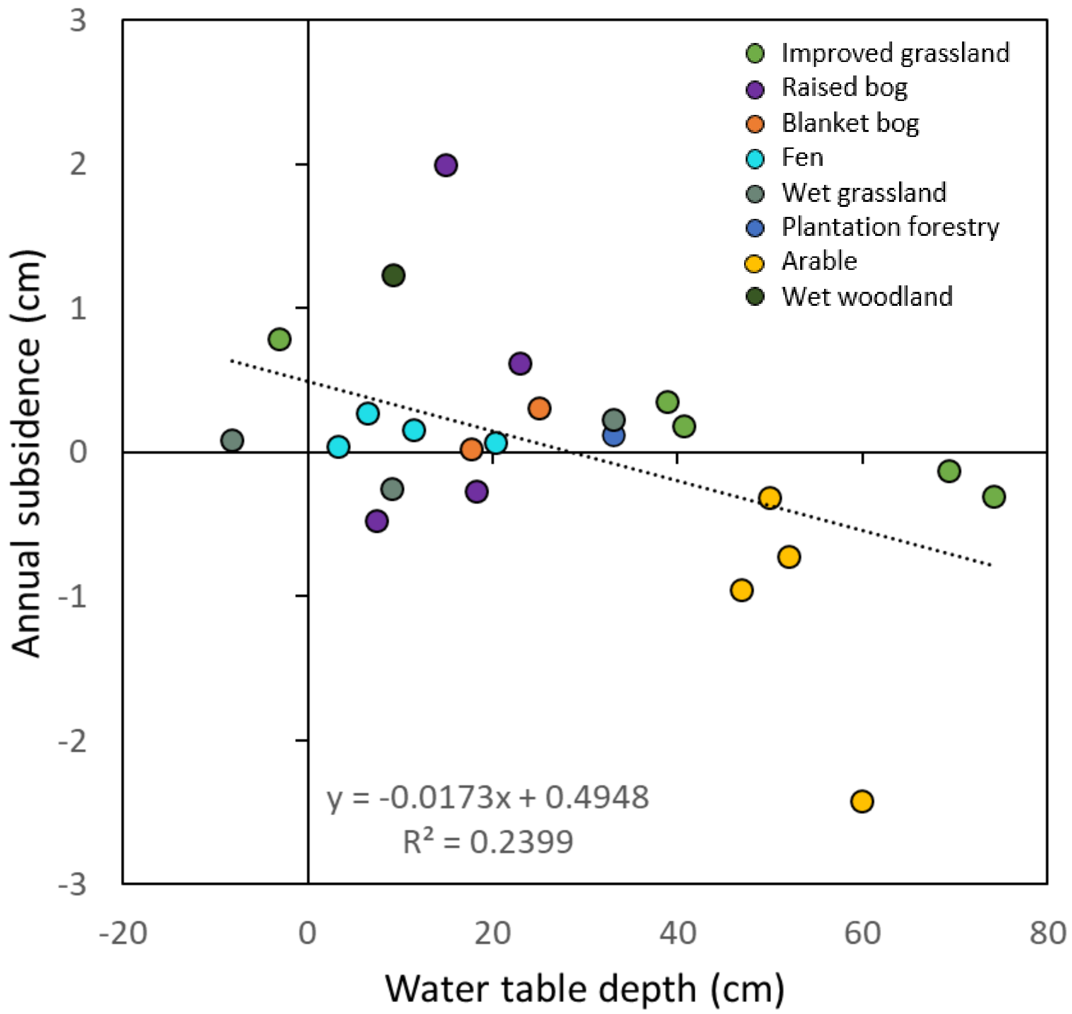


Figure 4-1 Annual peat surface level change as a function of mean annual effective water table depth. Coloured points represent land use at each site, while the regression line is the relationship between water table depth and subsidence across all data points.

Equation 2

$$subsidence\ (cm) = (-0.0173 * water\ table\ depth) + 0.49$$

The peat camera data has demonstrated that there is a relationship between annual subsidence and mean annual water table in English peatlands. In general, the more managed peatlands have deeper water table depths and greater rates of subsidence, while the restored and near natural sites have shallower water levels and less subsidence. There is, however, considerable variation in this relationship, likely exacerbated due to the short timeseries of available data and large observed between-year differences in hydrological conditions during the study period. The effects of inter-annual variability are relatively high compared to the longer-term rates of peat surface motion that were included in the results seen by Evans et al. (2019) and Couwenberg et al. (2011). We would expect that as the monitoring dataset becomes longer, the effects of year-to-year variability will become smaller, so that rates of peat elevation change more closely match the true long-term rate of peat subsidence or growth. This would be expected to result in stronger correlations with mean water table depths.

Peat Surface Oscillation

The most widely studied aspect of peat motion apart from annual subsidence is seasonal peat surface oscillation, sometimes referred to as ‘bog breathing’. In their natural state, peatlands have the capacity to regulate their surface elevation in response to changes in groundwater level through expansion and contraction, helping to retain high moisture levels near the peat surface even during dry periods, and thereby enabling peat to accumulate and persist. This natural behaviour may also provide some resilience against drainage, as noted above.

However, as a result of peat subsidence, with associated compaction (increase in bulk density/ reduction in hydraulic conductivity) and accompanying changes in vegetation (notably from *Sphagnum* mosses to vascular plants such as dwarf shrubs which root into the surface peat), it is likely that the capacity of the peat to adjust to changes in water level will be impaired. Bradley et al. (2022) refer to these changes as a transition from ‘soft’ to ‘stiff’ peat, with the latter tending to have smaller amplitudes of seasonal surface oscillation. In more extreme cases, for example as a result of cultivation, fire, peat extraction or sustained degradation, the entire peat-forming acrotelm may be lost, exposing the more compact catotelm beneath. This is again likely to reduce the capacity of the peat to shrink and swell in response to changes in water level (Howie and Hebda, 2018). These ‘haplotelmic’ peats, in which the acrotelm has been lost, are thought to be extensive across large parts of the English uplands, notably in the Southern Pennines, West Country moors and North York Moors.

The magnitude of peat surface oscillation was calculated as the difference between the month with the highest peat level and month with the lowest peat level. Although not strictly annual oscillation in all cases (as there was not always exactly 12 months of data available at each site) this calculation gives an estimate as to the extent to which the peat surface moves vertically for each land use category. The difference in water levels over the same timeframe was also calculated as the difference between the mean water levels for those months.

Table 4-2 shows the mean peat oscillation across all land use types, with the greatest vertical motion seen in improved grasslands and arable fields. These land use types have highly regimented drainage regimes and have lost any natural peat structure. Despite the loss of structure these sites are still exhibiting high levels of vertical motion due to the large differences in water level seen over the same time frame (Table 4-2 and Figure 4-2).

Table 4-2 Mean peat oscillation across land use types in this work and water table difference over the same time frame.

Land Use	Mean peat oscillation (cm)	Standard deviation (cm)	Water level difference (cm)
Arable	2.96	1.83	53.75
Improved grassland	4.19	2.37	49.43
Forest plantation	1.96	NA	38.19
Wet grassland	1.11	0.73	32.49
Wet woodland	1.04	0.49	23.88
Fen	2.15	2.19	20.70
Blanket bog	0.67	0.37	5.27
Raised bog	1.35	1.09	11.38

Of the semi-natural sites, fens show a relatively large vertical motion, though it should be noted that one of the fen sites in the Norfolk Broads appears to be exhibiting such high coherence between peat motion and water motion that it appears to be at least partially floating and linked to the river system. The origin of many of the Norfolk Broads fens as a process of terrestrialisation over open water (e.g. George 1992) makes this a likely reason for the motion seen. Blanket bogs show particularly low levels of vertical motion, and very small changes in water level. These sites are often stiffer, more dominated by shrubs and have had anthropogenic management including for grouse moors and grazing.

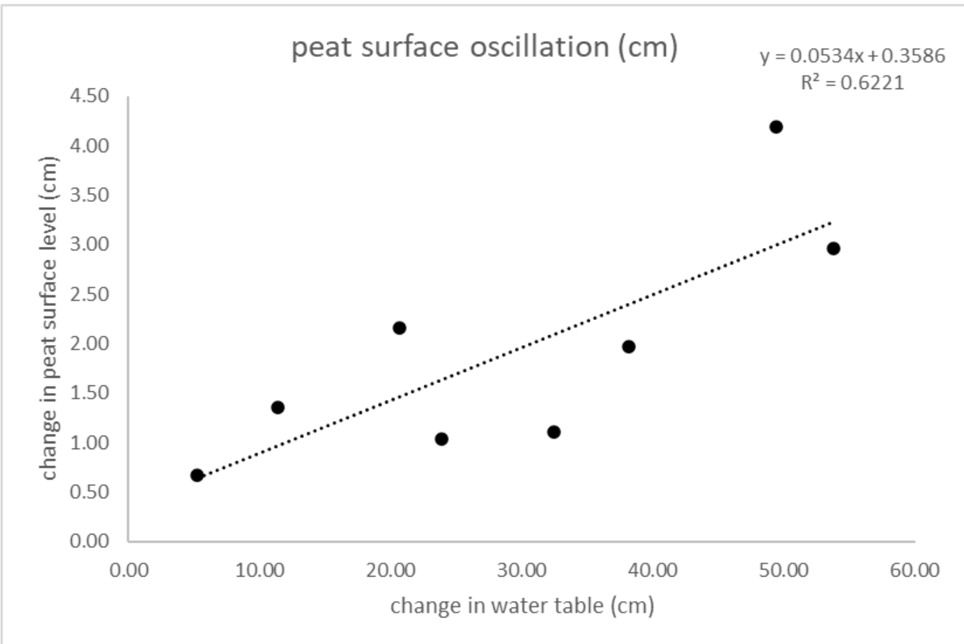


Figure 4-2 Relationship between the change in monthly mean water table and monthly mean peat surface level, showing that larger variations in water level lead to larger changes in peat surface level

The raised bog sites in this study provide a particularly interesting initial comparison of past land use history and the potential impacts on current condition metrics. Peat cameras 47, 49, 52 and 53 are all in the Border Mires in areas of comparatively undisturbed raised bog, and, with the exception of camera 47, show very little change in surface level or in the water level (Table 4-3). In contrast, the four raised bog sites that have a history of anthropogenic modification (peat extraction at sites 25 and 26 and plantation forestry at sites 42 and 43) followed by restoration to raised bog have greater annual oscillation and a larger change in the water levels over the same time period. This suggests that despite the return to semi-natural vegetation at the historically modified sites there are still some key differences in peatland functioning compared to the semi-natural sites.

Table 4-3 Raised bog peat cameras as an example of within peat category condition differences showing that the more modified locations (25 and 26 and 42 and 43) show greater vertical movement than the least modified locations in the Border Mires

Peat camera	Land use	Mean peat oscillation (cm)	water level difference (cm)
PeatCam_025	Former peat extraction, currently scrub	1.11	16.92
PeatCam_026	Former peat extraction, rewetted raised bog	3.38	22.29
PeatCam_042	Former plantation, rewetted raised bog	1.67	24.85
PeatCam_043	Former plantation, rewetted raised bog	2.87	30.69
PeatCam_047	Semi natural raised bog	1.17	5.26
PeatCam_048	Semi natural raised bog	0.36	2.44
PeatCam_049	Semi natural raised bog	0.49	-3.98
PeatCam_052	Semi natural raised bog	0.60	0.49
PeatCam_053	Semi natural raised bog	0.54	3.50

From the data available, it seems that across almost all camera locations there is a general positive relationship (Figure 4-2) between the magnitude of the peat surface oscillation and the change in water table depth over the same timeframe. The greater the change in water level the greater the magnitude of peat surface oscillation. Both the overall trend for greatest surface oscillation in the most managed sites, and the pattern seen within the range of raised bog site types where the more managed sites have greater surface oscillation, are in contrast with the results seen by Bradley et al. (2022). This study suggested that the best condition sites show greater surface oscillation, while the more degraded sites are stiffer and show less surface oscillation. However the degree of degradation at some of our sites likely exceeds that of the Bradley et al. (2022) sites in the Flow Country and water table fluctuations found in this study were typically larger. The high levels of peat oscillation seen in the highly modified arable and improved grassland peats show that these sites do not become less mobile despite peat degradation and compaction because of the large changes in water levels through the year.

Ratio of surface elevation change (ΔS) to water table elevation change (ΔW)

An additional and potentially valuable measure of peat condition is the ratio of surface elevation change to water table elevation change. In better condition 'soft' peats, this ratio should be high, whereas in degraded 'stiff' peats it should be low (Bradley et al., 2022; Howie and Hebda, 2018; Fritz et al., 2008). In one case, Fritz et al. (2008) observed extreme responsiveness of the peat surface to water level change (almost 1:1) which they attributed to the peat effectively floating on a layer of water (a situation which can occur in some natural fen peats). Conversely, Howie and Hebda (2018) observed almost no vertical movement in a natural lagg fen across a wide water table range.

The analysis of ΔS/ΔW can also be complicated by lags (hysteresis) in the response of the peat surface to changes in water level, so it is commonly determined by studying 'drying curves', i.e. by quantifying the change in surface elevation versus the change in water table over a period of sustained water level decline (e.g. Fritz et al., 2008). It is also likely that the relationship may to some extent be non-linear, for example a peat may sink rapidly in response to initial water table drawdown but less in response to additional drainage.

Table 4-4 Mean slope and standard deviation of the slope values for the relationship between monthly water level and monthly peat surface level

Land Use	Monthly ΔS/ΔW	Standard deviation
wet grassland	0.015	0.018
arable	0.021	0.006
blanket bog	0.039	0.026
fen	0.044	0.041
plantation	0.045	NA
wet woodland	0.049	0.054
improved grassland	0.059	0.035
raised bog	0.123	0.052

In order to assess the initial ratios of peat surface level to water table depth across all sites the relationship between median monthly surface level and mean monthly water table depth was calculated for each site. Any relationships that were non-significant (i.e. there was no relationship between peat surface level and water table depth) were removed from further analysis. One peat camera, camera 45, was also removed from further analysis. This site, a fen site in the Norfolk Broads, showed a very different relationship between surface level and water table depth, with an almost 1:1 relationship between the two variables suggesting that the peat is floating on the water surface at this site.

Apart from the fen site mentioned above, the site type that on average showed the greatest degree of variation with water level were the raised bogs, with an approximate ratio between peat level and water table depth of 12%, meaning that for every 10 cm drop in water table the peat surface drops by an average of 12 mm. At the other end of the scale are the wet grassland sites, where a 10 cm drop in water table would only result in a 1.5 mm drop in peat surface (Table 4-4). This ratio provides an interesting additional level of information to the peat surface oscillation above. Despite the high vertical oscillation seen in the arable sites there is a low ratio of peat surface drop per unit of water table drop. The large surface motion is driven by the very large variations in water table depth.

Within the semi-natural sites there is variability between locations but with the number of sites and length of data currently available the conclusions that can be drawn on within-category variability remain limited. The raised bog comparison, as mentioned in the peat surface oscillation section, suggests that less historically modified sites generally have a higher ratio of peat surface motion to water table motion (Table 4-5) but further analysis of this metric would benefit from some ancillary peat condition measurements such as bulk density. The blanket bog sites in this study show comparatively low ratios between peat elevation and water level, but at present these sites also show very small changes in water level over time. It should be noted that a number of the more degraded blanket bog locations showed no significant relationship between the peat level and the water level, so further investigation of this metric will be needed.

Table 4-5 Ratio of vertical surface motion versus water table depth for a selection of raised bog cameras

Peat camera	Land use	Monthly ΔS/ΔW
PeatCam_025	Former peat extraction, currently scrub	0.042
PeatCam_026	Former peat extraction, rewetted raised bog	0.077
PeatCam_042	Former plantation, rewetted raised bog	0.065
PeatCam_043	Former plantation, rewetted raised bog	0.103
PeatCam_047	Semi natural raised bog	0.176
PeatCam_048	Semi natural raised bog	0.085
PeatCam_052	Semi natural raised bog	0.202
PeatCam_053	Semi natural raised bog	0.097

Seasonal peak in peat surface elevation

The final metrics listed in Table 4-1 both relate to the timing of peat surface elevation changes. Work by Bradley et al. (2022) in the Flow Country suggests that more degraded bog types may show an earlier (autumn) seasonal elevation peak when compared to good condition, *Sphagnum*-dominated areas which peak during winter. This metric has potential for evaluating condition variations within particular regions and peatland types, but may be more limited when applied at larger scales. For example, fen-type peats may respond on different timescales to changes in groundwater input, while similar peatlands in different parts of the country may peak at different times due to regional variations in weather patterns. Another linked metric is the lag between peaks and troughs in groundwater levels, and the corresponding peaks and troughs in surface elevation, which results in hysteresis in the relationship between elevation change and water table change. This hysteresis appears to be greatest in naturally functioning undrained peatlands (Howie and Hebda, 2018). At a seasonal level this can give rise to the lagged seasonal peaks observed by Bradley et al. (2022), but similar behaviours can also occur over shorter timescales in response to individual dry-wet cycles.

Across most of the measured locations the lowest surface levels of peat occurred during the summer months, or at some sites into early autumn (September). In the most intensively managed sites, where the land use is arable or intensive grassland, the maximum peat elevation is generally seen in winter or spring, with a similar trend in the wet grassland and wet woodland locations. Across the more semi-natural land use types (fen, blanket bog and raised bog) the timing of the seasonal peak is varied though most are in winter or spring. The limited time frame of the analysis period to date precludes more detailed analysis but suggests that there are potential avenues to explore to investigate the differences within categories once multiple years of data are available.

4.3 Summary

As a relatively simple, long-term measure of peat growth and loss, with a direct mechanistic link to drainage depths and the peatland carbon balance, there is no doubt that annual peat elevation change is a valuable metric of peat condition and one that can be readily extracted from the peat camera data. This may be done either by comparing the equivalent period in successive years, or by fitting a linear regression to multiple years of continuous data (sometimes referred to as ‘velocity’, e.g., Marshall et al., 2022). Bearing in mind the strong observed seasonality in peat elevation, and the limited duration of the existing camera time series, we considered that annual elevation change is best measured by comparing successive winter elevation values, because the effects of short-term water table drawdown should be minimised at this time. However, over the time frame of the camera dataset there were many examples of very wet winter conditions in the second year of measurement compared to the first, which have skewed the results, especially where there is relatively large surface uplift. Data from other regions show strong variations in annual net subsidence between wet and dry years (e.g. Evans et al., 2021a), so there is a risk that a single year of elevation change data could be unrepresentative of the long-term rate. The effects of inter-year hydrological variations can be expected to diminish over time – i.e. the measured rate of elevation change should converge on the true long-term rate of peat subsidence or growth – making this a more robust metric, and likely a better predictor of the peat carbon balance, as the length of monitoring increases. However, the use of annual subsidence alone would effectively discard a large proportion of the high-frequency data collected by the peat cameras and therefore reduce the benefits of operating an automated monitoring system versus low-frequency manual monitoring of peat growth using subsidence poles or ‘Eyes on the Bog’ surface elevation rods. It is clear that the short-term dynamics of peat surface motion contain important additional information on peat condition and function, but that extracting simple metrics from complex time series (which vary over timescales from episodic to annual, and which differ between sites) is challenging.

Our assessment of peat surface oscillation from the camera data showed that across the wide range of English peatlands it is not simply the case that good condition peats show a greater surface oscillation than highly modified degraded peats. The most managed peatlands (arable and improved grassland sites) showed the greatest surface motion, due to the greater range of water table depths experienced at these sites. Within peatland types there are differences that may be attributable to variation in peat condition, as well as management history. For example, raised bogs that have undergone restoration from degradation by peat extraction or forestry show greater water movement, and peat surface motion compared to the sites that have remained as raised bog.

Comparison of the ratio of peat motion to water table depth requires further investigation as data collection continues, particularly as more data on peat carbon content and bulk density become available. If the short-term outcomes are representative of the longer-term trend, the balance between absolute surface motion and rate of surface motion per unit of water movement may prove a key metric that can be derived from the time-series to allow more detailed understanding of how quickly (and whether) restored sites return to near-natural functioning.

We observed a tentative relationship between mean annual effective water table depth and peat surface motion. However, the short-term nature of the subsidence estimates at present means that there are outliers caused by annual variability in water levels between measurement years. As such we would recommend that this exercise is revisited in around 3 years (based on evidence from other regions that reasonable subsidence estimates can be made from four years of data) to allow a more long-term subsidence calculation to be assessed for each site and to allow the effects of between-year variation on the remaining metrics to be incorporated into the analyses.

5. Monitoring surface motion from satellite data

5.1 Introduction

Interferometry of Synthetic Aperture Radar (InSAR) is a remote sensing technique for estimating ground surface displacements from radar satellites (Bürgmann, et al.2000; Massonnet and Feigl 1998). Recent developments have included the use of InSAR to monitor peatland surface motion in both time and space, including multiannual subsidence or uplift and annual oscillation of the peat surface level in response to groundwater level variation (e.g., Alshammari et al. 2020; Alshammari et al. 2018; Hrysiewicz et al. 2023; Hrysiewicz et al. 2024; Tampuu et al. 2023). Since open-access satellite radar data covering the entirety of the United Kingdom are available from the European Union’s Copernicus Earth Observation program, the InSAR technique offers the possibility of mapping and monitoring peatland ecohydrological behavior on a nation-wide scale. The Copernicus C-band Sentinel-1 satellite constellation consists of two identical radar imagery satellites (Sentinel-1A and Sentinel-1B) launched in April 2014 and April 2016 respectively. Until the loss of Sentinel-1B in December 2021, Sentinel-1 satellites had a temporal sampling period of min. 6 days (i.e., the revisit time for one satellite is up to 12 days) and at a spatial resolution of about 20 m per pixel.

Hrysiewicz et al. (2024) demonstrated that the accuracy of C-band InSAR on relatively intact to moderately degraded raised bogs is on the scale of a few mm. This accuracy was established by comparing InSAR ground motion data to in-situ measurements of ground motion made by peat cameras located on Cors Caron and Cors Fochno in Wales. Similar validation of InSAR-derived ground motions at other peatland types in the UK is limited to a precise levelling study of two near-natural blanket bog sites in Scotland (Marshall et al., 2022).

5.2 Methods

InSAR method overview

A Synthetic Aperture Radar (SAR) system comprises a transmitter and receiver of microwave radiation. For the Sentinel-1A/B satellites, the wavelength is 5.6 cm, which falls into the so-called C-band of radar wavelengths. The Earth is imaged by the radar from two satellite orbit passes: ascending and descending. Ascending datasets are acquired during the satellite’s track moving from south to north, while descending datasets are acquired during the satellite’s track from north to south. Sentinel-1 satellites are right-looking, which means that the Line of Sight (LOS) of the sensor is from toward the west on the descending orbit pass and is toward the east on the ascending orbit pass. Moreover, the satellite looks at the Earth at an oblique angle (look angle) of about 30-40 degrees from vertical.

Each pixel of a SAR image generated from the satellite sensor contains information on the amplitude and phase of backscattered radar signal. The ***amplitude*** corresponds to the observed power (or intensity) of the backscatter of the radar beam. The ***phase*** corresponds to the position on the wave form at which the return signal arrives at the receiver. The phase of the radar return is directly related to the travel time between the satellite and surface ground target.

Interferometry of Synthetic Aperture Radar (InSAR) refers to the procedure of differencing (subtracting) the phase information in two SAR images of the same area that are taken at different times and usually from different viewing positions. Once the two images have been spatially co-registered with one another, the phase difference at each corresponding pixel is calculated. The resultant image of ***differential phase*** is commonly termed an ***interferogram***. The differential phase values initially contain contributions from many factors, including satellite orbit inaccuracy, atmospheric delays, topography, ionospheric changes, and - importantly - displacement of the ground surface between the acquisition times of the two images (Massonnet and Feigl 1998). Once the other contributions are removed, the remaining differential phase at each pixel is proportional to the variation in distance between the ground and satellites (and so surface ground displacements) between the first acquisition date (reference date) and the second acquisition date.

InSAR time series analysis methods comprise a suite of techniques that estimate the temporal evolution of ground surface displacements. The goal of these methods is to produce a time series of ground motion at each pixel in a suite (or stack) of interferograms. The stack of interferograms is made from SAR images of the same area that are taken at many points in time and that are spatially co-registered with one another. Many different approaches have been developed to isolate reliable pixels and to obtain related displacements (e.g., Casu et al. 2006; Ferretti et al. 2011; Ferretti et al. 2001; Hooper 2008; Hooper et al. 2012; Hooper et al. 2004; Sowter et al. 2016; Sowter et al. 2013; Yunjun et al. 2019). A major advantage of time series methods is that they can be used to minimise the phase contribution from atmospheric delay, which is otherwise difficult to remove in a single interferogram and can be especially significant if ground motion components in that interferogram are subtle/small (Osmanoğlu et al. 2016). Atmospheric effects are non-negligible in the context of the U.K. given the spatially and temporally variable atmospheric moisture levels in the temperate oceanic climate that prevails there (Figure 5-1).

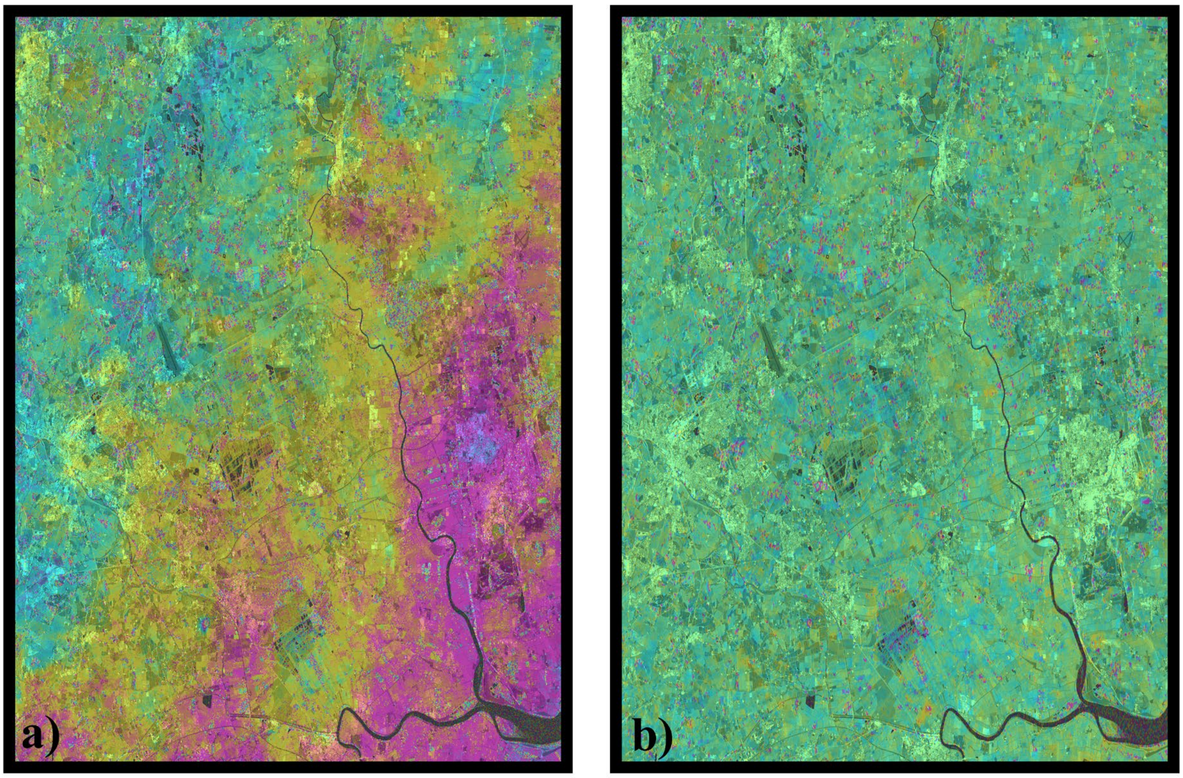


Figure 5-1 Example of atmospheric effects on an interferogram. (a) interferogram containing an InSAR atmospheric phase visible via a fringe. This corresponds to 1 wave cycle of ‘apparent’ displacement. In b), the interferogram has been ‘flattened’ by atmospheric correction. The image is of Somerset in England.

InSAR via Interferometric Point Target Analysis®

Sentinel-1 A/B data was used in Interferometric Wide (IW) mode, between 2015 and March 2024, in both orbital directions (ascending and descending). This allowed the lowest temporal resolution of 6 days over most of the observation period. The selected tracks of the two orbital passes over England are shown in Table 5-1.

For coregistration (the alignment of SAR images), the reference images are in spring 2019 for both passes (ascending and descending). Precise orbits and the SRTM Digital Elevation Model (DEM) (Farr et al. 2007) were used during processing. TopSAR coregistration was performed using the GAMMA® processor (Wegmüller et al. 2015).

After obtaining the two SAR image stacks coregistered with the reference images (ascending and descending) for each site, extraction of displacements from each sub-stack was performed using the Interferometric Point Target Analysis® (IPTA) approach (Werner et al. 2003). The multilooked phases were estimated using a 15/3 factor. Only the pixels with high temporal consistency and high coherence were analysed as part of the IPTA processing (Werner et al. 2003).

Table 5-1 Table of Sentinel-1 tracks

Peat soils	Type	Ascending track	Descending track	Date
Fenn's & Whixall	Raised	30	154	2015 - Mar. 2024
North Pennines	Blanket	132	154	2018 - Mar. 2024
Pollybell	Fen	132	81	2015 - Mar. 2024
Somerset	Fen	30	154	2015 - Mar. 2024
Norfolk Broads	Fen	59	81	2015 - Mar. 2024

In detail, different workflows of IPTA have been applied for each peat-soil type:

- For raised bog at Fenn's & Whixall, an IPTA multi-reference approach was used following that of Hrysiewicz et al. (2024). It uses a combination of "long temporal baseline" and "short temporal baseline" interferogram networks. The term "long temporal baseline" refers to an interferogram formed from two SAR images acquired 1 year apart. The "short temporal baselines" refer to interferograms formed from two SAR images acquired 6, 18, 24, 36 or 48 days apart. A long-term network is needed to constrain the long-term trend of surface motion, whereas a short temporal baseline network is needed to accurately capture the high annual oscillation of peat surface motion typical of raised bogs.
- For the blanket bogs in the North Pennines, a conventional IPTA approach with long temporal baselines was used following that of Hrysiewicz et al. (2023). It differs from the approach on the raised bogs in that only the long-term interferogram network was used. Time series were extracted only from 2018 to March 2024;
- For the former fens (agricultural peatlands), the long-term interferogram network was used to estimate the atmospheric delays. The estimated atmospheric phases were then subtracted from the interferograms (see Figure 7.1). The time series of peat surface displacements were extracted using a *daisy-chain* combination in which only consecutive 6- or 12-day interferograms were used without redundancy of observations: i.e., the uncertainty of IPTA InSAR observation will be very high. In this work, no IPTA InSAR coherence considerations were taken into account when processing for agricultural and fen peatlands. In addition, a detrending was applied to the *daisy-chain* computations considering no linear trends for *in-situ* measurements. Displacement rates should not be analysed.

Unless otherwise indicated, ground surface displacement results are presented as vertical displacement. No interpretation will be made for horizontal displacements: further information can be found in Hrysiewicz et al. (2024). Some Line of Sight (LOS) displacements – into the direction of the satellite – are also presented and can be interpreted in terms of vertical displacements: i.e., negative displacements can be associated with subsidence and positive displacements for uplift. A factor of 1.2 – 1.3 can be used to estimate the magnitude of vertical displacements from the LOS displacements.

The comparison between InSAR-derived results and peat camera data was performed following the estimators defined by Hrysiewicz et al. (2024). Briefly, displacement rates are compared using the root means squared error (RMSE) value. Displacement oscillations are compared by using the Pearson's correlation coefficient and the RMSE: the first estimator quantifies the similarity in the oscillation periodicity, while the second estimator captures the similarity regarding the amplitude of these oscillations.

Advanced Pixel System using Intermittent SBAS (APSIS)®

APSIS (Advanced Pixel System using Intermittent SBAS) is a system for the determination of land motion characteristics from the processing of stacks of satellite Interferometric SAR (InSAR). APSIS was invented in 2012 at the University of Nottingham by Dr Andy Sowter and is currently Patent Pending in Europe and North America.

The motivation behind the development of APSIS was to improve the spatial coverage of conventional InSAR. Conventional InSAR methods are commonly based upon the exploitation of persistent, or permanent, scatterers that exist naturally in the landscape. These scatterers are fixed in position and give a strong backscatter and phase response in all SAR observations. Typically, they are hard targets such as rocky outcrops, buildings and infrastructure. This is the basis of almost all conventional InSAR techniques. Natural targets in vegetated terrain generally fail the requirement of being 'persistent' scatterers as they are almost constantly changing and, hence, conventional InSAR results in poor coverage over rural areas. Some improvements in coverage can be made if the requirement for backscatter response is relaxed in favour of consistently high correlation, or coherence, between observations but this can be challenging over many terrain and vegetation classes.

For each of the five project sites, a stack of ascending and descending orbit Sentinel-1 data was processed using APSIS. In each case, the period covered was:

- Somerset Levels: April 2021-March 2024
- Pollybell: March 2019 – March 2024
- North Pennines: March 2019-March 2024
- Norfolk Broads: April 2019-April 2024
- Fenns Whixall: March 2019-March 2024

The products output from the APSIS processing are in a raster (GeoTIFF, format) provided in a UTM coordinate system. Also, the processed ascending and descending LOS results were also resolved into Up-Down and East-West directions using stereo triangulation.

Regarding the peatland focus of this project, the APSIS processing was modified slightly in an attempt to improve the quality of the results. For example, we have found in previous projects that the selection of a good reference point to use as a benchmark for the surveys is critical. Such a site must be a permanent strong scatterer on the ground and is usually a building or rocky outcrop. This is the case for all InSAR surveying. However, some of the sites here are remote, particularly the North Pennines, with many areas that could be mistaken for hard targets. Therefore, much more care was taken to find a reference point than is usual. Additionally, we used a relatively short temporal baseline for the selection of pairs in order to improve the capability to detect seasonal signatures. Because APSIS uses many interferometric pairs, the effect of a long baseline can tend to reduce the ability to detect such signals.

European Ground Motion Service (EGMS)

As a derived product based on the Sentinel-1 dataset the European Ground Motion Service (EGMS) provides a stand-alone InSAR time series updated annually, currently covering the time period 2018 – 2022. This provides England-wide coverage at a 100 m pixel resolution for the vertical ground surface displacement product.

5.3 Results

Spatial coverage

Eight peat cameras were installed on North Pennines blanket bog. This study area represents a surface area of 3,000 km^2. The peat cameras are installed on various vegetation types (*Calluna* and *Molinia* dominated bog), with some eroded areas of the bog. The elevation ranges from 400 m to 800 m, which means that there can be extended periods of snow coverage during winter.

After IPTA InSAR processing, the coverage is relatively high, so that each peat camera can be linked to the IPTA InSAR data. Over most parts of the blanket bog, vertical displacement rates show stability and subsidence < 10 $mm \cdot yr^{-1}$ over the observation period (see Figure 5-2 a-d). It is worth noting that it was decided to remove images with snow coverage to avoid any loss of coherence and any processing artefacts. The time series obtained therefore mainly cover the spring, summer and autumn periods between 2018 and March 2024.

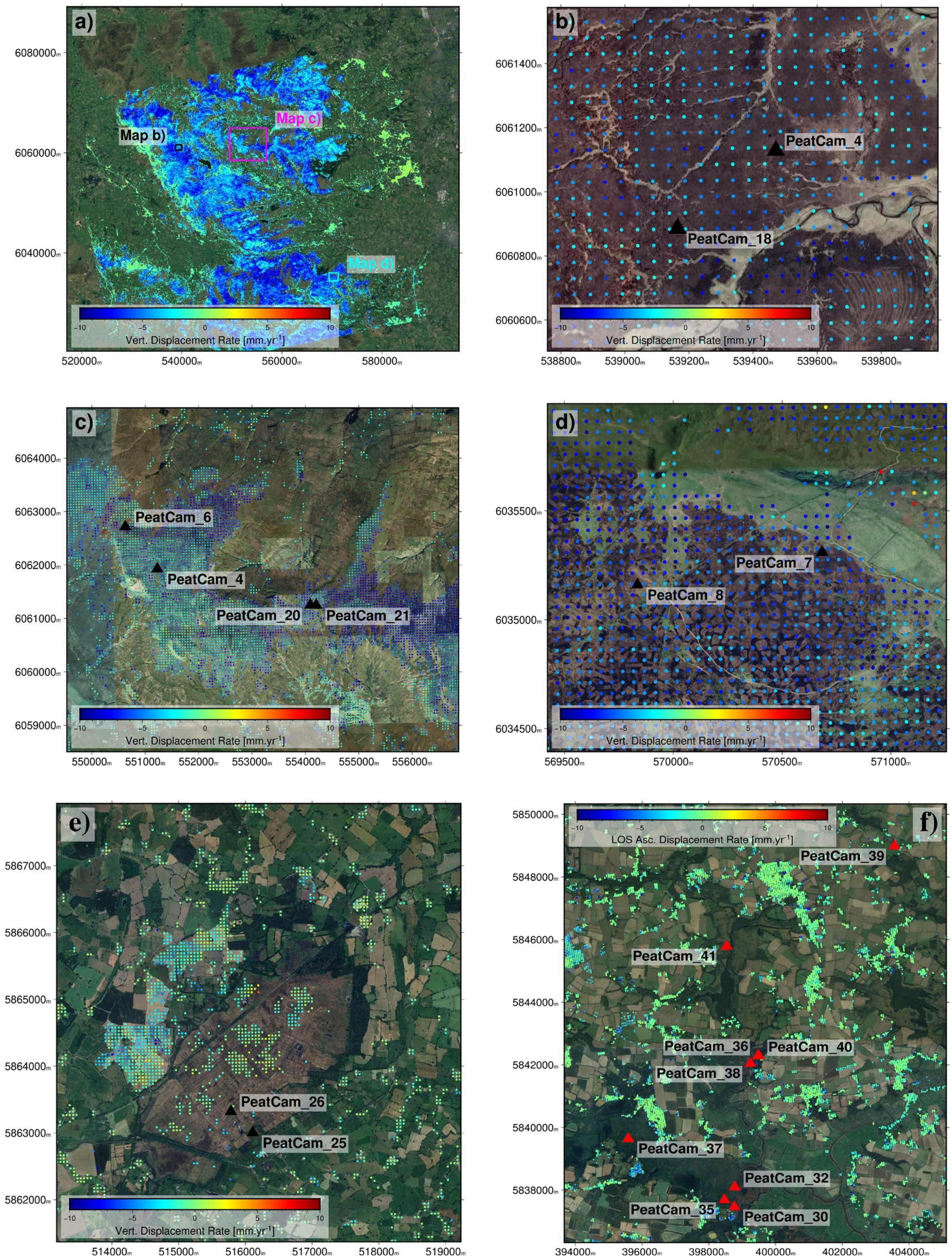


Figure 5-2 Maps of vertical displacement rates for example camera locations, with the locations of the peat cameras shown by black or red triangles. a-d) North Pennines. e) Fenns & Whixall and f) Norfolk Broads. Coordinates in EPGS:32620. Basemap Data: Google, Landsat / Copernicus / ©2024 TerraMetrics / ©2024 Airbus / ©2024 Maxar Technologies / IBCAO

Full coverage using IPTA methods was not achieved at Fenns & Whixall because larger areas that do not meet the threshold for InSAR quality measurements (i.e. phase and coherence uncertainty). The calculated points are mainly located at the centre of the bog, with a few isolated observation points towards the south-west. The peat surface vertical displacement rates are close to zero: i.e., the peat surface is relatively stable in the long term. However, some points in the south-west appear to be subsiding during the observation period (Figure 5-2 e).

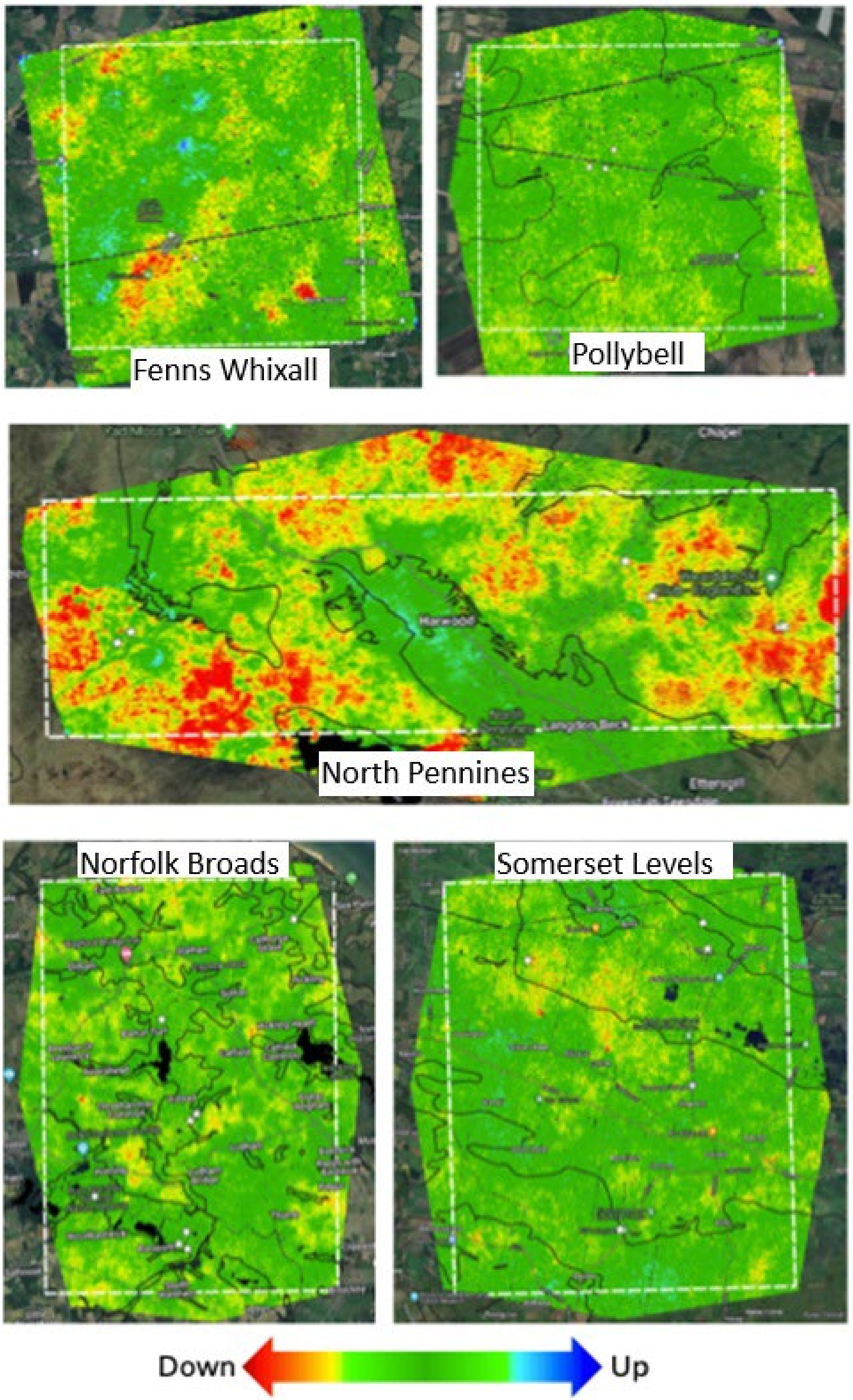


Figure 5-3 Average Up-Down velocity shown for each of the five sites. The white dashed boxes are the required areas of interest and the black contours are the extent of peat areas from the England peaty soils layer. Note the latter is not shown for Fenns & Whixall as the peat layer does not cover Wales. Google Maps.

For all study sites in fenlands, agricultural areas and wet woodlands, no observations from IPTA InSAR time series analysis could be linked to the peat cameras (Figure 5-2 f). This can be explained by low IPTA InSAR coherence over these vegetation types. Thus, an investigation of *daisy-chain* results was performed to identify the IPTA InSAR capability.

In comparison, in each of the areas of interest APSIS InSAR was able to cover at least 98% of the area (Figure 5-3). It is worth noting that there are occasionally diagonal lines of missing data from the surveys, most obvious on the Fenns & Whixall and Pollybell results. These lines, usually only one pixel wide, sometimes occur at the burst boundaries within the input Sentinel-1 data products and are beyond the control of the APSIS process.

Peat surface motion accuracy

Fenns & Whixall

The two cameras at Fenns & Whixall are in contrasting habitats: camera 025 is in an area of small trees on the edge of the bog dome, while camera 026 is in a recently rewetted area with open, low-growing vegetation. The APSIS data showed weak agreement with both cameras, while the IPTA InSAR could not provide time series data to compare with camera 025 but showed good agreement with camera 026 (Figure 5-4).

The tree cover at camera 025 likely limited the use of InSAR to determine surface motion at this site, while as seen in previous work (Hyrsiewicz et al., 2024) the IPTA InSAR analysis works well over the open raised bog, reproducing both the vertical displacement at the location and the timing of peaks and troughs in the peat surface motion, as further shown in the correlation analysis (Figure 5-5).

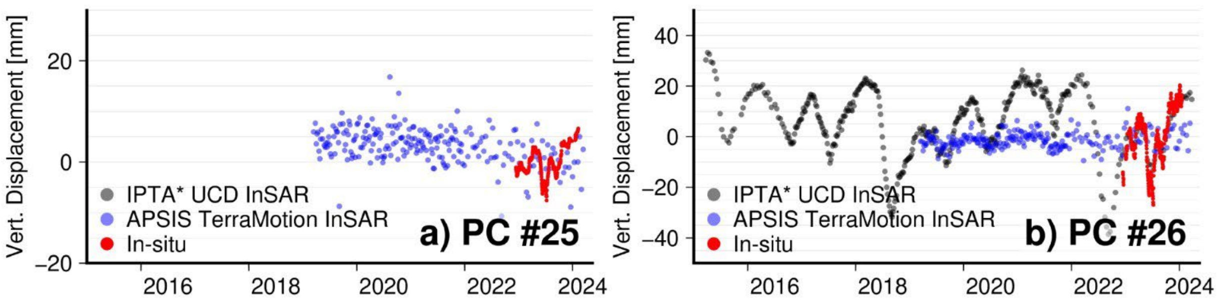
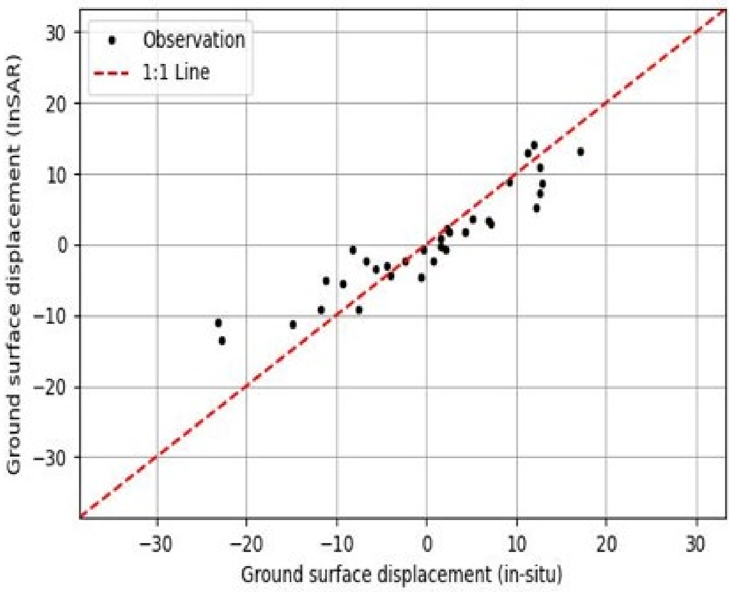


Figure 5-4 Comparison of InSAR time series with camera surface motion for peat cameras 025 and 026 at Fenns and Whixall Moss



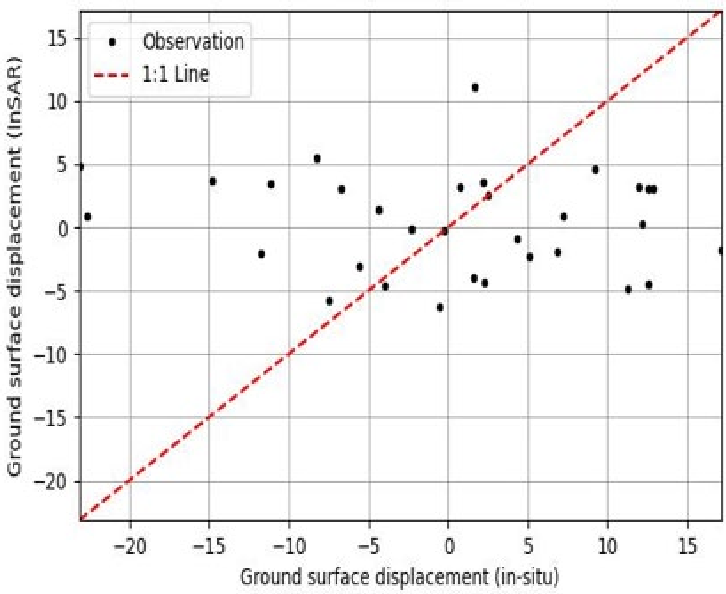


Figure 5-5 Time series correlation with measured data for IPTA InSAR (top) and APSIS InSAR (bottom) for camera 026 the raised bog site at Fenns and Whixall Moss

North Pennines

The peat surface motion at the North Pennines sites is characterised by small amounts of vertical displacement each year (less than 5 mm), the rate of which is generally well reproduced by both InSAR methods. However, when looking at the historic surface motion patterns predicted by the two InSAR methods there are some distinct differences between the patterns. The APSIS InSAR is noisier, with less of a defined seasonal pattern (Figure 5-6).

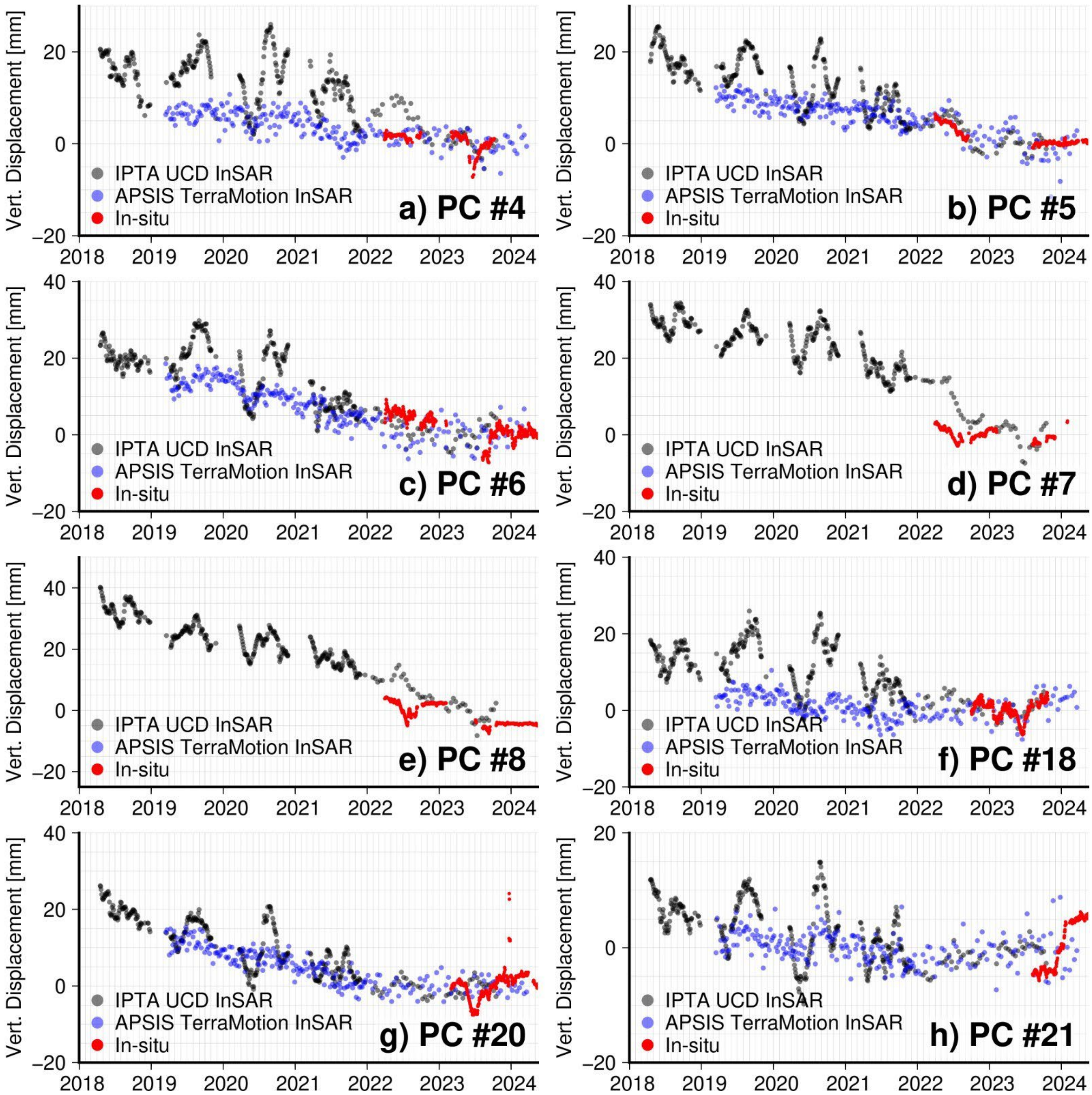


Figure 5-6 Comparison of InSAR time series with camera surface motion for peat cameras in the North Pennines. Gaps in the IPTA record are where there was snow coverage.

Although the ground data are limited, the camera data to date do not support the idea of “noisy” within-year motion, but do seem to suggest a more defined seasonal pattern. Correlation between measured and modelled surface displacement is more “noisy” at these blanket bog sites (Figure 5-7). However, with the very small vertical displacement at this site, small variation within a pixel could be amplified.

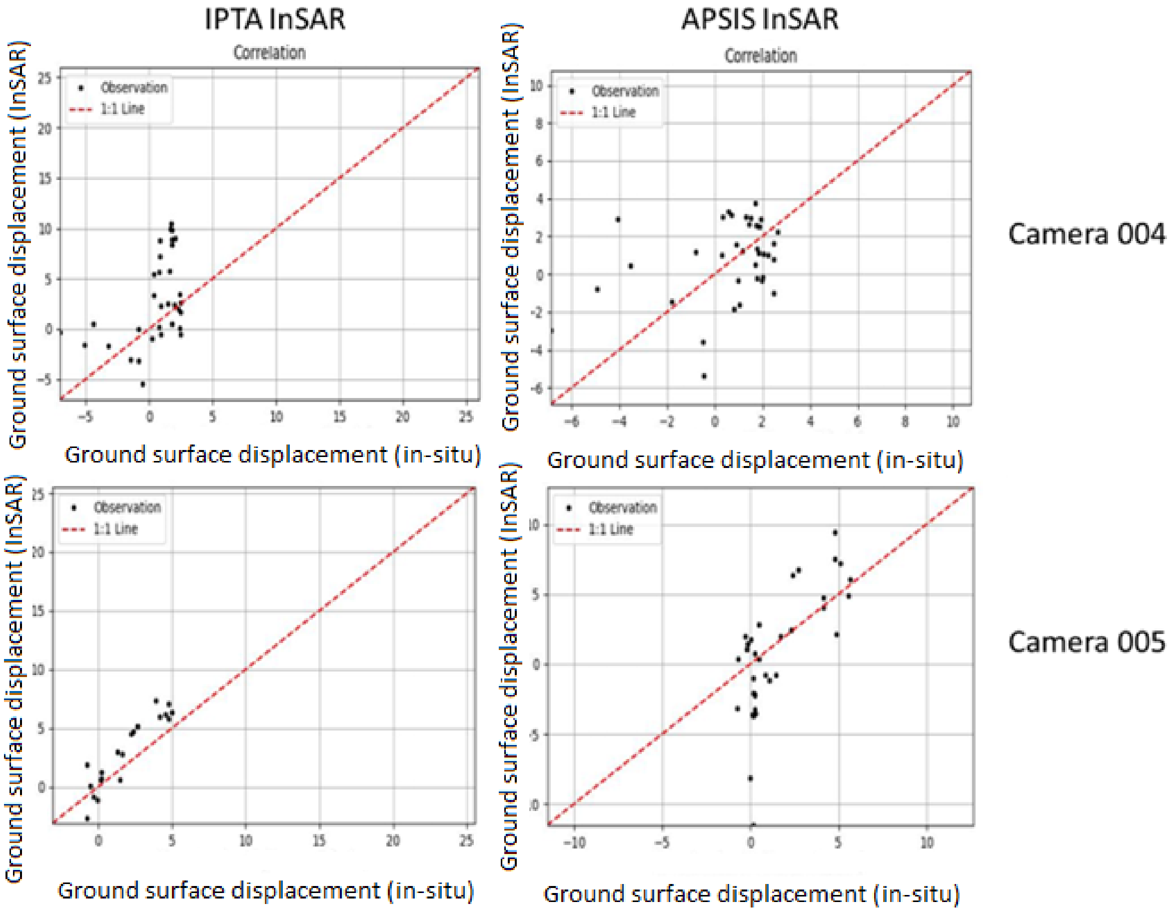


Figure 5-7 Correlation between measured and modelled surface motion for IPTA and APSIS InSAR (left and right graphs) and cameras 004 and 005 (top and bottom graphs)

Somerset Levels

Across the Somerset Levels three of the cameras were on permanent grassland, while the fourth was in tall vegetation fen. A large summer oscillation appears for each in-situ time series of displacements (± 20-30 mm). The IPTA InSAR-derived ascending and descending time series are consistent and the vertical displacements compare well with in-situ measurements. The average correlation is 0.67 with a RMSE of 18.48 mm. Regarding the use of daisy-chain processing, a good agreement is observed for this region, except for peat camera #13 for which the amplitude of oscillations is not similar to in-situ measurements. However, the temporal behaviour is consistent (i.e., small amplitude in summer 2023). At these sites the APSIS InSAR had a weak relationship with the camera data and did not reproduce the timing or amplitude of seasonal peaks in surface motion, or the overall vertical displacement. The Daisy-chain method showed good reproduction in the timing of seasonal peaks in surface motion, while the accuracy of the amplitude varied from site to site, with camera 14 showing the best relationship between modelled and measured data (Figure 5-8 and Figure 5-9).

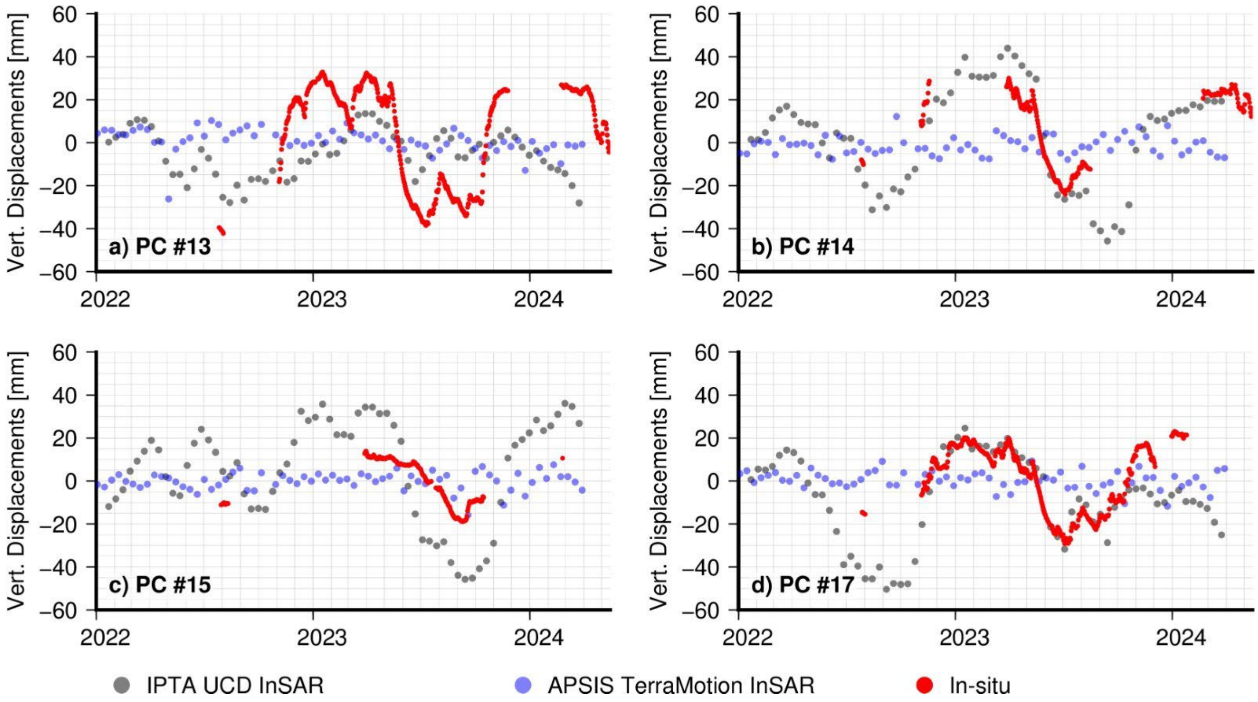


Figure 5-8 Comparison of InSAR time series with camera surface motion for peat cameras in the Somerset Levels

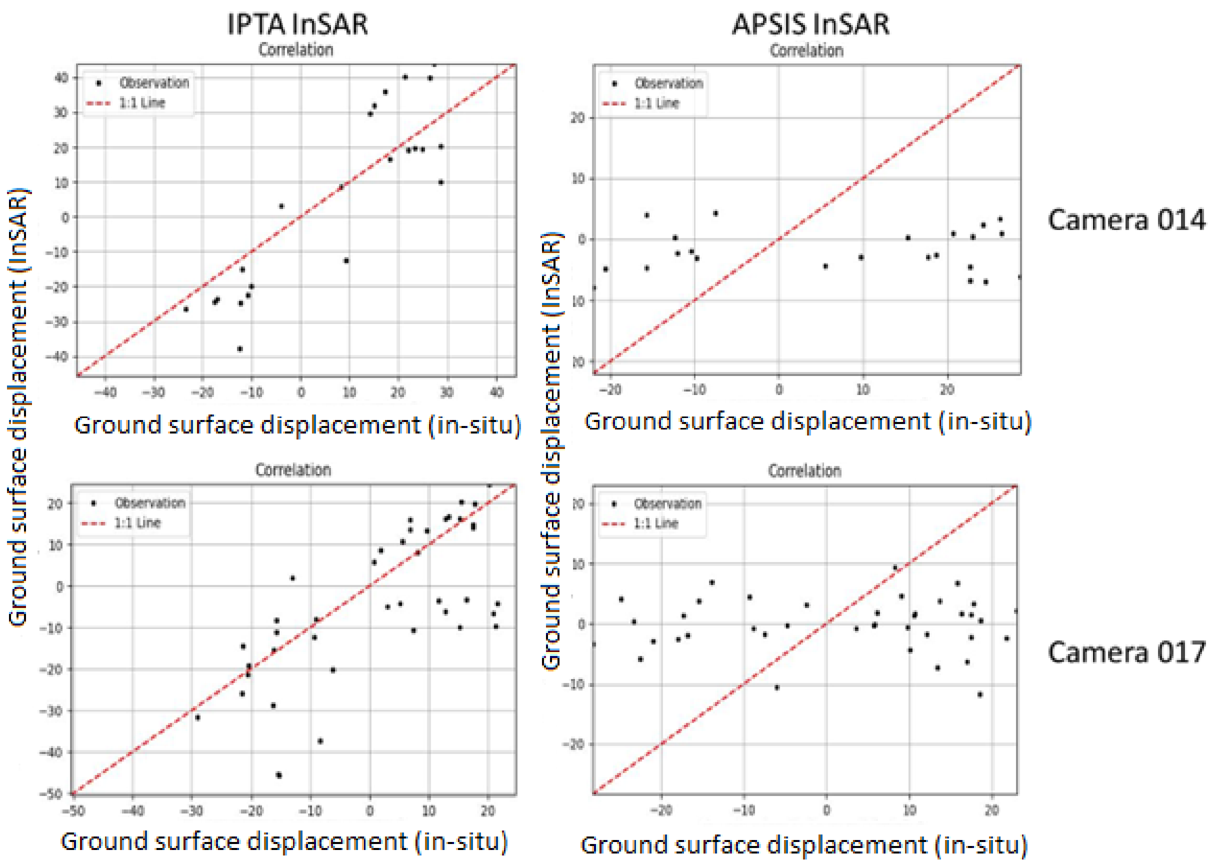


Figure 5-9 Correlation between measured and modelled surface motion for IPTA and APSIS InSAR (left and right graphs) and cameras 014 and 017 (top and bottom graphs)

EGMS

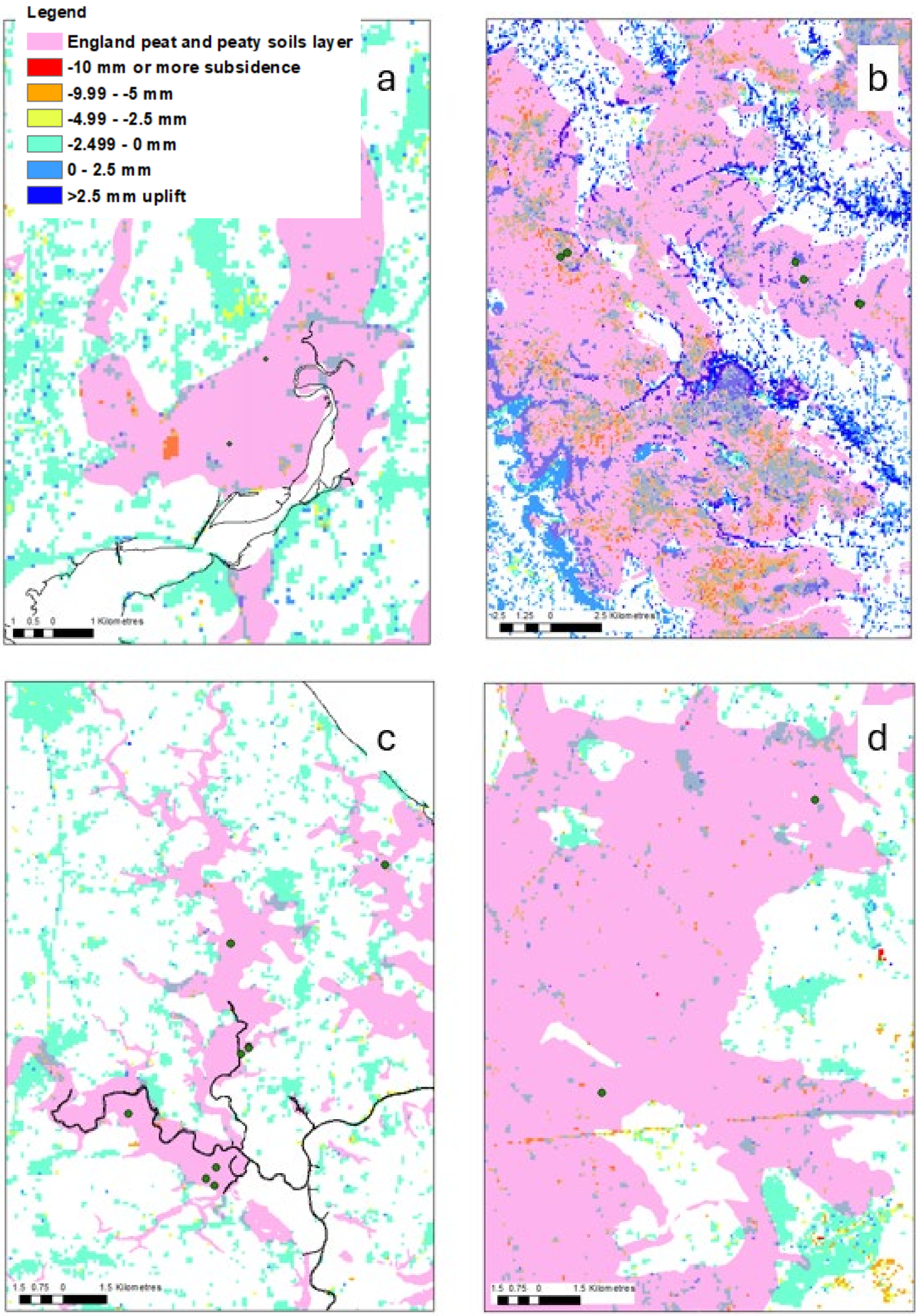


Figure 5-10 EGMS data (2018 – 2022) data coverage across England showing annual vertical displacement in mm for four example areas of England: a) Foulshaw Moss raised bog; b) Moorhouse blanket bog; c) Norfolk Broads fens; d) East Anglian Fens (primarily arable farming). EGMS data used is licensed under CC BY-SA 3.0 IGO.

The EGMS dataset currently covers a defined time slice from 2018-2022, though there are plans to update annually, with each update covering a 5 year time slice (https://land.copernicus.eu/en/news/contract-signed-for-new-egms-updates). This should allow for continued temporal use of the dataset. However, spatial coverage of peatland areas in England is poor, especially in areas with lowland peat under agriculture, grazing and semi-natural vegetation (Figure 5-10). Coverage is slightly improved in the upland blanket bog habitats of the north Pennines and Border Mires (Figure 5-10). Overall, 22% of the England peaty soils layer is covered by the EGMS dataset. This 22% is concentrated in upland blanket bog areas, though even at these locations coverage is insufficient to provide spatially complete coverage of the peatland landscape.

5.4 Discussion

InSAR results for raised bogs

The IPTA InSAR results obtained for Fenns & Whixall bog are consistent with the study of Hrysiewicz et al. (2024) regarding InSAR results and relationships with groundwater levels. Although IPTA InSAR coverage[1] is partial on this bog, better spatial variability of peat surface displacements can be acquired via IPTA InSAR, without significant degradation in the accuracy of displacement results.

APSIS derived InSAR provided full coverage of the raised bog area but was unable to replicate the temporal trends seen at the camera locations during the time period that the cameras were operational at the site. Comparison of measured vs modelled surface motion showed little relationship, suggesting that the APSIS InSAR method is not qualitatively detecting the trends as well as not quantitatively matching the ground data (Figure 5-5).

InSAR results for blanket bogs

Although the coverage of IPTA InSAR is relatively good on the blanket bog, it does not capture the annual behaviour of peat surface displacements. First, the periodicity of annual oscillations may be opposite (i.e. higher in summer) and have different amplitudes. APSIS InSAR has good spatial coverage over the blanket bog locations but also does not fully capture the temporal trends. This could be explained by the low (compared to InSAR noise) amplitudes of peat surface displacements and the difficulty of minimising atmospheric delays over large areas.

[1] Recent – between 2017 and 2022 – restoration work was carried out on Fenns & Whixall: i.e., contour bunding. This could explain the loss of InSAR coherence for several parts of the bog and should be confirmed by further investigations.

InSAR observations for agricultural and fen peatlands

APSIS InSAR had good spatial coverage over these sites but did not capture the quantitative temporal trends in surface motion.

Agricultural and fen peatlands are the most challenging targets for InSAR applications. IPTA InSAR peat motion datasets were relatively consistent with peat camera data for Somerset (permanent grasslands) but could not be validated for Pollybell or the Norfolk Broads. One of the main challenges on these peat soils is InSAR coherence. Although InSAR coherence oscillates due to changes in soil moisture on raised bogs (Hrysiewicz et al. 2023; Hrysiewicz et al. 2024), IPTA InSAR coherence on fens is low (Figure 5-11). Even if IPTA InSAR processing increases coherence, they drop to a low value during summer (dry) periods, meaning that interferograms are very noisy.

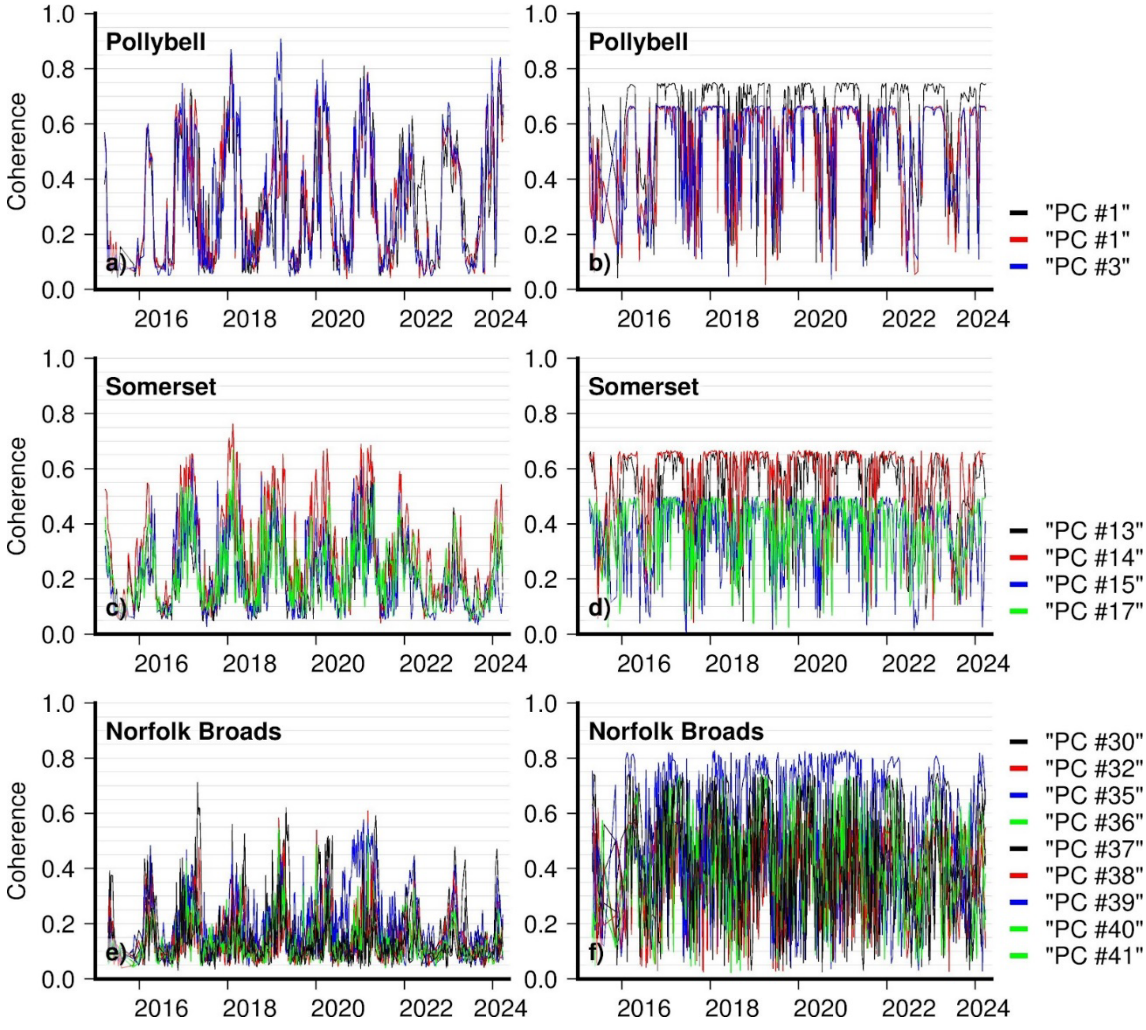


Figure 5-11 "Time series" of ascending IPTA InSAR coherences, i.e., quality of InSAR phase between 0 (poor) and 1 (high) for agricultural and fen peatlands. The first column corresponds to the InSAR coherences computed from the complex reference and secondary images. The second column corresponds to the InSAR

coherence computed from the interferograms after processing. The secondary dates of the interferograms are used for plotting.

In the agricultural and fen peatlands the noise of each interferogram causes errors during the unwrapping step and induces shifts in the time series of displacements. This explains why the oscillations are more significant because the InSAR phase is weakly constrained during summer periods (because of low coherence). To address this issue, larger multi-looking windows (average of InSAR phase values) can be used: i.e., contextual data (proposed from Conroy et al., 2023). In this case, the phases are averaged regarding the ground characteristics: e.g., same farmlands, etc. For Pollybell, the statistical values are improved: average Pearson's coefficient of 0.61 (previously 0.20) and RMSE of 8.67 mm (previously 10.58 mm) (Figure 5-12). Using a peat camera as reference for displacements does not improve the results much (Figure 5-12). Indeed, the challenge remains unchanged: i.e., it is an issue with the unwrapping of interferograms in a context of intense noise.

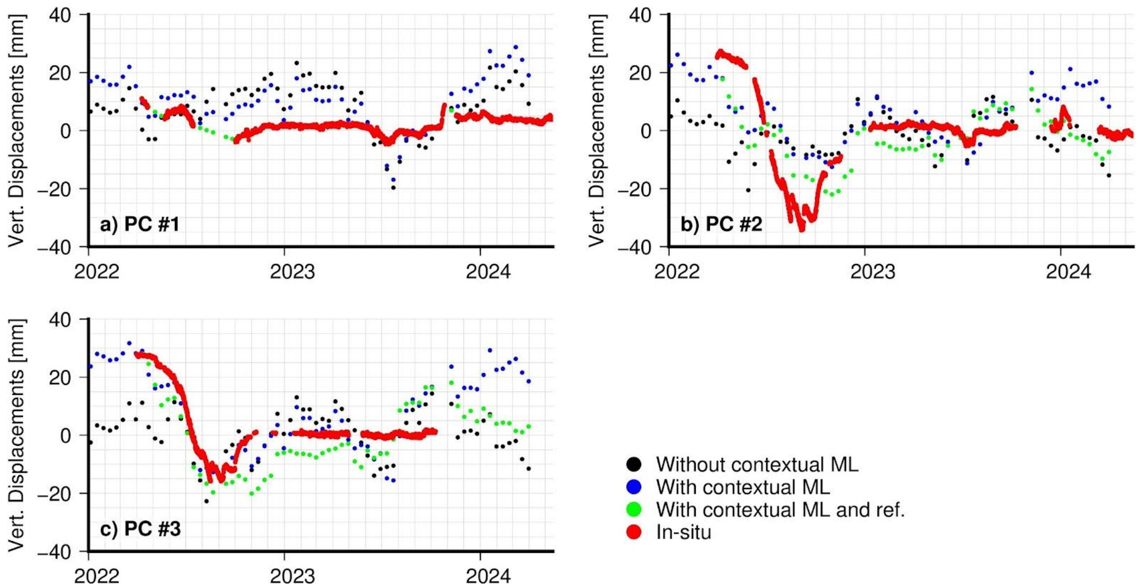


Figure 5-12 Time series of vertical displacements for Pollybell with contextual multilooking and PC #1 used as reference

A solution proposed by Conroy et al. (2023) for Dutch grassland fields uses various contextual data (i.e., cadastral data, soil map, groundwater data, meteorological data, etc.) to conduct the unwrapping and reconstruction of displacements time series, using machine-learning models. Since the problem is related to InSAR phase noise, this solution needs to be tested for the targeted agricultural and fen peatlands for the study sites of this project. However, low displacement changes are expected to be complex to estimate with any methodology (without and with contextual data) because the amplitude of the noise will be larger than the displacements (i.e., for Norfolk Broads).

5.5 Conclusions and Recommendations

At present none of the InSAR methods tested provide a ready to operate solution to the question of how to develop a nationally consistent monitoring strategy to quantify the surface motion of peatlands across all peatland condition classes. The APSIS based InSAR has demonstrated large scale mapping potential for blanket bogs in Scotland (Alshammari et al., 2018, Marshall et al., 2022), whereby the trends in measured amplitude are used to classify pixels into defined condition classes. However, quantitative reproduction of peat camera measured surface motion has not been demonstrated in English peatlands in this study. IPTA InSAR allows accurate quantification of the surface motion in raised and blanket bog sites where spatial coverage is sufficient, but methods to date have not demonstrated success over fens, wet woodlands and more intensively managed peatland landscapes.

This chapter has provided an overview of 2 methods of InSAR mapping (IPTA and APSIS) and their results on three types of peat soils: (1) raised bog; (2) blanket bog and (3) agricultural and fen peatlands. For raised bogs IPTA InSAR has incomplete spatial coverage at the tested location but where data is available there was a close relationship between modelled and measured surface motion, while APSIS InSAR did not demonstrate a quantitative link between measured and modelled surface motion. At the blanket bog locations, measured vertical motion in the peat surface was much lower and showed some relationship with both the IPTA and APSIS InSAR results. In the agricultural and fenland locations there was a limited relationship between IPTA InSAR and measured surface motion, although the methodology is in its relatively early stages at present. There was little quantitative relationship between APSIS InSAR time series and the measured data.

Comparisons in this chapter are between point location measurements from the peat cameras and from the more broad-scale pixel based InSAR data. A future recommendation would be to check the extent to which these point camera measurement are representative of the wider scale surface motion, although the generally high coherence between different cameras in the same land-use within regions such as Somerset suggests that the extent of spatial heterogeneity in peat motion is unlikely to be great enough to explain weak relationships between InSAR and camera data.

It should be noted that this work was carried out with the C-band Sentinel-1 sensors and needs to be compared with the new L-band satellites: i.e., NISAR (launched in 2024/2025), ALOS-4 (launched in July 2024), and TanDEM-L (launch planned). The wavelength of L-band SAR is larger (23 cm vs. to 5.5 cm in C-band) which should increase InSAR coherence. This means that the accuracy of InSAR-derived displacements could be reduced, but data may be less sensitive to noise associated with vegetation, which should increase the spatial coverage.

6. Monitoring greenhouse gas emissions from surface motion

6.1 Introduction

An important aspect of peatland monitoring, particularly as regards national peatland reporting, is the greenhouse gas (GHG) emissions from peatlands. Conceptually the approach currently used to incorporate GHG emissions from peatlands into the UK GHG inventory follows the emission factor approach. This takes the estimated peatland area within each condition category multiplied by an associated emission factor. In the UK, emission factors at Tier 2 level (i.e. nationally specific emission factors derived from analysis of regionally relevant GHG flux data) were first developed in 2017 (Evans et al., 2017) and updated in 2023, incorporating additional data published in the intervening 6 years (Evans et al., 2023).

Recent analysis of GHG flux data has shown the close link between GHG fluxes and mean annual water tables (Evans et al., 2021b), providing the possibility that if water table depths could be estimated at a large enough scale, then a modelling approach to GHG emissions reporting could be developed based on measurable characteristics of peatland areas beyond their broad condition category.

Section 5 of this report shows that InSAR modelling, while not able to produce estimates of surface motion across all land use types, seems to provide an accurate analogue of surface motion for raised bogs and to lesser extent blanket bogs, suggesting that there is potential to be able to map surface motion at scale in some peatland types. Similarly, Section 4 shows that there is a relationship between annual surface motion and annual water table depth across the peat camera sites allowing us to develop a potential relationship between *in situ* measured subsidence and GHG fluxes based on the equation in Section 4, and the equations published in Evans et al. (2021b).

This chapter compares the GHG emissions estimates from camera locations based on annual subsidence values and annual water table depths to the current GHG emissions factors for that peatland type and, where available, from measured GHG flux tower data.

6.2 Methods

The annual effective water table depth (i.e. whichever is the shallower of the water table depth and the peat depth) and subsidence rates are available for a subset of 24 of the cameras, across the range of land use types. In this section we use the equations published in Evans et al. (2021b) to estimate carbon dioxide flux (net ecosystem productivity or NEP) from the sites based on the measured water table (Equation 3). These are compared to existing emission factors for peat soils in the UK from Evans et al. (2023). Equation 1 in Section 4.2 linking subsidence with water table depth was incorporated into the carbon dioxide equations from Evans et al. (2021b) as shown in Equation 4. This allows us to predict carbon dioxide flux from subsidence.

Equation 3: Original Net Ecosystem Production (NEP) calculation from Evans et al. (2021)

$$NEP = (0.1341 * WTD - 1.73) * 44/12$$

Equation 4: NEP with the water table substituted for subsidence

$$NEP = \left(0.1341\left(\frac{0.49 - SUBS}{0.0173}\right) - 1.73\right) * 44/12$$ (NEP with the water table substituted for subsidence)

Measured GHG flux data was collated from the UK GHG flux network latest datasets. A subset of peat cameras are co-located with GHG flux towers measuring continuous carbon dioxide fluxes between the ground and the atmosphere, of which three had data available for the same time period as the peat cameras. These continuous measurements are converted to annual fluxes.

6.3 Results

The mean estimates of CO_2 flux modelled from the effective annual water table depth are shown in Figure 6-1. There are currently no equivalent emission factors for plantation forestry, wet grasslands and wet woodlands. These results show that estimated emissions from improved grasslands closely match CO_2 emission factors. Arable sites have lower estimated emissions compared to the published emission factors, though the arable camera locations are all in areas of borderline wasted peat, i.e. where less than 40 cm peat remains due to past decomposition and subsidence, though the location of the peat camera at each site is in an area where 40 to 60 cm peat remains. The CO_2 emission factor for crops on wasted peat is 15.98 t CO_2 ha^{-1} yr^{-1}, which is closer to the estimated CO_2 emissions at these locations, suggesting that they are acting more like wasted peat sites than deep peat sites.

The blanket bog camera locations with sufficient time series data for GHG estimation are all in areas of modified semi-natural bog, hence the modelled emissions are compared to the modified semi-natural bog emission factor. Modelled CO_2 emissions are higher than the emission factor at these sites and are similar to the emission factor for eroding bog (5.44 t CO_2 ha^{-1} yr^{-1}), showing that the modelled results are within the range of variability seen in the UK GHG Inventory emission factors.

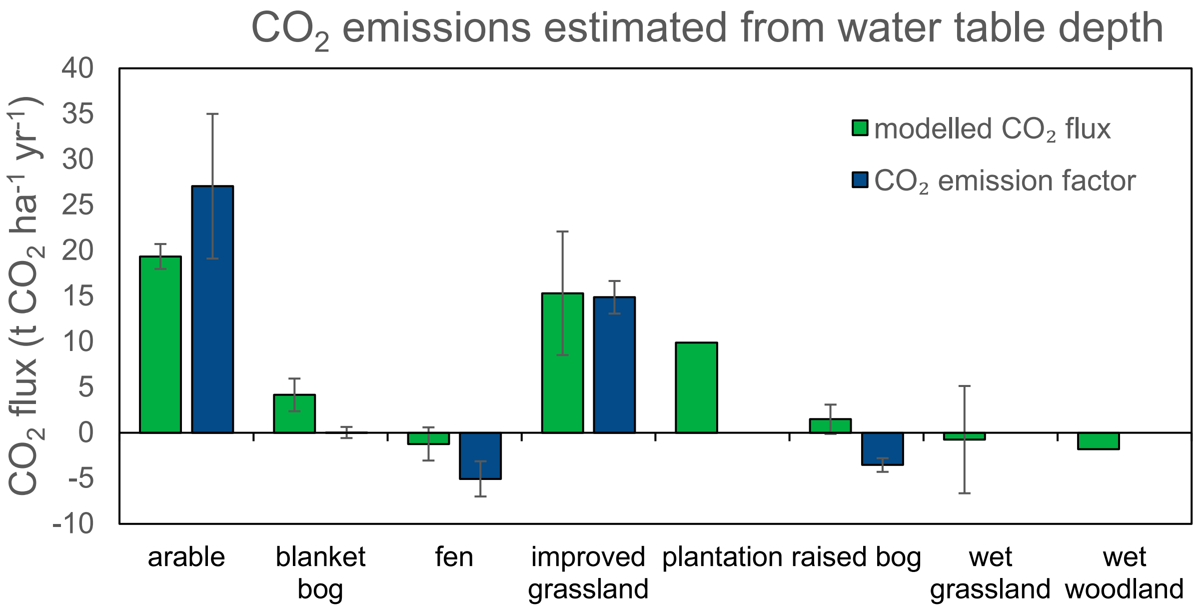


Figure 6-1 Modelled CO_2 fluxes from effective water table depth measured by peat cameras compared to emission factors for UK peatlands. Results are shown as the mean ± standard error for both modelled fluxes and emission factors.

Three of the raised bog sites in this study have deeper water table values than would be expected. This is likely to be due to their past management history where disturbance has left the bog less intact. This has led to them being estimated to be small sources of CO_2. Without site level measurement of GHG fluxes at these locations we cannot be sure whether the sites are sequestering or emitting CO_2 at present.

There are no concurrent flux tower data for any of the semi-natural peatland sites for direct comparison, though historical data from Moor House suggests that this site has been a CO_2 sink in the past, despite measured water table depths in this work suggesting that the site is currently a small net source of CO_2. The blanket bog in this area is, however, quite heavily modified, with erosional features including gullies nearby.

At present, three of the locations have concurrent flux tower and peat camera data, though more will become available over the coming year as additional flux measurements and cameras are co-located in the Defra funded Lowland Peat 3 project. CO_2 fluxes estimated from water table depth closely match measured fluxes at Stretham (Figure 6-2), but over-estimate at the Great Fen site, and to a lesser extent at Pollybell.

These results suggest that water table depth measurements can provide a valid low-cost estimate of CO_2 fluxes from peatlands, though further comparison with measured fluxes are needed to fully demonstrate the validity of the methodology.

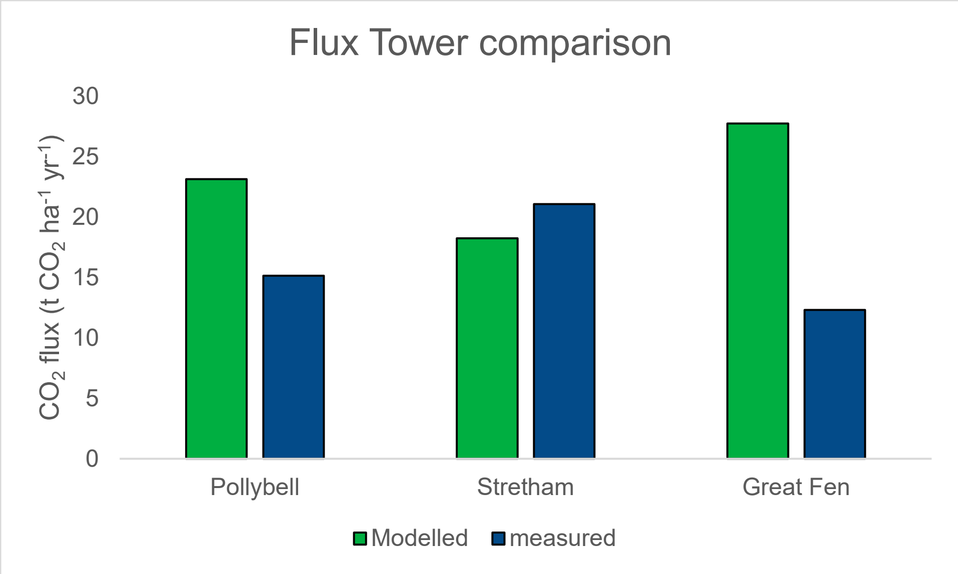


Figure 6-2 Flux tower comparison with modelled data

One of the initial hypotheses for this work was that surface motion could be used as the input for calculating CO_2 fluxes (as shown in Equation 4). As an intermediate step in testing this hypothesis we compared the modelled from subsidence and measured annual effective water table depths (Figure 6-3). The relationship between measured and modelled water table does centre on an almost 1:1 relationship, but at present, due to the variations in subsidence estimates that have resulted from short-term variations in winter water levels, there is a high degree of variation around the regression. Only 5 of the 24 sites showed a difference between measured and modelled effective annual water table depth of less than 10 cm: the Moor House blanket bog site (camera 4), the Stretham arable site (camera 10) and three of the Norfolk Broads fen sites (cameras 27, 38 and 39). When using these sites to estimate CO_2 fluxes they showed the expected outcome with highest emissions from the arable site and lowest from the fen sites (Figure 6-4). As discussed previously, the influence of inter-annual 'noise' in the subsidence data is expected to decline as the peat motion time series increase in length.

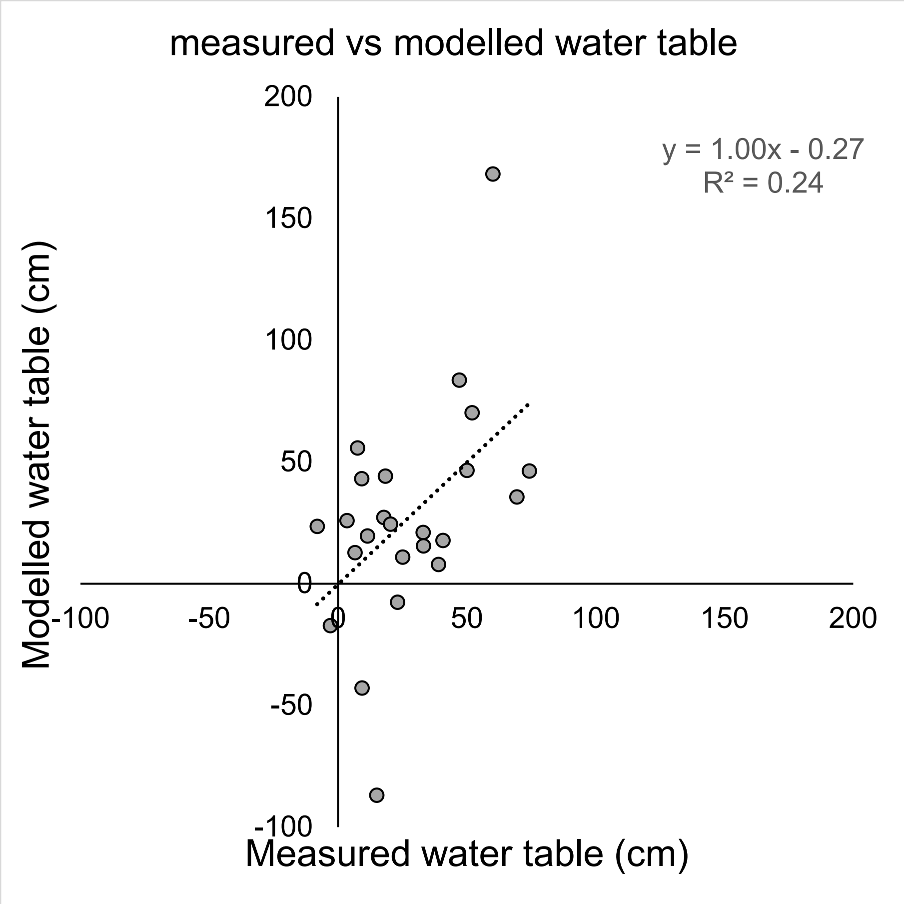


Figure 6-3 Comparison of modelled from subsidence versus measured water table depth

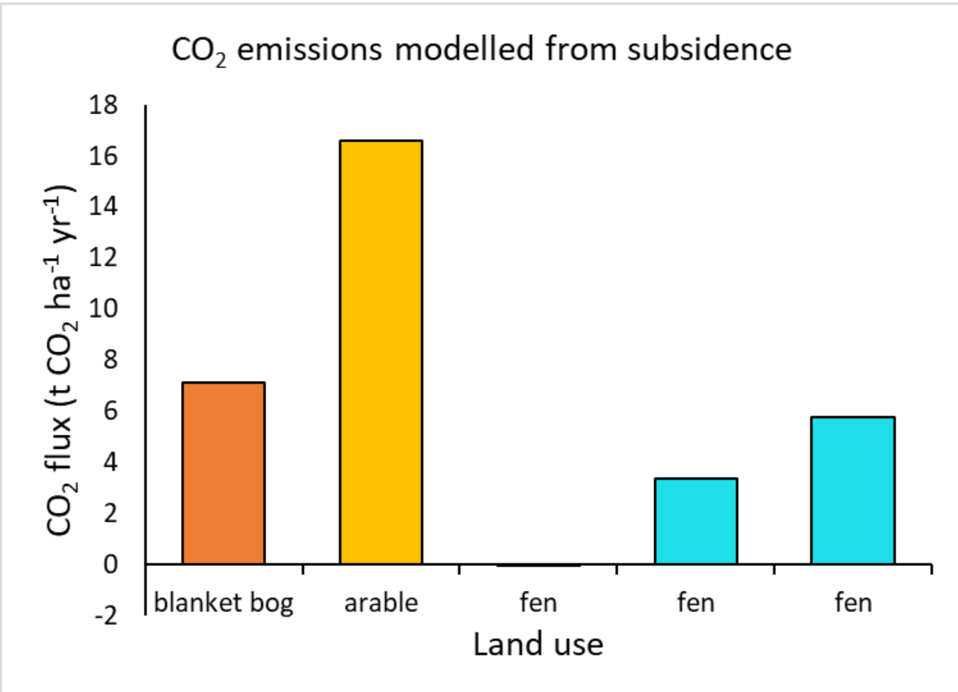


Figure 6-4 CO_2 emissions modelled from measured annual subsidence

6.4 Conclusions

This assessment suggests that CO_2 fluxes can be broadly modelled from the measured annual effective water table depth across the range of peatland types measured in this work. This finding is in line with previous literature (e.g. Evans et a., 2021b). The findings are also in broad agreement with the values and uncertainties associated with CO_2 fluxes as reported in the UK GHG Inventory for peatlands.

Where the present dataset has more limited utility is to understand whether we can use subsidence to model water table depths and hence CO_2 fluxes. The current calculations of subsidence from the peat camera time series are based on the difference between elevation between winter year 1 and winter year 2. This period was significantly affected by short-term differences in water tables caused by the wet winter 2023/24, with many sites showing uplift values that are not related to peat growth but are an effect of short-term swelling. Therefore, we do not yet know if subsidence (measured via cameras or InSAR) can be used to estimate GHG flux for peatlands in England. However, this approach has been widely used (based on manual subsidence data) for other regions, including the calculation of emission factors for tropical peatlands in the IPCC Wetlands Supplement (IPCC, 2014), suggesting that it should be applicable in England based on longer time-series.

We recommend that the work undertaken in this section is repeated in 2 – 4 years' time when the camera locations have 4 – 6 years of available data. This will allow subsidence calculations based on long-term time-series analysis which will better represent average conditions and be less affected by the short-term changes in water levels caused by inter-annual variability.

7. Monitoring water table using satellite data

7.1 Introduction

Several studies have demonstrated the overriding importance of WTD on peat GHG fluxes (e.g. Couwenberg et al. 2011, Evans et al. 2021b) showing it to be a strong and widely applicable predictor of peat GHG emissions. Most peatland restoration projects focus on raising water levels, ideally to a level that allows the re-initiation of carbon sequestration via peat formation (Gatis et al. 2023). While the role of WTD as a control on the peatland carbon and GHG balance is well established, cost-effective and reliable Monitoring, Reporting and Verification (MRV) remains a major challenge. Water table depths can readily be measured at individual locations, but large-scale monitoring across large projects can be prohibitively expensive.

One area of research that makes large-scale, long-term monitoring of peatlands possible is satellite based remote sensing. There is increasing availability of pre-processed data from high resolution spectral, hyperspectral and Synthetic Aperture Radar (SAR) satellites. A number of studies have attempted to use optical data to either classify peatland vegetation (e.g. Williamson et al. 2018, Ball et al. 2023) or to infer water table depth, for example using the Normalised Difference Water Index (NDWI) metric (Kalacska et al. 2018) or the Optical Trapezoid Model (OPTRAM) (e.g. Burdun et al. 2023). This approach is severely hampered by typically high levels of cloud cover over most peatlands, as well as issues such as phenological variations in the optical properties of vegetation and seasonally varying light levels and angles.

As a result of these challenges, there has been growing interest in the use of SAR for peat condition monitoring. A main advantage of SAR data is that, although corrections may be needed in the event of heavy precipitation at the time of the image acquisition (Carrasco et al. 2019), data are not affected by cloud cover in the same way as spectral and hyperspectral data. With a return period of 6 to 12 days (dependent on satellite operation), open-source SAR backscatter data collected by the ESA Sentinel 1 satellites allow monitoring of the land surface at a spatio-temporal scale that would not be possible using ground, aircraft or optical satellite measurements. This offers the potential to monitor the trajectory of change in peatland condition at a high spatial and temporal resolution.

Increasing numbers of studies have demonstrated a relationship between Sentinel-1 SAR backscatter data and soil wetness, and a number of global SAR-based soil moisture products exist (e.g. Das et al. 2019, Beale et al. 2021) and have been used to infer peat wetness (e.g. FAO 2021). However, these products tend to saturate at the high moisture levels characteristic of natural or even modified peatlands, limiting their utility for this purpose. Several studies have developed specific SAR-based methods to predict WTDs in peatlands under varying management, including near natural and restored blanket bogs (Lees et al. 2021, Toca et al. 2023), raised bogs (Williamson et al 2023) and lowland grazing meadow and pasture (Asmuss et al. 2019), though other peatland studies have found a better relationship between optical data and water table depth (Rasanen et al. 2022).

7.2 Methods

Site history

Fenns, Whixall and Bettisfield Mosses collectively make up the third largest area of lowland raised bog in the UK. Restoration of the site started in 1990, following drainage and industrial peat extraction across the site. The most recent set of restoration measures have included contour bunding across the site, with the aim of raising water levels within the peat. Water table levels have been monitored with a mix of manual and automated dipwells in transects across the site (Figure 7-1).

Datasets

SAR data

Annual Sentinel-1 high-resolution Level-1 Ground Range Detected (GRD) imagery for Fenns and Whixall between 2018 and 2022 at a 10 m resolution was downloaded through Google Earth Engine (GEE). Imagery was pre-processed, radiometrically calibrated, and corrected for terrain (GEE 2023). These data were multi-looked and projected to ground range using an Earth ellipsoid model (ESA 2023). Once downloaded, median monthly VV and VH polarisation (the method of pulses being emitted and received from the sensor, VV = vertical transmit, vertical receive; VH = vertical transmit, horizontal receive) backscatter values were calculated for both ascending and descending orbits and were analysed further using ArcMap v10.8.2 and R v 4.4.0. Note that this technique uses the same satellite product as that of InSAR as discussed in Section 5. However, instead of comparing differential phase images to attain an interferogram this approach calculates 'SAR backscatter' for each image.

Water table depth data was provided by Natural England. Data analysis focussed on the automated data loggers, which provided water table measurements at 6 hour intervals.

NextMap UK 5 m pixel Digital Elevation Model (DEM) provided elevation data for each of the dipwell locations across the three bog domes. The elevation at each point location (vertical RMSE 1 m) was extracted in ArcMap v10.7.1. The DEM was used to calculate the mean slope for each pixel using the "slope" function in ArcMap v10.7.1. Datasets were resampled to 10 m to align with Sentinel-1 image resolution.

The England peaty soils layer and Welsh Unified Peat Map were used to estimate the distance from the edge of the peat dome for all water table monitoring locations. Distance from peatland edge was calculated from points in a 10 m x 10 m grid to the nearest boundary of the dataset and converted to a 10 m raster. This variable was found on upscaling to produce a spurious artifact in the modelling with a strip of deeply drained peatland uniformly around the edge of the site. Although there are paths around the edge of the site we decided to reproduce the modelling without the distance from the peat edge as a variable, despite its significance in previous testing (Williamson et al., 2023).

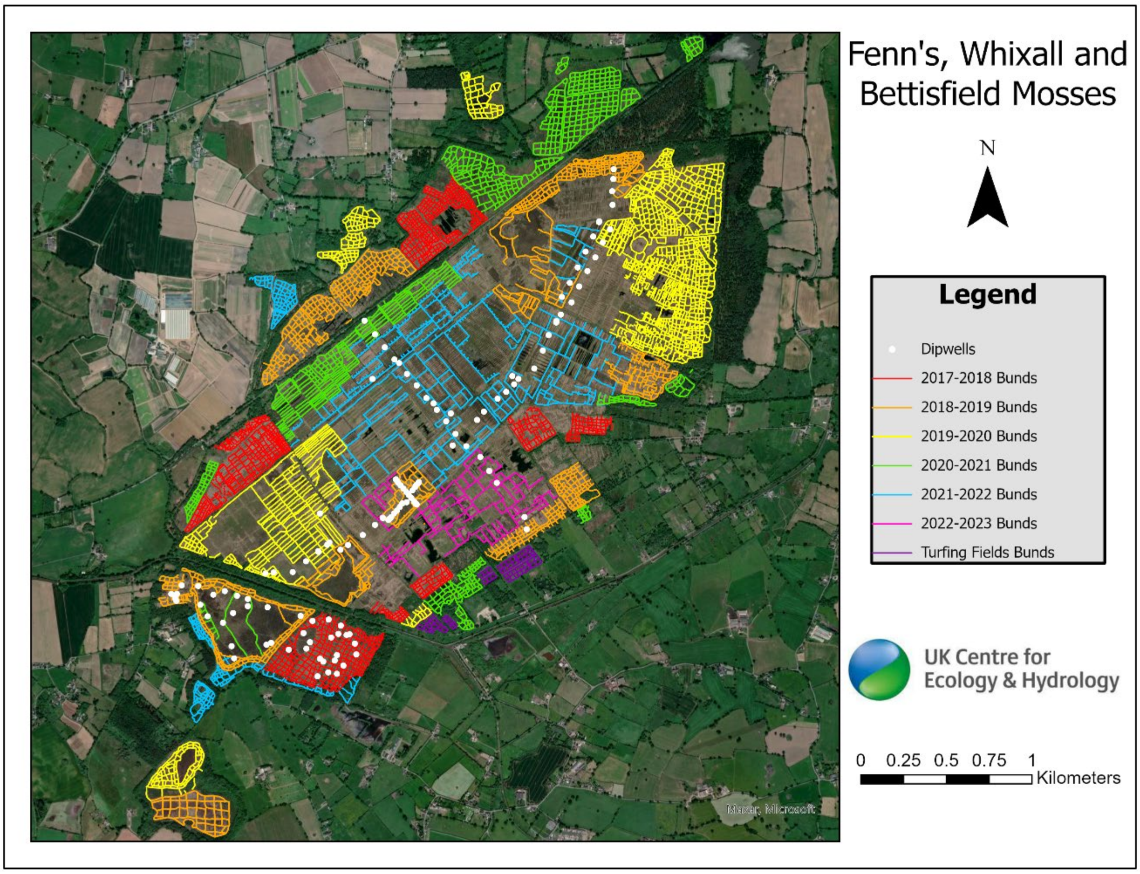


Figure 7-1 Fenns, Whixall and Bettisfield Mosses showing the dipwell locations and the bunding works across the site between 2017 and 2023. Background imagery source: Esri, Maxar, Earthstar Geographics, and the GIS User Community.

Random Forest modelling

To determine the relationship between SAR backscatter data and water table depth the relationship between VV and VH polarisation backscatter data, water table depth, elevation, slope, and distance from peatland edge were assessed using a Random Forest machine learning approach. The dataset was split into calibration (70%) and validation (30%) subsets. All statistical modelling was conducted in R v4.4.0 (R Core Team 2022) using the RandomForest package (Breiman 2001). The model was restricted to 500 decision trees.

7.3 Results

The modelling work was conducted with the ascending and descending backscatter separately, with VV and VH descending (satellite direction of travel north – south) backscatter data giving a better relationship with water table depth, compared to ascending (satellite direction of travel south – north). This agrees with previous work carried out using data from Cors Caron, a lowland raised bog complex in mid Wales.

The random forest model using the descending SAR data describes 58% of the variation in the data. Using the validation subset, the model showed a significant ($P<0.0001$) relationship between measured and modelled water table depth with an R^2 of 0.58 (Figure 7-2a) while the relationship between the modelled and measured data for the entire dataset gave a higher R^2 of 0.74 ($P < 0.0001$) (Figure 7-2b).

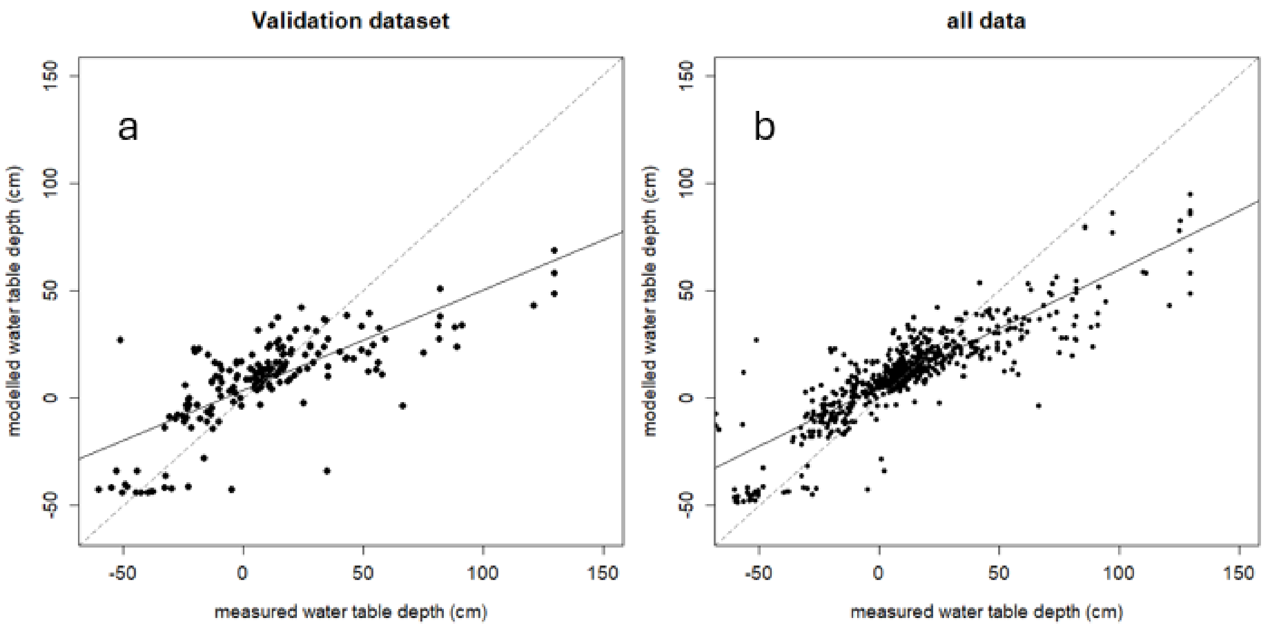


Figure 7-2 Comparison of measured and modelled water table depth for Fenns and Whixall Moss (a, left; b, right)

Time series comparison with WTD data showed good agreement across sites, including those with moderate water table draw down and sites that were flooded for part of the year (Figure 7-3).

Following the time series analysis the results were upscaled to the whole site, thus far for 2023 (the most recent year with full satellite data coverage) for both water table (Figure 7-4) and CO_2 flux (Figure 7-5), using the relationship between water table depth and carbon dioxide flux shown in Evans et al. (2021b). The northeast of the site is the driest area, with areas where the mean water table depth in 2023 was greater than 20 cm below the ground level. The centre of the main bog dome has a mean annual water level of between 5 and 15 cm across much of the surface, suggesting that the water levels are on average high at the bog centre, despite some water level draw downs during the summer.

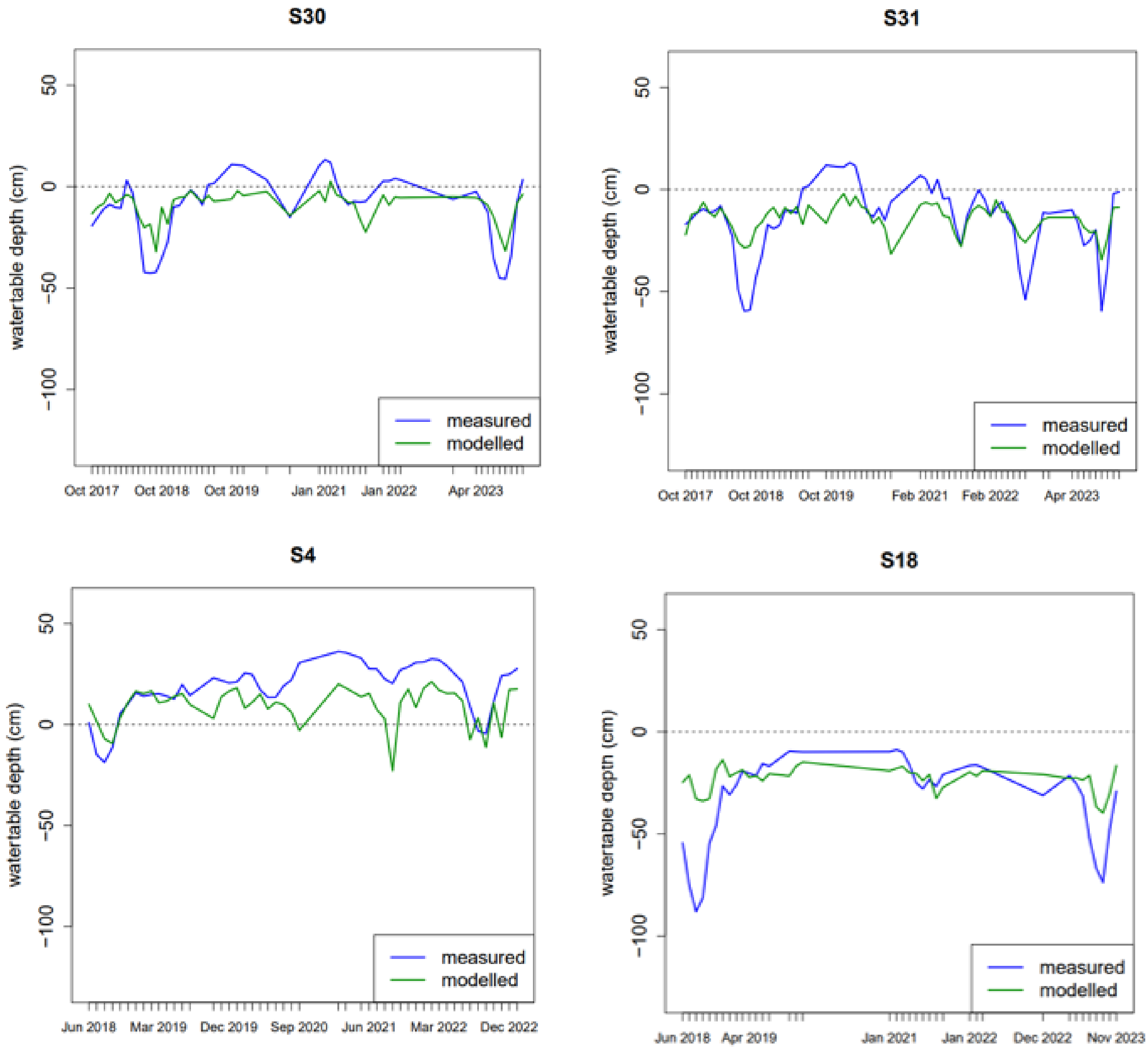


Figure 7-3 Time series comparison for automated dipwell locations at Fenns and Whixall Moss

The modelled carbon dioxide flux (Figure 7-5) suggests that the majority of the site was a small CO_2 sink during 2023, but that the drier areas of the site are likely to still be a CO_2 source. At present there are no site level data to compare the modelled GHG fluxes against. To further develop the modelling at this site we need to compare the modelled water table depth outputs with the area on the ground to better understand some of the spatial patterns seen in the model outputs. However, a further measure that would be extremely useful would be the measurement of GHG fluxes from areas across the site so that modelled data can be compared with direct on the ground measurements.

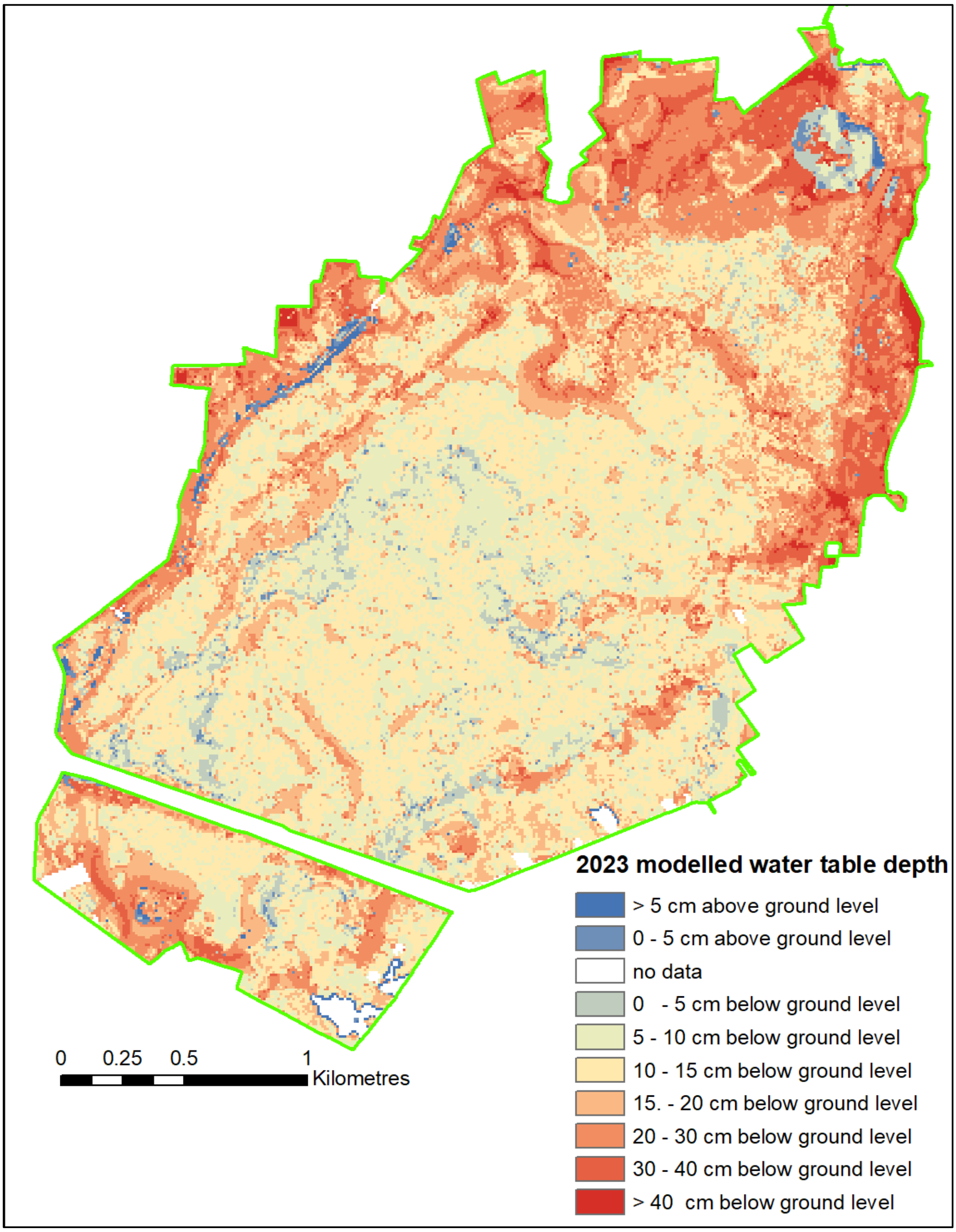


Figure 7-4 Modelled water table depth at Fenns & Whixall Moss for 2023. Note the gap in the map is the Llangollen canal, which splits the site.

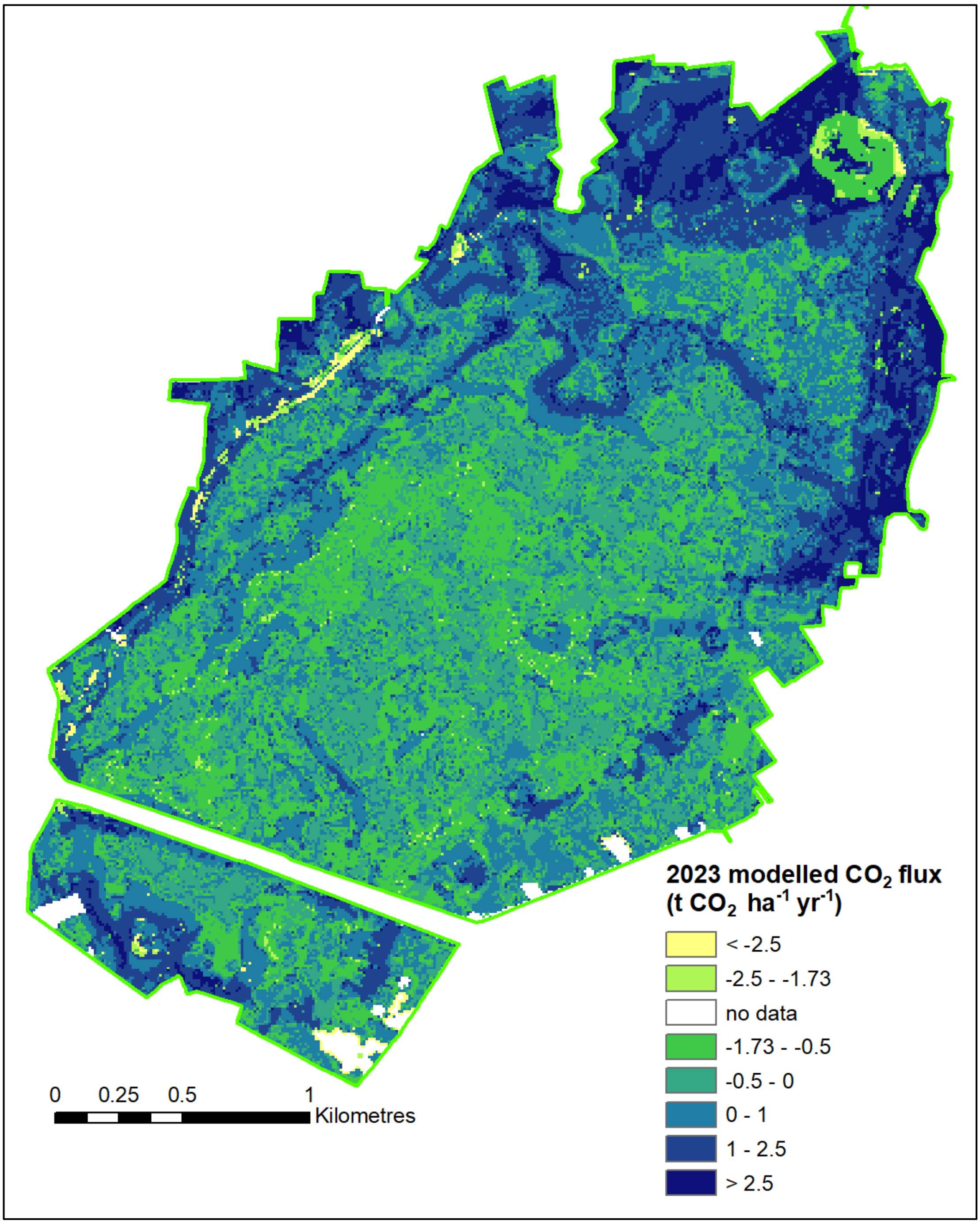


Figure 7-5 modelled carbon dioxide flux for 2023 at Fenns & Whixall Moss. Note the gap in the map is the Llangollen canal, which splits the site.

7.4 Discussion

Our analysis demonstrates the potential for large scale mapping of water table depths, and hence GHG fluxes, from semi-natural peatlands under conservation and restoration management. The methodology has the potential to provide a comparatively low cost, near real time (depending on satellite data download), independent and quasi-continuous MRV solution for peatland restoration, thus increasing confidence in long-term carbon monitoring of these ecosystems. Our results build on previous evidence that Sentinel 1 backscatter data can detect water table depth relationships in both restored and near natural blanket bogs (Toca et al. 2023). The additional environmental variables that were most important were the slope and elevation. Slope has been found to be important in peatland condition monitoring (Trippier et al. 2020). For water table specifically, flatter slopes will hold water better than steeper slopes, meaning water table will be closer to the surface (Daniels et al. 2008).

The relationship between modelled and measured water table depth showed signs of becoming less linear as the water table dropped to more than 50 cm below the surface. This outcome is similar to that seen by Toca et al. (2023) and suggests that this may be a limitation of the use of Sentinel 1 backscatter depth for monitoring of deeper peatland water tables. One point to determine is what exactly is being detected by the Sentinel-1 backscatter data. Previous work has suggested that it can be used to directly model water table depths in peatlands (Bechtold et al. 2018, Asmuss et al. 2019, Toca et al. 2023), however, it seems that the data are actually directly influenced by the surface and near surface soil moisture (Millard and Richardson 2018, Hrysiewicz et al. 2023), rather than water table depth per se, because C-band SAR does not penetrate more than a few cm into the soil surface (Hrysiewicz et al. 2023). During the drier months the SAR backscatter intensity reduces as the water table depth drops and the surface moisture reduces (Hrysiewicz et al. 2023). Bechtold et al. (2018) suggested that the relationship between water table depth and SAR backscatter is approximately linear to water table depths of 1 m, and we were able to replicate the more deeply drained nature of some of our sites, though not all draw-downs were fully modelled.

At present our methodology has only been tested on semi-natural raised bogs, where the water table is near the surface and the vegetation is primarily low, slow growing and perennial. For this methodology to work across peatland types and to map the impacts of changing land management, especially on highly modified agricultural peatlands with deep drainage and annual cropping, further investigation is needed. Even if deep drainage cannot be fully accurately quantified, the method shows promise for detecting time periods when peat soils are deep drained, compared to shallow water tables. This work has shown that, for raised bogs, median monthly SAR backscatter data, combined with simple spatial metrics can reproduce the spatial and temporal variability in monthly water table depth. The resulting spatial model of site-wide water table depth can be converted to an estimate of site wide annual GHG fluxes.

8. Summary

8.1 Peat cameras

The work undertaken during this project brings together the first England-wide automated peatland surface motion monitoring data, where surface level and water table depth have been concurrently continuously monitored across over 50 sites. Furthermore, automation of the image processing and data analysis has occurred meaning data will be available daily for visualisation and download.

Peat cameras were installed across all main peatland types in England covering all peatland regions, with the exception of Dartmoor. This range allowed detailed investigation of the interactions between surface motion and water table depth and how these can be assessed to derive and understand of the condition of the peat.

A further aim of the work was to determine the extent to which remote sensing data from open source satellite monitoring can be used to provide national scale monitoring of the condition of peat across England. Additionally, if such a solution is not yet at a stage where it can be operationalised, what further research and development is needed to work towards that aim. There are existing platforms using optical satellite imagery to provide large-scale land cover assessments at a national scale (for example Living England (https://naturalengland-defra.opendata.arcgis.com/datasets/Defra::living-england-habitat-map-phase-4/about) and the UKCEH Land Cover Map (https://www.ceh.ac.uk/data/ukceh-land-cover-maps)) so this area of work focussed on using radar imagery as a mechanism for determining condition within broad scale condition classes, such as arable, blanket bog, raised bog etc. As well as providing NE with a mechanism by which peatland condition in England can be monitored and reported, an additional benefit of this methodology would be that it would enable the UK to move towards a Tier 3, modelling, approach to reporting GHG emissions from peatlands in the national GHG Inventory.

The peat cameras have been shown to be an effective means of monitoring surface motion and water table depth. The work has shown that the cameras do need a degree of ongoing maintenance in order to maximise data collection. In particular, in places with limited mobile phone reception a lack of connectivity at the point of data upload can result in the system freezing and needing a manual restart. One of the aims that we are working towards is for groups of cameras having a local point of contact to visit and carry out regular maintenance to reduce the ongoing costs. We have produced field guides and maintenance logs to assist with this and it is working particularly well for the Kent and Norfolk Broads sites. We would recommend that this is further developed over the next phase of work to increase data collection reliability.

8.2 Condition monitoring from surface motion characteristics

The results show that despite the short-term nature of the subsidence data there is a tentative relationship between mean annual effective water table depth and peat surface motion. However, the short term nature of the subsidence estimates at present means that there are outliers and as such we would recommend that this exercise is revisited in 3 – 5 years to allow a longer-term subsidence calculation to be assessed for each site and to allow the effects of between-year variation on the remaining metrics to be incorporated into the analyses.

To date, assessment of GHG flux from the sites has been limited and will benefit from future co-location of flux towers and cameras. The calculations from mean annual water table depth showed that the CO_2 flux can be estimated from a simple to measure metric but that at present the estimation of water table depth from annual subsidence is limited in accuracy, which limits the estimation of CO_2 flux from subsidence.

8.3 Using InSAR to monitor surface motion

At present none of the InSAR methods tested provide a ready to operate solution to develop a nationally consistent monitoring strategy of peatland condition based on remotely sensed surface motion characteristics. IPTA InSAR allows accurate quantification of the surface motion in raised and blanket bog sites where spatial coverage is sufficient. However, IPTA methods to date have not demonstrated success over fens, wet woodlands and more intensively managed peatland landscapes. Furthermore, the limited spatial coverage across peatlands of both IPTA and EGMS limit the usability of the approach for condition monitoring. APSIS InSAR is able to provide near complete spatial coverage across all peatland types in England. However, the APSIS data could not quantitatively nor qualitatively reproduce the peat camera measured surface motion timeseries at the majority of locations used in this work.

It should be noted that this work was carried out with the C-band Sentinel-1 sensors and should be compared with the new L-band satellites when data becomes available. Indeed, the InSAR coherence will be better for each peat soil, but the wavelength will be higher (23 cm vs. to 5.5 cm in C-band). This means that the accuracy of InSAR-derived displacements could be affected, but, with better spatial coverage of the InSAR results.

8.4 Using SAR to monitor water table depth

The final section of this report covers the successful application of SAR data to directly model water table depth. At present our methodology has only been tested on semi-natural raised bogs, where the water table is near the surface, and the vegetation is primarily low, slow growing and perennial. For this methodology to work across peatland types and to map the impacts of changing land management further investigation is needed, especially in areas where the peat is deeply drained. Even if deep drainage cannot be fully quantified, the method shows promise for detecting time periods when peat soils are deep versus shallow drained. The work at Fenns & Whixall has shown that median monthly SAR backscatter data can reproduce the spatial and temporal variability in monthly water table depth and be used to estimate GHG fluxes from the site.

8.5 Recommendations

The next areas of focus needed to build towards an operational national peatland monitoring strategy include both ground-based data collection and analysis as well as further investigation of satellite data. These include:

- Continue ground data collection so that we have a minimum length dataset of 4-5 years in order to disaggregate the long-term trends from short-term impacts of inter-annual variability in weather and land management. This would also include improved data collection of site information such as carbon stock, bulk density and peat decomposition.
- Continued co-location of cameras and flux towers on a range of peatland types to determine the extent to which we can estimate GHG fluxes.
- Investigation of the usability of the water table assessment from SAR data across varying land use types, including those where there is more intensive drainage. This step is likely to be constrained by the availability of multi-year time series of water table data with sufficient spatial replication to allow model development.
- Determine whether a single national methodology is an appropriate tool to use to report on peatland condition, or whether InSAR reporting on raised and blanket bogs may provide sufficient information for these sites but an alternative method is needed for fens, grassland, woodland and arable sites.
- Test the InSAR approach with new L-band SAR data as sufficient time series of data come online. This may provide a more widely applicable solution than C-band InSAR.

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10. Glossary

Abbreviation	Definition
APSIS	Advanced Pixel System using Intermittent SBAS
ArUco	Augmented Reality University of Cordoba
DEM	Digital Elevation Model
EGMS	European Ground Monitoring Service
GHG	Greenhouse Gas
InSAR	Interferometric Synthetic Aperture Radar
IPTA	Interferometric Point Target Analysis®
LOS	Line of Sight
LTE modem	Long-term evolution modem
NCEA	Natural Capital Ecosystem Assessment
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
SRTM	Shuttle Radar Topography Mission
UKCEH	UK Centre for Ecology & Hydrology
WTD	Water Table Depth (in this work relative to the ground surface)

11. Appendices

11.1 Appendix 1: Installed cameras

Camera number	Camera name	Region	Peat type	Condition category	Date of first data collection
1	HH-Pollybell (GGPR1)	Humberhead	Fen	Temporary grassland/cropland (intermediate drained)	April 2022
2	HH-Pollybell (GGPR2)	Humberhead	Fen	Temporary grassland/cropland (deep drained)	March 2022
3	HH-Pollybell (GGRP3)	Humberhead	Fen	Temporary grassland/cropland (deep drained)	March 2022
4	NP-Moor House (flux tower)	North Pennines	Blanket bog	*Calluna* dominated bog	March 2022
5	NP-Valance Lodge (degraded)	North Pennines	Blanket bog	*Calluna* dominated bog	March 2022
6	NP-Valance Lodge (Harthope Moss)	North Pennines	Blanket bog	Eroded bog (gullied *Calluna*-dominated)	March 2022
7	NP-Barningham (north)	North Pennines	Blanket bog	*Molinia* dominated bog	March 2022
8	NP-Barningham (north-west)	North Pennines	Blanket bog	*Molinia* dominated bog	March 2022

Camera number	Camera name	Region	Peat type	Condition category	Date of first data collection
9	EA-Redmere	East Anglian Fens	Fen	Cropland on shallow peat	March 2022
10	EA-Stretham (wasted peat)	East Anglian Fens	Fen (wasted)	Cropland on wasted peat (deep drained)	March 2022
11	EA-Great Fen (Waterworks)	East Anglian Fens	Fen	Permanent grassland (medium drained)	March 2022
12	EA-Stretham (wet)	East Anglian Fens	Fen (wasted)	Cropland on wasted peat (shallow drained)	May 2022
13	SL-Honeygar grassland (south)	Somerset Levels	Fen	Permanent grassland (shallow drained)	July 2022
14	SL-Honeygar grassland (north)	Somerset Levels	Fen	Permanent grassland (shallow drained)	July 2022
15	SL-Graylake	Somerset Levels	Fen	Tall vegetation dominated fen	August 2022
16	SL-West Sedgemoor	Somerset Levels	Fen	Permanent grassland (shallow drained)	July 2022
17	SL-South Drain grassland	Somerset Levels	Fen	Permanent grassland (shallow drained)	July 2022
18	NP-Moor House (eroded)	North Pennines	Blanket bog	Eroded bog (*Calluna* dominated revegetated gullies)	September 2022
19	Old Park Wood restored	Lake District	Blanket bog	*Molinia* dominated bog	December 2022

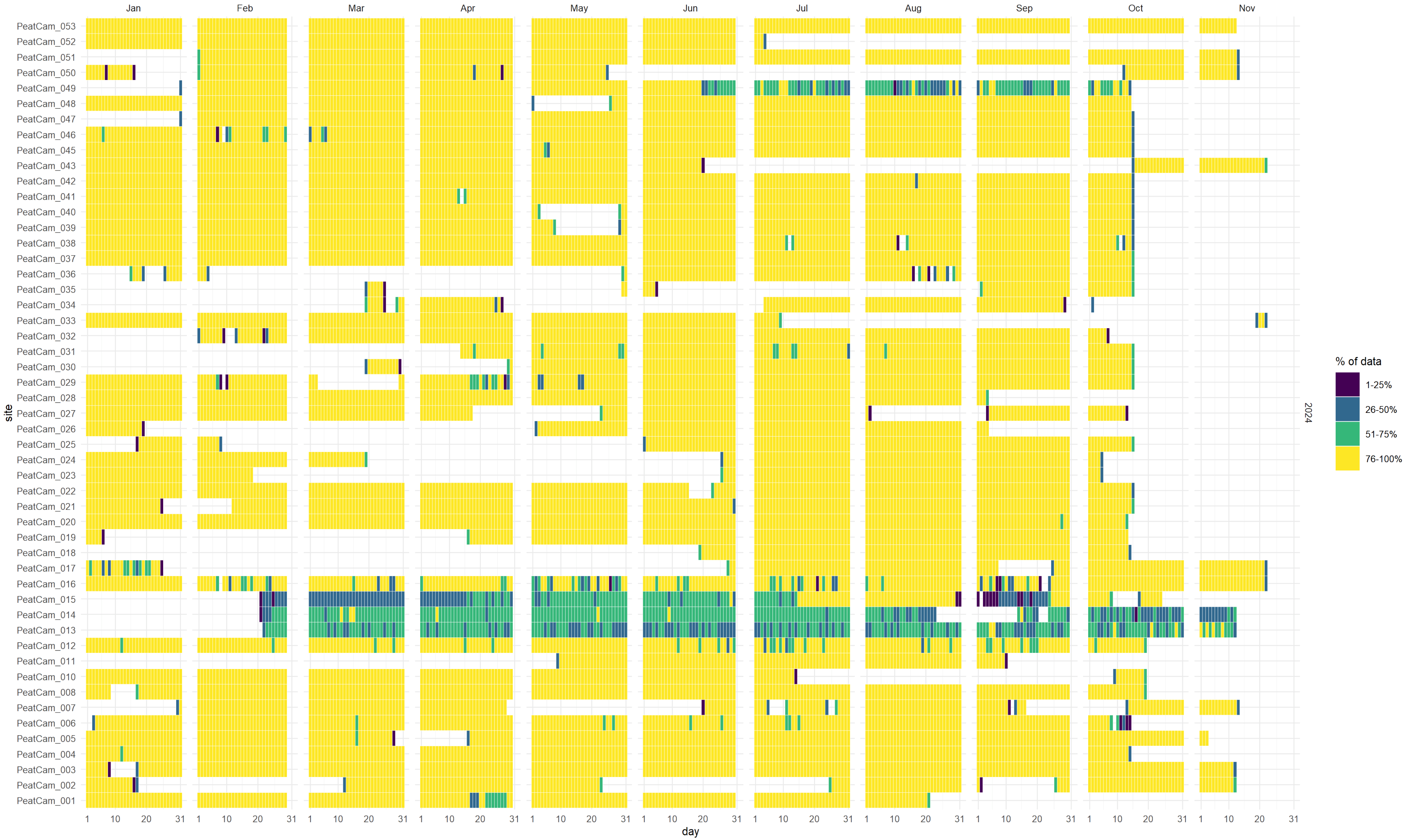
Camera number	Camera name	Region	Peat type	Condition category	Date of first data collection
20	NP-Westernhope Moor (*Molinia*)	North Pennines	Blanket bog	*Molinia* / *Eriophorum* dominated bog	March 2023
21	NP-Westernhope Moor (eroded)	North Pennines	Blanket bog	Eroded bog (Vegetated but with nearby gullies)	February 2023
22	Old Park Wood afforested	Lake District	Blanket bog	Afforested bog (recently replanted)	December 2022
23	K-Ham Fen (site 1)	Kent	Fen	Tall vegetation dominated fen	January 2023
24	K-Ham Fen (site 2)	Kent	Fen	Tall vegetation dominated fen	October 2022
25	SS-Bettisfield Moss (scrub)	Shropshire	Lowland raised bog	Dry grass/scrub dominated bog	December 2022
26	SS-Bettisfield Moss (*Sphagnum*)	Shropshire	Lowland raised bog	*Sphagnum* dominated bog	December 2022
27	SS-Aqualate Mere (grassland)	Shropshire	Fen	Permanent grassland (shallow drained)	December 2022
28	SS-Aqualate Mere (reedbed)	Shropshire	Fen	Tall vegetation dominated fen	December 2022
29	NF-Bressingham (grassland)	Norfolk	Fen	Permanent grassland (shallow drained)	January 2023

Camera number	Camera name	Region	Peat type	Condition category	Date of first data collection
30	NF-Ranworth (reedbed)	Norfolk	Fen	Tall vegetation dominated fen / reedbed	February 2023
31	NF-Bressingham (wet woodland)	Norfolk	Fen	Wet woodland	January 2023
32	NF-Ranworth (wet woodland)	Norfolk	Fen	Wet woodland	January 2023
33	EA-High Fen Farm	East Anglian Fens	Fen	Permanent grassland (medium drained)	January 2023
34	NF-Heckingham farm	Norfolk Broads	Fen	Permanent grassland (deep drained)	February 2023
35	NF-Leists Farm (wildflower meadow)	Norfolk Broads	Fen	Short-vegetation dominated fen	February 2023
36	NF-Woodbastick (woodland)	Norfolk Broads	Fen	Wet woodland	February 2023
37	NF-Woodbastick (meadow)	Norfolk Broads	Fen	Short-vegetation dominated fen	February 2023
38	NF-Wildflower meadow (How Hill)	Norfolk Broads	Fen	Short-vegetation dominated fen	February 2023
39	NF-Manor farm	Norfolk Broads	Fen	Permanent grassland (deep drained)	February 2023

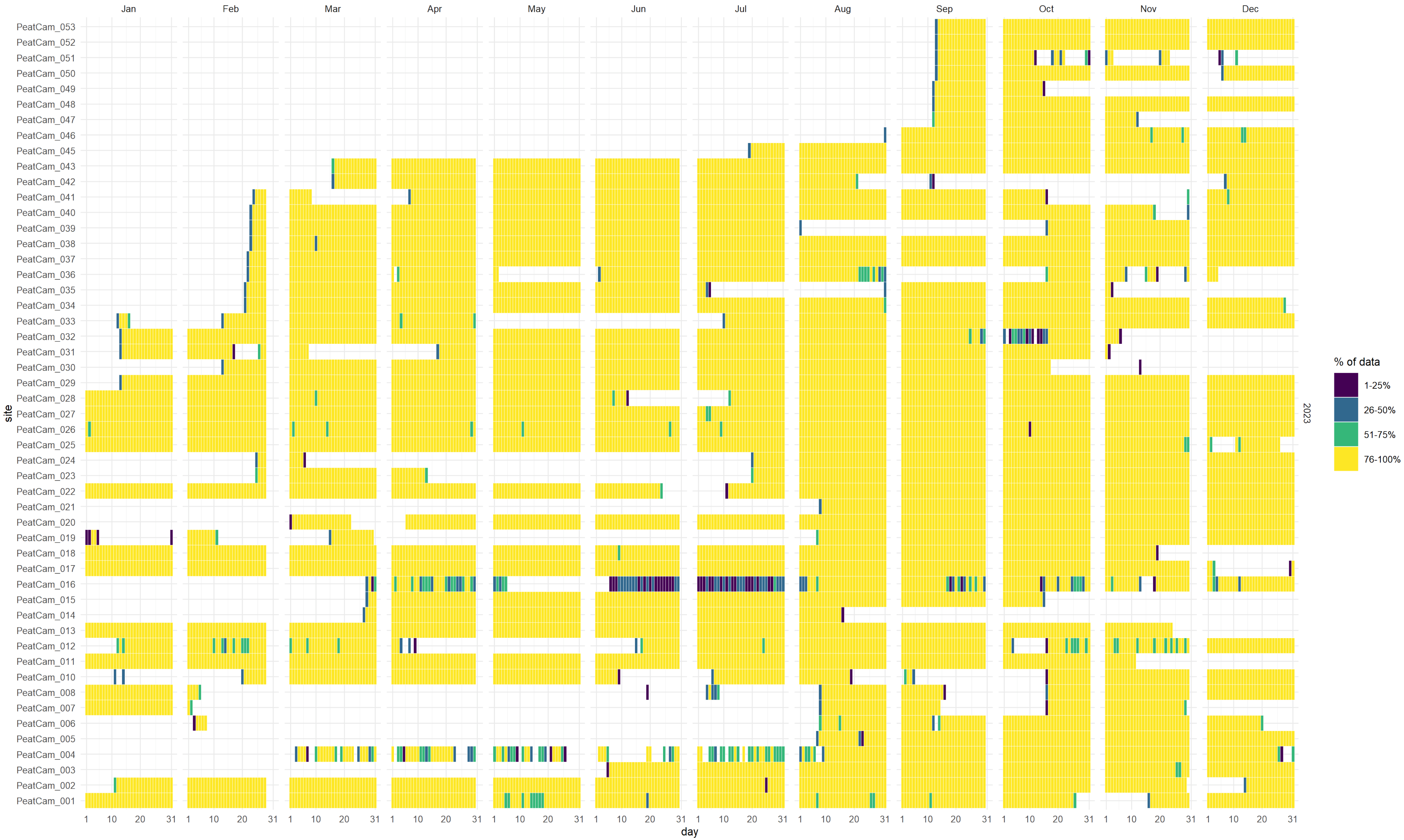
Camera number	Camera name	Region	Peat type	Condition category	Date of first data collection
40	NF-Pigeon wood (How Hill)	Norfolk Broads	Fen	Wet woodland	February 2023
41	NF-Barton Fen	Norfolk Broads	Fen	Scrub-dominated fen	February 2023
42	LD-Foulshaw Moss	Lake District	Lowland raised bog	*Molinia* dominated bog	March 2023
43	LD-Foulshaw Moss	Lake District	Lowland raised bog	*Molinia* dominated bog	March 2023
45	NF-Strumpshaw fen	Norfolk Broads	Fen	Short-vegetation dominated fen	July 2023
46	NF-Buckenham marsh	Norfolk Broads	Fen	Permanent grassland (shallow drained)	July 2023
47	BM-Wou Bog edge	Border Mires	Upland raised bog	*Molinia* dominated bog	September 2023
48	BM-Wou Bog middle	Border Mires	Upland raised bog	*Sphagnum* dominated	September 2023
49	BM-Wou Bog Sitka	Border Mires	Upland raised bog	*Calluna* dominated bog	September 2023
50	BM-Coom Rigg Moss clearfell	Border Mires	Blanket bog	*Calluna* dominated bog	September 2023

Camera number	Camera name	Region	Peat type	Condition category	Date of first data collection
51	BM-Coom Rigg Moss less degraded	Border Mires	Blanket bog	*Calluna* dominated bog	September 2023
52	BM-Falstone Moss 01	Border Mires	Upland raised bog	*Sphagnum* dominated	September 2023
53	BM-Falstone Moss 02	Border Mires	Upland raised bog	*Molinia* dominated bog	September 2023

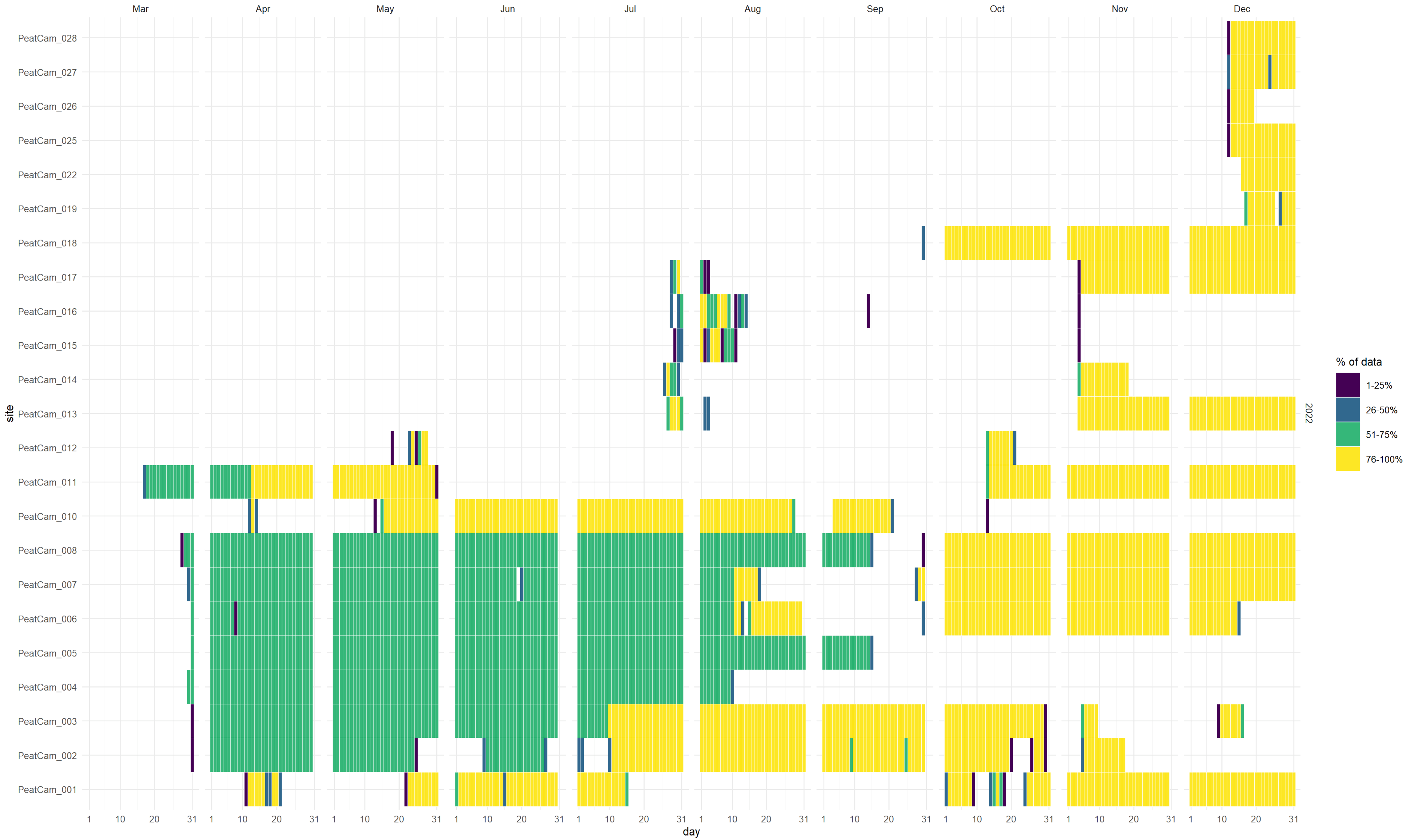
11.2 Appendix 2: Data coverage for peat cameras in 2024



11.3 Appendix 3: Data coverage for peat cameras in 2023



11.4 Appendix 4: Data coverage for peat cameras in 2022



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