Estimating the Carbon Stock in the Lye Valley’s peat fen

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

CO_2: Carbon dioxide

GHG: Greenhouse Gases

$tCO_2\ ha^{-1}\ yr^{-1}$: tonnes of carbon dioxide per hectare per year

LOI^{550}: Loss on ignition at 550 (% organic matter content)

LOI^{950}: Loss on ignition at 950 (% carbonate content)

tC: tonnes of carbon

Corg: Organic carbon

BD: Bulk density

SSSI: Site of special scientific interest

C: Carbon

g/cm^3: grams per cm3

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Declaration of Individual Authorship

The author confirms that this research project contains no unacknowledged work or ideas from any publication or work by any other author.

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Abstract

This project focused on the Lye Valley, an alkaline peat fen in Headington, Oxford, which is currently under threat due to urban development. The peat is currently drying out and eroding due to impacts on its natural hydrology, leading to oxidisation of up to 14,000 years' worth of accumulated carbon (Webb, 2014). Peatlands are the UKs greatest store of terrestrial carbon, however, when degraded they become carbon emitters and globally, degraded peatlands are responsible for 25% of CO_2 emissions from the land use sector (Reed *et al*., 2014; Joosten *et al*., 2012; Moxley *et al*., 2011). To achieve Oxfords aims to reach net zero emissions by 2040, much effort will be needed including finding sustainable methods of carbon sequestration and reducing carbon emissions (OCC, 2021a)

This project involved estimating the peat carbon stock in Lye Valley in order to prove the lands value as a carbon storage ecosystem and highlight the potential emissions that will be incurred if the site continues to degrade. The purpose is to provide information for cost-benefit analysis and encourage funding for the restoration of the site.

The results indicate that Lye Valley has a high carbon stock of 5504 tC with an estimated value over £2 million. In a healthy peatland scenario, Lye Valley would accumulate an estimated 8.4 tC per year. In a degraded peatland scenario, Lye Valley would emit an estimated 168.7 tC annually. If restored and made healthy Lye Valley would both accumulate carbon, as well as avoiding emissions due to erosion. This means the potential benefits of restoration would lead to reduced annual emissions of 177.13 tC per year. The equivalent of annual average emissions of the use of 412 cars (Carbon Independent, 2007). This would lead to saved annual costs of up to £65,000 per year.

These findings provide insight on the carbon fluxes within alkaline peat fens, for which data is currently limited. It is recommended that funding is directed towards restoration and enhancement of Lye Valley. Not only because of its potential in future carbon sequestration and climate mitigation but also due to the avoided emissions that would be caused by neglecting to restore the site. It is recommended that this funding is given the upmost importance, as leaving the site to further degrade can mean a lost opportunity for successful restoration and the eventual emissions of 5504 tC (Bain *et al*., 2011). This will help Oxford in reaching net zero emissions targets by 2040.

Keywords: Peat, fen, carbon, sequestration, conservation, restoration
Word Count: 13,095 words

1. Introduction

This project focused on Lye Valley, an alkaline peat fen in Headington, Oxford, which is currently under threat due to urban development impacting hydrology (Webb, 2014). This tufa forming valley fed by lime rich springs is an internationally rare habitat, rich in biodiversity. Though covering a small area, the site represents 12.7% of the last remaining habitat of its kind in England which highlights the rarity of the site (FoLV, 2020).

Urban development within the water catchment area, has reduced permeability of the land surface and reduced the amount of water feeding into underlying geology, which provides the fen with the mineral enriched waters that have shaped the rare species present on site and are necessary to continue to support them.

Instead, water now travels over ground and into drainage pipes, which at times of high precipitation, surge in large quantities through the valley, eroding peat. The fast flow of this channel of water draws water away from the fen and downstream, meaning as well as eroding the banks, the peat is drying out.

In the UK peatlands represent the most significant source of terrestrial carbon but, when degraded, peatlands become carbon emitters and, in the UK, alone, around 3.7 megatons of CO_2 are emitted annually as a result of peatland degradation (Fens for the Future, 2012; Worrall *et al*., 2011; Joosten *et al*., 2012; Moxley *et al*., 2011).

In natural healthy peatlands, plants absorb CO_2 and when plants eventually collapse, the waterlogged conditions inhibit the full decomposition of plant matter due to reduced oxygen. Oxygen limitations cause inefficiencies of anaerobic microbes which are not able to decompose matter faster than the rate of input (UKCEH, 2020). This has led to the accumulation of partially decayed plant matters which for some areas has been ongoing since the last ice age, forming deep peat cores, containing more carbon than tropical rainforests (Natural England, 2010). Peatland offers a more stable carbon storage than woodland and can store carbon for millenia. However, peat must remain wet to preserve the anaerobic condition which prevent ancient organic matter from decomposing and releasing large stores of greenhouse gases (GHG).

The project will involve estimating the peat carbon stock in Lye Valley to evaluate the lands value as a carbon storage ecosystem. With the carbon stock data an estimation of the carbon value will be made using figures set by the UK government for valuing greenhouse gas (GHG) emissions (BEIS, 2021). An estimate will also be made of potential emissions in greenhouse gas due to the continued degradation of the habitat. This will help to emphasise the sites value in climate change mitigation with the aim of encouraging funding to support the conservation of this rare habitat and the much need rewetting of the fen.

Organic matter and carbonate mineral content will be investigated using standard carbon evaluation techniques. The investigation into inorganic as well as organic carbon within peatland is a unique element to the project, as little research has been done on this topic thus far. This will establish a deeper understanding into the soil characteristics of alkaline fens such as Lye Valley which are not well represented in current peatland data as most data is focused on upland blanket bogs (Evans *et al*., 2011).

2. Background

2.1. Climate Change and Biodiversity Loss

Anthropogenic emissions have increased rapidly since the preindustrial era, namely due to both increases in population and economic growth. This in turn has caused between 0.8 – 1.2 °C warming since preindustrial era, if this continues at the current rate, global warming will likely reach 1.5 between 2030-2052 (IPCC, 2018). With climate change we are already seeing significant changes in our planet including sea level rise, ocean acidification, changes in precipitation resulting in increased drought and flooding, increase in extreme weather events such as heat waves and biodiversity decline. These changes are only expected to get worse with current trends, resulting in long lasting and irreversible damage to health, food and water security and livelihoods (Allen, 2018).

Alongside climate change, pressures from population and economic growth have led to major land use changes at the expense of natural environments. This has led to biodiversity loss, to meet essential food and housing needs alongside the production of commodities to allow for economic growth. Some scientists indicate that we are entering a sixth mass extinction with rate of species loss up to 100 times greater than background rates (Ceballos *et al*., 2015; Ceballos *et al*., 2020). This includes a significant loss in insect diversity and abundance which has worrying implications for larger ecosystems due to cascading effects (Parikh *et al*., 2020).; Hallmann *et al*., 2017; Sanchez-Bayo and Wyckhuys, 2019). Losses can be attributed to habitat loss, predominantly due to agricultural uses, chemical use and habitat fragmentation (Sanchez-Bayo and Wyckhuys, 2019).

At COP 21 in Paris, on 12 December 2015, the Paris Agreement was tabled which saw almost all parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreeing to work together to limit global warming to below 2 degrees Celsius above pre-industrial levels, with a higher goal of limiting the temperature increase to 1.5. This would be achieved by Nationally Determined Contributions (NDCs) in which individual countries pledge their responses to mitigate and adapt to climate change and are then required to frequently report on their progress in meeting these targets. The Paris Agreement’s aim is to reduce emissions, ultimately leading to net zero emissions by 2050 to limit the expected warming (UNFCCC, 2015).

The UK has a target of net zero emissions by 2050 in order minimise damage caused by climate change. To achieve this, much effort will be needed including finding sustainable methods of carbon sequestration and reducing carbon emissions.

2.2. The Role of Peatlands in UKs Carbon Sequestration and Emissions Reduction

In Article 4, paragraph 1(d) of the Paris Agreement, parties are encouraged to conserve and enhance, as appropriate, sinks and reservoirs of GHGs (UNFCCC, 2015). Enhancement of natural carbon sinks such as peatland, not only offer solutions to carbon storage and emissions reduction but also biodiversity enhancement and climate change mitigation such as reduced flood risk.

Globally, degraded peatlands are responsible for 25% of CO_2 emissions from the land use sector (Reed *et al*., 2014). Degradation of peat soils has been found to be one of the highest contributors to climate change in the land use sector due to a combination of GHG emissions and the reduction in land carbon sinks (Shukla *et al*., 2019). The recognition of their role in climate change mitigation is relatively new and peatlands were only included in the UKs GHG inventory in 2020 (DEFRA, 2021).

Peatlands store more carbon than all vegetation types combined, despite their covering only 3% of land surface (UKCEH, 2020; IUCN; 2020). The UK has a relatively high land surface area of peatland which covers 12% of the UK in comparison to the global 3% average (UKCEH, 2020). Peatlands account for over half of the UKs soil carbon stock and therefore offer an effective method of carbon sequestration if managed and maintained properly. This has been recognised in the peatland action plan which requires all peatlands to be restored and enhanced to meet emission and biodiversity targets (IUCN, 2018). Alongside carbon storage, peatlands boast benefits in water filtration and water storage, whilst supporting many rare and declining species.

Peatlands are currently threatened by drainage, erosion and land use changes, leading to release of carbon and an inability to further accumulate carbon. Collectively fens are being lost at a rate of 2cm per year causing a large carbon release of around 3.7 megatons of CO_2 annually, in the UK alone (Fens for the Future, 2012; Worrall *et al*., 2011). Despite the high amount of loss in recent years, remaining peatlands worldwide contain an estimated 550 gigatons of carbon, equating to 42% of all soil carbon (IUCN, 2020b). For this reason, the UK peatland strategy aims to protect enhance and manage 95% of our peatlands by 2040 (IUCN, 2018). Peatland restoration requires immediate attention, as if left to degrade too much the likelihood of restoration success diminishes (Shukla *et al*., 2019).

2.3. The Need for Estimating Carbon Stocks in Supporting Conservation and Meeting Emissions Targets

Using and managing land sustainably is the 3rd policy within the 25-year environment plan, to meet the aim, one of the objectives is to restore vulnerable peatlands through sustainable management by 2030 (DEFRA, 2018). The Paris agreement also requires that the carbon within peatlands is protected by keeping peatlands wet (IUCN, 2018). The England peat action plan was created to indicate plans in which these aims are to be achieved which included understanding research gaps.

Amongst other goals, the plan aims to create a detailed peatland map by 2024 which is to include an understanding of carbon stock (DEFRA, 2021). Currently, there is a lack of understanding of peat depth and carbon storage throughout the UK, which is needed to effectively value costs versus benefits of restoration (Bain *et al*., 2011). It is likely that due to resource availability choices will have to be made on which peatlands to target for restoration, this requires an understanding of the opportunity cost of not conserving peatland versus the potential benefits resulting from restoration (Bain *et al*., 2011; Reed at al., 2014). Natural England has facilitated the National Natural Capital Atlas, mapping indicators which will be used to inform understanding of our natural assets this is necessary to enabling the distribution of provisions to be identified (Natural England, 2020). Carbon mapping and understanding of our natural capital carbon stocks of peatlands are necessary to identify hotspots and allocate provisions as ecosystem services are spatially variable (DEFRA, 2013; Glenk *et al*., 2014; Reed *et al*., 2014)

3. Aims and Objectives

3.1. Aims

This project seeks to support the conservation and restoration of the Lye Valley peat fens by demonstrating the ecosystems carbon storage capacity and its potential in climate change mitigation. This will involve estimating the carbon stock of sediment collected from transects within the site. There is currently no published data on carbon stock estimates of Lye Valley, so this project will be beneficial to those currently involved in its ongoing restoration by providing evidence to support the sites value. There is also very little understanding on sediment composition and spatial variability within alkaline peat fens because most published literature on peatland restoration is dedicated to blanket bogs (Baird *et al*., 2019). This investigation will allow insight into whether they behave similarly in terms of sediment composition and spatial variability and whether current averages and estimations that are based on research on blankets bogs can also be applied to alkaline fens. Focus will be placed on key gaps within peat carbon research which have be outlined within the peat action plan. This information will then be used to estimate a financial value of the carbon stocks to support its need for funding towards its restoration, it will also be used to estimate the potential carbon emissions the site could emit if no restoration work is done.

3.2. Objectives

These aims will be met by fulfilling the following objectives:

1. To determine carbon content (% Corg) of soil cores, the average depth profile of the peat, and variation in different areas of the site through the loss on ignition method
2. To determine a carbon stock estimate using organic carbon (% Corg) data and bulk density data
3. To estimate potential value of carbon stocks if funding is gained to rewet the peat and restore the fens
4. Estimate the potential cost in carbon emissions if area is not restored and left to further degrade
5. To apply findings to restoration of the peat fens

4. Literature Review

4.1. Ecosystem Services and Threats

There are 3 types of peatland in the UK; Blanket bog; Raised bog; and Fens (UKCEH, 2020; IUCN, 2018). The benefits of a healthy peatland as well as costs of a degraded peatland can be seen in Figure 4.1.1. (IUCN, 2018; Great Fen, 2020). This project will focus on Fens which are fed by groundwater, river water and precipitation which has passed through underlying geology, the minerals enriching the water impact the plants that grow, and the type of fen created which in this case focuses on an alkaline fen fed through lime rich geology (OFNS, 2019).

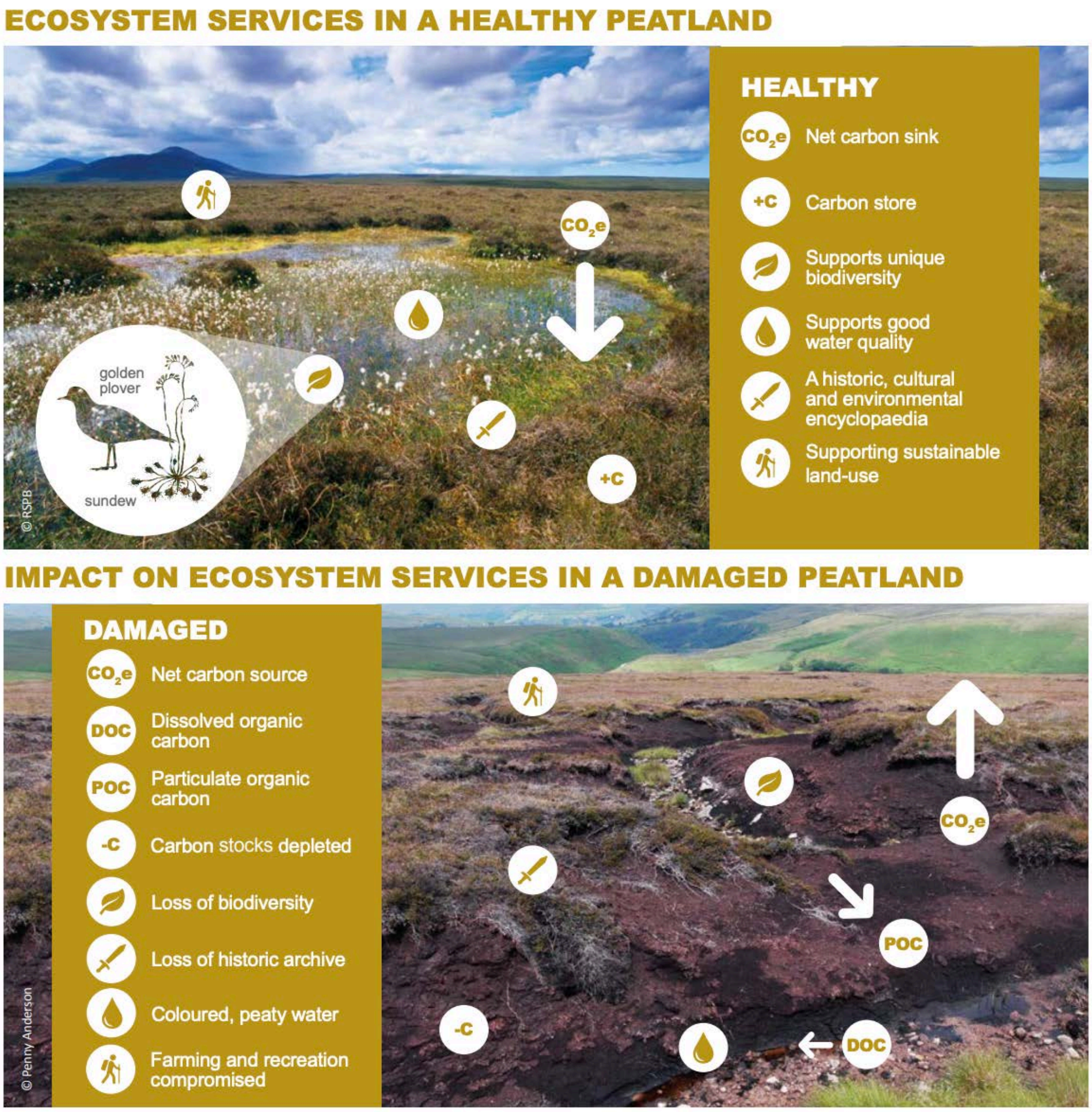


Figure 4.1.1. Annotated photos showing ecosystem services in healthy versus degraded peatlands. (Source: IUCN, 2018)

Due to the high fertility of the

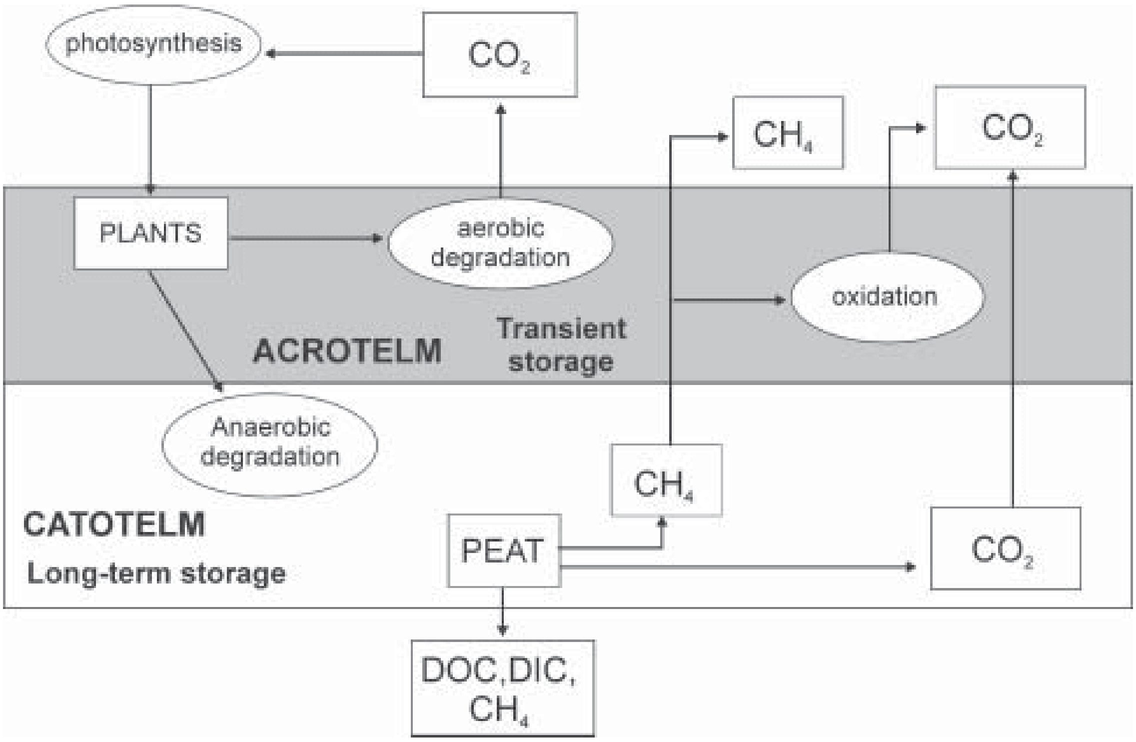
soil, these ecosystems have been exploited for agriculture, burned for grouse shooting and extracted for use by the gardening and whiskey industries (UKCEH, 2020). They have also been impacted indirectly through urbanisation and impermeable materials placed within the water catchment zone, preventing recharge of the aquifer which is needed to maintain the unique water chemistry that the environment relies on.

The lack of awareness of the value of these habitats has resulted in lack of funding and poor management. Naturally, without management, succession takes over, replacing the unique botanical diversity with scrub and trees, removing the water from the soil, resulting in oxidisation of peat. Though trees have their own value as carbon accumulators, the amount is they store is incomparable. Trees can store carbon for their lifetime (up to hundreds of years) and eventually this carbon will be released in the atmosphere during decomposition. Peat on the other hand, when kept wet, can store and accumulate carbon for thousands of years. Making peatland a higher and more stable carbon storage per surface area than the woodland.

4.2. Carbon Sequestration in Healthy Peatlands

Natural healthy peatlands are wetland landscapes with a surface layer of living plants. The plants absorb CO_2 and when plants eventually collapse, the waterlogged conditions inhibit the full decomposition of plant matter due to reduced oxygen. Oxygen limitations cause inefficiencies of anaerobic microbes which are not able to decompose matter faster than the rate of input (UKCEH, 2020). The peat carbon cycle can be seen in Figure 4.2.1. Undisturbed peatlands are commonly thought to contain two layers: the acrotelm which is the surface layer, a few decimetres thick, containing living and newly accumulated peat and the catotelm, which is permanently saturated and can be several metres thick, containing dead, compacted, ancient peat (Morris *et al*., 2011). A thin peat layer of just 30cm has an equivalent carbon store hectare by hectare to a tropical rainforest, however, peat is often much deeper than this (Lindsay *et al*., 2019) There are an estimated 3 billion tonnes of carbon stored in UK peatlands, the same as in all forests in UK, Germany and France combined (Moors for the Future, 2019; OFNS, 2019). The Paris

Agreement states these habitats should be protected by ensuring peatlands remain wet (IUCN, 2018).



4.2.1. Peatland carbon cycle (Source: McLaughlin, J.W., 2004)

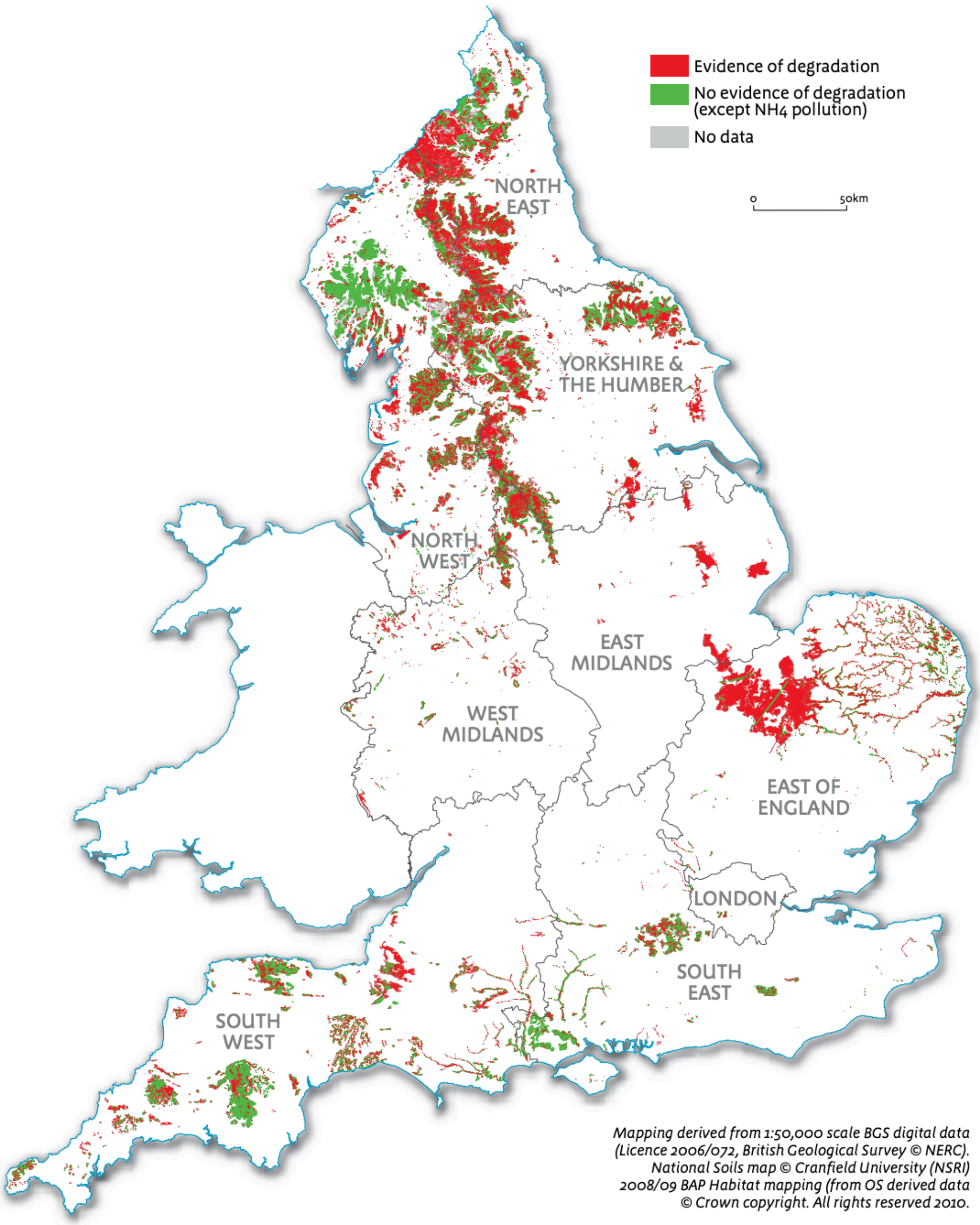
4.3. Greenhouse Gas Emissions in Degraded Peatlands

Carbon can be lost through drainage, erosion, and land use changes such as cultivation. The large amounts of carbon stored in these environments mean changes in their condition can turn them from carbon sinks into carbon sources (Natural England, 2010). The extent of this degradation can be seen in Figure 4.3.1.

When water tables are low, oxygen can reach the partially decomposed layers of peat, allowing previously stored carbon to decompose and be released as CO_2, whilst also halting peat accumulation. For this reason, drainage changes are said to have the greatest impact on greenhouse gas (GHG) release in peat fens (Natural England, 2010).

Erosion can also contribute to GHG emissions, decomposition of lower levels of peat can make the peat more vulnerable to erosion through the creation of peat pipes.

Water flows through gaps in the degraded peat, further eroding them into pipes. Carbon is transported through the peat pipes as dissolved carbon into water bodies where it can release as CO_2 (Natural England, 2010). Peat can be dissolved in water if there is enough flow and erosion which can also be exacerbated if the vegetation surface is degraded (OFNS, 2019). Eroded peat appears as brown water and dissolved organic carbon in peat water has doubled in the last 30 years (Yallop *et al*, 2010). It is estimated that 80% of peatlands in the UK have experienced some level of degradation making many of the UK peatlands no longer peat forming



environments (IUCN, 2018; Joosten *et al*., 2012).

4.4. Greenhouse Gas Emissions in Healthy Peatlands

As well as carbon, peatlands can also be the source for more powerful greenhouse gases, methane and nitrous oxide (Natural England, 2010). It is important to note that unlike carbon, sources of methane and nitrous oxide tend to be higher in healthy peatlands.

In healthy peatlands, microorganisms known as methanogens inhabit the deep anoxic layers of peat and break up methane which can release into the atmosphere through bubbles of 'marsh gas' or through hollow tissues of peatland shunt plants (Natural England, 2010). At the surface layer another group of microorganisms methanotrophs break down methane into $CO_{2.}$ Due to the microorganism's favour for anoxic conditions, rewetting peatlands usually results in an increase in methane emissions.

Not all restored peatlands can be considered carbon sinks, however, they do have less impact on global warming than unrestored peatlands (Baird *et al.*, 2009). Whether peatland rewetting restoration is an effective method for carbon storage or not depends on whether the increase in sequestration and reduced carbon emissions outweighs inevitable methane emissions. Methane emissions can be controlled in restoration projects by gaining control over water levels and controlling the abundance of methane shunts which release marsh gas from deeper layers.

Figure 4.3.1. Land area of degraded vs non degraded Peatlands in the UK. (Source: Natural England, 2010)

anoxic conditions and impede methane release (Natural England, 2010; Hausmann et al., 2016).

Nitrous Oxide can be produced in low oxygen conditions such as those found in peatlands, however this relies on nitrate in the soil which tends to be limited in waterlogged peatlands (Natural England, 2010). In Lye Valley nitrate levels are low so this is unlikely to be a significant issue (Webb, 2014).

Though this project focused solely on carbon, it is important to be aware of the potential emissions because of restoration, so management plans can incorporate methods to reduce other GHG emissions. However, restored fens produce higher carbon sequestration (Baird *et al*., 2009).

4.5. Peatland Restoration

Restoration of peatlands often involves raising the water table, revegetating the surface with moss and removing scrub (Cobbaert *et al*., 2004; Baird *et al*., 2019). Rewetting creates the anoxic conditions that allow peat formation to restart and significantly reduces carbon emissions by reducing the rate of decomposition; this is thought to be a key element in limiting carbon loss and must be achieved by recharging aquifers to ensure correct water chemistry (UKCIP, 2009). Revegetation of moss species allows reduction in erosion of ancient peat and enhanced water storage. The committee on Climate Change suggest 55% of peatlands should be restored by 2050 to meet carbon targets (ONS, 2020). In the UK peatlands represent the most significant source of terrestrial carbon and unlike other areas, their restoration creates little conflict with food security making them an optimal choice for carbon storage (Joosten *et al*., 2012; Moxley *et al*., 2011). Since the UK has a large amount of peatland compared with other countries, focus and prioritisation of peatland restoration seems a logical choice in enhancing our carbon sequestration, avoiding catastrophic carbon emissions and meeting carbon targets.

Management and restoration of peatlands are expensive and must cost less than benefits in carbon storage. Investigation by the Office for National Statistics reveals that although restoration of the UKs degraded peatland could cost between £8 billion- £22 billion, over the next 100 years, £109 billion would be saved due to reduced carbon emissions (UKCEH, 2020). However, assessment of the carbon potential of individual peatlands will be necessary to ensure the appropriate level of funding and efforts are put towards to most valuable sites and ensure that they become both nationally and locally protected and prioritised for funding.

While most published literature on peatland restoration is dedicated to blanket bogs, a successful example of fen restoration in the UK is the great fen restoration project

(Baird *et al*., 2019), an ongoing project aiming to restore 14 square miles of fen in Cambridgeshire within 50 years. Methods to deliver this target include connecting nature reserves to reduce fragmentation, controlling water levels and revegetation. It is estimated that the reduced peat erosion is already saving 350,000 tonnes of CO_2 annually whilst also providing flood mitigation through enhanced water storage and habitat for a number of rare and threatened species (Great Fen, 2020). Per year in a healthy fen around 1mm of peat is accumulated per year and in a degraded fen around 2cm per year is lost (Parish *et al*., 2008; UKCEH, 2020).

For Peatlands, prioritising restoration is imperative as degraded sites become more vulnerable to damage and restoration methods become less effective (Bain *et al*., 2011). Across the UK between 1990 and 2013 an estimated 110,000 ha of peatland have had some degree of restoration with the majority being rewetting (Artz *et al*., 2019). However, for many projects the success of these restoration efforts remains unclear without standardized methods to measure success. Estimating the carbon storage capabilities of sites can help to measure success of the conservation and restoration of peatlands. It is also important to measure these carbon storage capabilities against potential emissions if habitats are drained and degraded. Even if rewetting does not create a significant carbon sink, when taking into consideration the avoidance of potential emissions, restoration may still be a valuable option (Mrotzek *et al*., 2020).

4.6. Valuing Ecosystem Services

The world's economy would cease to exist without the resources and services that the natural world and its biodiversity provide. The services provided by the worlds terrestrial ecosystems were estimated at 75 trillion USD, approximately equivalent to the annual global Gross Domestic Product (Shukla *et al*., 2019). This is likely an undervaluation as it does not consider the immeasurable values provided by the natural environment in mental and spiritual wellbeing, inspiration, and aesthetic beauty (Shukla *et al*., 2019).

To be sustainable, the economy must be able to profit from the enhancement or protection of ecosystems, as these provide ecosystem services fundamental to our survival, such as water purification, air purification and fertile soil. If protecting and enhancing our environment comes at a cost to the economy ultimately natural resources and processes will become depleted and cease to exist over time, resulting in the loss of the fundamental survival needs of humanity. For this reason, valuing essential commodities often leads to an undervaluation (Heal, 2000). Valuing ecosystem services allows for a communion between ecology and economics in which the interconnection between the two disciplines can be both recognised and enhanced together, making way for a sustainable future. In many cases this involves payments for conservation based on avoided costs of the habitat’s degradation.

Financially valuing ecosystem services has been found to encourage engagement with policy makers and lead to successful restoration. Carbon services can be valued by using market prices for carbon. For landowners to conserve degraded ecosystems it must be a more attractive option and financial incentives help to ensure this (Heal, 2000). The valuations can be used to provide payments to landowners and communities as an incentive to restore, enhance and conserve ecosystems. Schemes such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries) have already been successful in protecting woodland using financial incentives. While some may not understand the complex interactions that result in ‘human gain’ nor the inherent value of an ecosystem, many can understand a financial value. Valuing ecosystem services has been used successfully as a means of encouraging funding and policy changes.

Ecosystem services are often under acknowledged as an economic asset. Valuing ecosystem services involves considering the costs avoided and value gained because of the presence of a healthy ecosystem or a specific element of one. This allows a monetary value to be placed on conservation efforts which gives clarity for policy makers on the value of a site. It helps in choosing areas to target for funding and in the amounts that can be placed to conserve different initiatives while still understanding that a profit is being incurred in the long term.

Valuing land-based resources will assist in coming to challenging conclusions about which ecosystems to focus on based on the areas of highest value and those in most critical need (Reed *et al*., 2014). Decision makers can be better equipped to establish whether funding may or may not be beneficial so that resources can be allocated effectively. It allows us to develop a deeper understanding of ecosystem functionality, giving potential insight to create strategies and find solutions to issues such as climate mitigation and adaptation whilst also developing databases which lead to more accurate valuations in the future.

4.7. Spatial Variability of Peatland Carbon Stocks

Carbon stock estimations can be variable both within and between peatland environments which highlights the need to map individual locations rather than extrapolating current data.

Peatlands are highly heterogeneous environments (Lindsay *et al*., 2010; Jianwie *et al*., 2019; Parry *et al*., 2012). Even within sites soil carbon content varies vertically and horizontally (Agus *et al*., 2011). Agus *et al*., 2011, found peat depth varied from 0.5 m to 15 m but is most commonly between 2–8 m depth. This highlights the large range in depth which can impact the accuracy of carbon stock estimations.

Published figures suggest peat to be an average of between 1.5m to 2.4m, however, this is not based on extensive systematic sampling and relates mostly to peatlands in Scotland. (Lindsay at al., 2010). Though most data on peatlands is gathered in Scotland it is used to make assumptions about carbon stocks of peatlands in Britain, this represents a bias within data and a need to expand research to other areas of te United Kingdom to ensure estimations are applicable.

As well as depth variation, this is also true for rates of erosion and carbon loss which vary from 0.6mm to 5cm per year (Lindsey at al., 2010). However, loss rates of 1-2cm per year are more commonly used (Page *et al* 2020; UKCEH, 2020).

Carbon content estimations may also be misrepresentative due to calculation errors. Carbon content is often calculated by an assumed fraction of 50% of found organic matter content. However, this has also been found to be variable and depends upon the quality of organic matter inputs. Some areas have a higher proportion of carbon within organic matter and therefore undervaluation can occur (Chambers *et al*., 2011).

Variability in carbon stock estimations are not only a result of variable soil composition but also due to differing ideas on the definition of peat. Definitions of peat soil vary across disciplines and authorities in terms of minimum depth and % organic matter (Lindsay *et al*., 2010; IPS, 2021). For example, the U.S. Department of Agriculture Soil Classification define peat a soil that contains a minimum of 20% organic matter (IPS, 2021). In the UK the Soil Survey of Scotland uses a minimum depth of 40 cm for pure-peat soils, whereas the limit for the Soil Survey for England and Wales ranges from 30 cm to 50 cm (Lindsay *et al*., 2014). Because of differences in definition of peat, estimates of peat extent varies. When only considering peat greater than 1m depth, peat extent is said to cover 1.5 million ha of the UK as opposed to the 5 million ha it truly covers (Lindsay at al., 2010).

This study was concerned with estimating carbon stock, so definitions on whether soils are considered peat did not apply as the entire soil core was systematically sampled at set resolutions to obtain an average estimate of carbon for the site. However, when comparing results to estimates from other studies this is important to take into consideration as some studies focusing specifically on carbon stored within peat may have taken out samples from data sets of cores of less than 30cm or of less than 20% organic matter even if they are within a peatland environment.

Spatial variability of peatlands paired with differing definitions and calculation methods highlight the need for standardised approaches to carbon mapping of peatlands to ensure data can be generalised and appropriately compared in the future.

4.8. Data Gaps on Lowland Peatlands

Peatland soils are highly heterogeneous and vary greatly in terms of depth, organic matter and carbon content (Jianwie li, 2019; Lindsay *et al*., 2010). Because of spatial variation typical of peatlands, carbon mapping is needed in order to spatially prioritise restoration projects (Glenk *et al*., 2014). Despite the understood differences in peat function and GHG fluxes, current data does not allow differentiation between bog and fen peat (Evans *et al*., 2011). Most published literature on peatlands is dedicated to blanket bogs in upland areas as this represents 90% of peatland within the UK (Baird *et al*., 2019). Relatively few studies have been undertaken on lowland peatland so data used in average emissions may not be representative of lowland peat environments such as alkaline fens (Haddaway *et al*., 2014). Though lowland peats account for less than 10% of peatland in the UK they are subject to greater land use pressures than upland peatlands. Land use pressures on peatlands account for 70% of peatland emissions and 54 % of total emissions from peatlands are thought to have derived from lowland sites (Worral *et al*., 2011). Despite covering a much smaller land surface, current data suggests lowland peatlands may have a greater impact on emissions than upland peatlands due to land use pressures (Worral *et al*., 2011). If this is the case, it is important that emissions inventories be reflective of the different peatland environments and focus should be made on closing the data gap on the carbon stock, accumulation, and erosion rates of lowland peatlands (Haddaway *et al*., 2014).

4.9. Lye Valley: Study Site

Lye valley peat fen covers 1.5 ha. It is a rare habitat which is c.8,000-years-old. The valley forms tufa and is fed by lime rich springs; an internationally rare habitat located in Headington, Oxford. Though covering a small area, the site represents 12.7% of the last remaining habitat of its kind in England which highlights the rarity of the site (FoLV, 2020). The site supports 14 plant species on England's red list including *Epipactis palustris* marsh helleborine and *Parnassia palustris,* grass of parnassus, 10 rare invertebrate species including *Lampyris noctiluca*, glow worms and *Thecla betulae,* brown hairstreaks, 27 nationally scarce invertebrate species and an abundance of reptiles and amphibians (FoLV, 2020). Due to the sites ecological value, part of the area is a designated Site of Special Scientific Interest (SSSI) and the rest of the site is a local nature reserve, the boundaries of which can be seen in Figure 4.9.1. Lye Valley is one of several Oxon alkaline fens that are targeted by Natural England for condition improvement due to their value (Webb, 2014).

The alkaline springs filter through Beckley Sands in the west side of the north fen which has a high iron content. This forms iron oxide and creates orange or oil like slicks on the water due to chemotrophic bacteria which feed on the iron input. The underlying geology is porous limestone from a Jurassic Coral Reef and below this is Oxford clay. The aquifer water supply feeds thorough porous limestone which enriches the water with dissolved calcium carbonate giving it a high pH of 7.5. When the calcium carbonate oxidises it can be seen as white deposits known as tufa which can be seen in soil cores and on overlying vegetation (Webb, 2012). Vegetation is dominated by brown moss communities (European Commission, 2008).

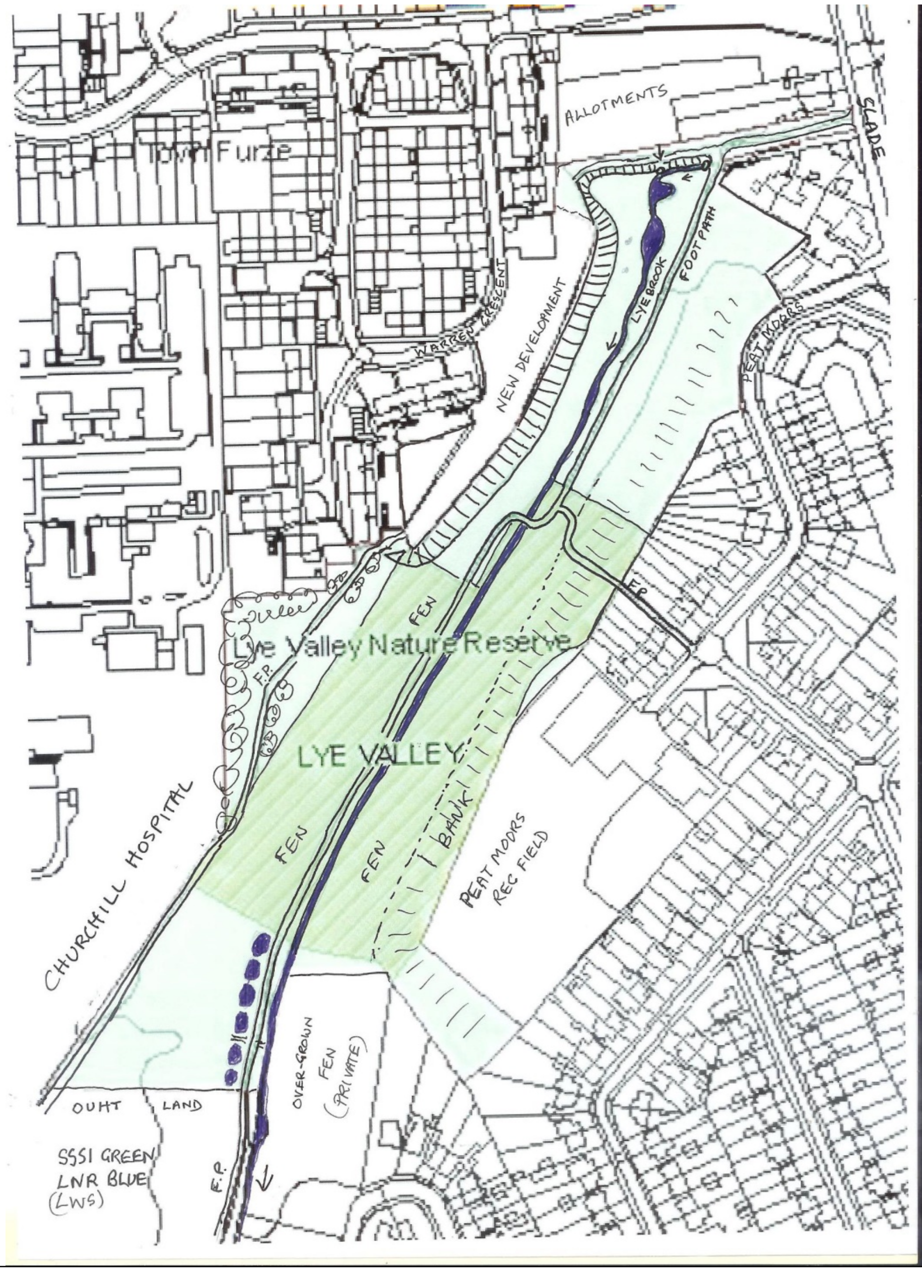


Figure 4.9.1. Map of Lye Valley highlighting the SSSI boundaries (Source: FoLV, 2020)

4.10. Threats to Lye Valley

Due to urbanisation within the valleys water catchment area and the use of impenetrable materials, surface run off has increased and groundwater has decreased which would have previously fed and supplied the aquifer with the mineral rich waters that the species rely on. The alkaline fen and the rare species inhabiting it have adapted due to the water supply and its chemistry. Water runs through the underlying geology which creates water characteristics of high pH, high calcium, low nitrate, low phosphate; urbanisation has reduced the supply of water with these characteristics. This reduction is ongoing as urbanisation has continued and effects can be delayed by as much as 20 years. (Webb, 2014). Water supplied by the overland drainage flows quickly, eroding peatland at times of high precipitation and exposing more peat to oxidisation as the drains are deepened. Funding aims to target this hydrological issue, by directing flood waters away from the fen in order to protect botanical interests and encourage water from the aquifer. The focus is also on reducing erosion cause by fast flow from storm drains. Locally sourced willow is being used to reinforce banks providing a barrier between the water and peat to reduce erosion. As well as this, locally sourced woody materials have been used to create leaky dams, slowing the flow of water from the groundwater drainage pipe which flows at high velocity at times of heavy rainfall. This is currently being carried out by Friends of the Lye Valley but more work and investment is needed to rewet and preserve the peat, including halting future development within the aquifers water catchment area, and finding a solution such as the use of permeable ground materials so that water continues to reach the aquifer rather than moving overground and eroding the peat.

Poor management such as tree growth has also impacted water supply, this is a common issue in peatland fens. Natural succession leads to scrub domination and woodland formation and can further drain the peatlands. The site was historically managed by grazing, the short turf allows greater biodiversity, this is being replicated by scything under current management which has reduced reed and nettle dominance and enhanced botanical diversity. Current site targets are to restore tufa fen areas around the SSSI, restore short fen habitat and extend the SSSI limits to cover them (Webb, 2014). The Lye Valley SSSI provides an important seedbank for repopulating other SSSI alkaline fens within the county, however, management efforts must restore the site to a ‘Favourable Condition’ under the Natural England assessment criteria before this is possible (Webb, 2014). Natural England had a target of returning all Oxon alkaline fens to favourable condition by 2020, however this was not achieved, likely due to lack of funding and prioritisation of this rare habitat. This project aims to support the sites targets by demonstrating the value of the site that will encourage funding to restore the tufa fen. Several other research projects are also underway which will help to give a greater insight into the sites value.

4.11. Oxford Carbon Targets

Low Carbon Oxford is a network of 40 organisations working together to achieve the city’s target of reducing emissions in Oxford by 40% (in comparison to a 2005 baseline) by 2020. Since achieving this target Oxford set a 'vision' for reaching Net Zero by 2040, 10 years faster than the Government’s legal deadline of 2050. (LCO, 2021)

To achieve this Oxford created a roadmap outlining the steps that must be taken by each sector to reach the goal of net zero by 2040. If the steps are followed at the agreed deadlines, it is predicted that by 2040 the combined efforts of each sector will lead to a reduction of 88% carbon emissions when compared to 2018. Residual emissions are predicted to be 88.7 ktCO_2e and will be offset using carbon credits to meet net zero targets (OCC, 2021a).

Despite these ambitious aims, the natural asset of its rare peatland habitat, which are known to store the greatest percentage of terrestrial carbon, are not mentioned within the GHG emission report, net zero Oxford plan, zero carbon plan, sustainability strategy, low emission strategy or carbon management plan (OCC, 2021b). Even though these plans focus on current emissions in Oxford and consider ways to reduce them. Peatlands are known to have high carbon storage capacity as well as contributing to significant emissions when in a degraded state and should be considered within emission reports and sustainability strategies.

In the biodiversity action plan, it is stated “The council is committed to sustainability and carbon reduction, to which biodiversity is key.” The Lye Valley Fen is mentioned here but only in terms of biodiversity. The carbon storage and site degradation is not commented upon and its potential in climate mitigation is not highlighted (OCC, 2015).

Though biodiversity has been recognised as a key element in carbon reduction, natural land use enhancement has focused on tree planting (Spencer and Robinson, 2021). This may be due to lack of knowledge on the carbon stocks of Lye Valley and their potential in GHG emissions which this project aims to highlight.

5. Methodology

The project estimated the peat carbon stock in Lye Valley. Lye Valley is currently under threat due to urban development impacting hydrology, meaning the peat is drying out. The research will help to prove the lands value as a carbon storage ecosystem and its potential in climate change mitigation.

With the carbon stock data an estimation of the carbon value was made as well as an estimation of potential costs in emissions of greenhouse gas due to the continued degradation of the habitat. This will help to emphasise the need for funding to support the conservation of this rare habitat such as the much need rewetting of the fen. This will allow the thousands of years’ worth of accumulated carbon to remain stored and enable to continuation of carbon sequestration in the future. Findings can inform a cost-benefit analysis to give suggestion on whether funding will be a worthwhile choice when comparing expected emissions resulting from the ongoing degradation of the site.

Soil cores were extracted from the site and measured for both organic matter and carbonate mineral contents by heating samples until the organic matter and carbonate mineral content oxidises into CO_2. The investigation into inorganic as well as organic carbon within peatland is a unique element to the project, as very little research has been done on this thus far. This project focused in on key gaps identified within peat carbon research which have be outlined within the peat action plan, including carbon mapping (DEFRA, 2021).

5.1. Field Methods

Part of the Lye Valley Nature Reserve is a designated SSSI and the extraction of peat fell within the operations requiring consent. Therefore, permission was first gained by the Oxford City Council and Natural England to allow for coring to take place.

Figure 5.1.1. Darcey Haldar and Terry Newsome Coring in Lye Valley using a Russian Corer with extension pole

Following this, coring was undertaken on the SSSI area of the fen to preserve botanical interest of the site before rarer species fully come into flower. Fieldwork was undertaken with help from the Friends of Lye Valley group (Figure 5.1.1.) and Oxford Brookes University staff with local knowledge of the site.
Peatlands have high spatial heterogeneity even within sites (Glenk *et al*., 2014). Systematic sampling has been found to increase accuracy of results for soil sampling in peatlands and requires intensive sampling of at least a few hundred (Jianwei, L., 2019). This was taken into consideration and transects were measured at 30m apart along the valley. Cores were extracted every 2m along the transect unless there were obstructions such as sewage pipes, rubble, or rare plants.

Cores were extracted using a Russian corer with samples both measured for depth and taken back to the lab for analysis on inorganic and organic carbon content. For cores longer than 1m an extension pole was used. The Russian peat corer is a commonly used tool for peatland sediment investigations since its introduction in the mid-20th century (Franzeng and Ljung, 2009). It is an ergonomically efficient tool which can provide fast access to soil cores, however they can cause compression particularly in more stiff or fibrous sediment (Franzeng and Ljung, 2009).

Figure 5.1.2. Locations of core extractions in Lye Valley (Source: ArcGIS)

34 cores were extracted, equating to a depth of 2279cm depth and measured 595 samples from this. The corer was washed between extractions to prevent contamination of samples. GPS coordinates of each core were recorded and transect locations can be seen in Figure 5.1.2. Cores were measured (Figure 5.1.3.), wrapped, labelled, and immediately transported to Oxford Brookes cold store to

Figure 5.1.3. Measuring a soil core extracted from Lye Valley

preserve them before analysis.

5.2. Lab Methods

5.2.1. Determining Dry Bulk Density

5.2.1.1. Rationale

Bulk density shows the moisture holding capacity of sediment. This indicates characteristics of the sediment such as porosity and highlights changes within the depth profile. As bulk density increases, moisture holding capacity tends to decrease. Lower bulk density is typically associated with a higher organic content. The dry bulk density is also a necessary process prior to loss on ignition so that any weight caused by moisture content is removed and does not impact estimations of organic matter and carbonate mineral content which were measured afterwards.

Figure 5.2.1. Weighing scales and pre calibrated brass crucibles used in bulk density analysis at Oxford Brookes laboratory

5.2.1.2. Methodology

Samples were placed in pre calibrated brass pots using fine metal spatulas. Samples were taken at varying resolution. The largest core from each transect was measured at a higher resolution, with a sample taken every 2cm. Time constraints meant that the remaining samples had to be taken at a lower resolution with a sample taken every 6cm. Samples were measured to 4 decimal places. Equipment used can be seen in Figure 5.2.1. Samples were then placed in the oven at 105°C for a minimum of 12 hours. Samples were then cooled and reweighed to 4 decimal places. This gave the dry weight of the samples once the water had evaporated. Following the weighing, samples were placed into an enclosed drying rack containing silicone beads to ensure they did not regain any water. These were then used to measure loss on ignition.

5.2.1.3. Formula

Wet bulk density (g/cm3)
(weight of pot + wet sediment weight)- (weight of pot)/ (weight of pot + water) – (weight of pot)

Dry bulk density (g/cm3)
(weight of pot + wet dry weight)- (weight of pot)/ (weight of pot + water) –(weight of pot)

Moisture Content (%)
100- (weight of pot + dry sediment) – (weight of pot)/weight of pot + wet sediment)- (weight of pot) x 100

5.2.2. Determining Organic Matter Content

5.2.2.1. Rationale

Organic matter is made up of partially decomposed plant and animal matter and microbes, microfauna and their by-products. The extent of organic matter within sediment is dependent on the accumulation of biomass during the life of the organism and the preservation of that biomass during decomposition.

LOI involves oxidising the organic matter to produce carbon dioxide and ash, the loss can be measured by the changes in weight before and after heating the samples (Heiri *et al*., 1999). A number of studies have shown that volatile salts, inorganic carbonate and structurally bound water can occur between 425°C and 550°C leading to over estimations of organic matter content (Heiri *et al*., 1999). LOI will give you the mass load on ignition and not the actual amount of carbon. Most studies overlook this and therefore overestimate C. LOI is a commonly used method to estimate organic and carbonate content in sediment. LOI provides a cost effective and fast way to estimate organic content (Heiri *et al*., 1999).

Positioning within the muffle furnace has been found to impact results when undertaking LOI 550 (Heiri *et al*.,1999). At 550°C, samples within the centre of a muffle furnace have been found to lose greater weight than those surrounding them indicating a possible bias (Heiri *et al*., 1999). The muffle furnace available at Oxford Brookes University can hold only 50 samples at a time, therefore, due to time constraints, if samples were only placed in the centre of the muffle furnace to avoid this potential bias, a much lower resolution and fewer samples would be possible which would likely impact the accuracy of results much more profoundly than the muffle furnace positioning. Considering these options and the number of cores, the muffle furnace was filled to its full capacity to allow maximum samples to be measured.

5.2.2.2. Methodology

Following dry bulk density, dry samples were individually disaggregated using a pestle and mortar. Porcelain crucibles were weighed to 4 decimal places and disaggregated samples were placed in them. This equipment can be seen in Figure 5.2. The filled crucibles were then reweighed to four decimal places. Crucibles were then placed in the muffle furnace at 550°C for 4 hours. The crucibles were then left to cool and reweighed to four decimal places.

Figure 5.2. Equipment used to prepare samples for Loss on ignition within the porcelain crucibles

5.2.2.3. Formula

$LOI^{550} = ((DW^{105} – DW^{550})/ DW^{150}) \times 100$*

**The mass of the crucibles were subtracted from the dry weights before making the calculation*

5.2.3. Determining Carbonate Mineral Content

5.2.3.1. Rationale

The tufa in the cores can be removed either by wet digestion (with HCl) or via LOI at 950°C which removes carbonates and mineral residue. At 950°C sample results are less impacted by sample size, position within furnace, lab methods and exposure time than at 550°C (Heiri *et al*., 1999). Loss on ignition method at 950°C has been found to produce accurate results after 2 hours (Heiri *et al*., 1999). Following organic matter oxidisation, the carbonate is estimated using an increased temperature of 950 this involves the release of carbon dioxide and oxide from the carbonate content. Carbonate mineral content is then estimated by measuring the weight before and after heating (Heiri *et al*., 1999)

5.2.3.2. Methodology

After recording results from organic matter content analysis, samples were then placed back into the muffle furnace at 950°C for 2 hours to oxidise carbonate and minerals. Samples were then left to cool and reweighed to four decimal places.

5.2.3.3. Formula

$LOI^{950} = ((DW^{550} – DW^{950})/ DW^{150}) \times 100$*

5.3. Data Analysis Methods

5.3.1. Statistical Analysis

An ANOVA test was conducted to ensure all cores were not significantly different, this helps to understand whether the sample size was large enough and whether estimations can be considered as reliable.

The tukey method was used on depth profile results to pick out any outliers that may be as a result of human error. Outliers were removed from the data and estimations were made using the remaining results.

5.3.2. Estimating the Carbon Stocks

The organic carbon content (%Corg) is estimated by multiplying LOI^{550} results by 0.5. This is because organic matter is typically 50% carbon, however, this can be spatially variable (Chambers *et al.*, 2011). Carbon stocks per hectare were estimated by using BD which is already in g/cm^3 (due to pre calibration of brass pots), %Corg and average depth of site (Cowley and Fryirs, 2020). Estimations are then made for the area of the site.

5.3.2.1. Formula

Carbon density (g/cm^3)= (Bulk density g/cm^3 * %Corg)/100

Carbon stock (g/cm^2)= Average carbon density of core (g/cm^3)* depth of core (cm)

Carbon stock (tC/ha)= Carbon stock g/cm2* 100

Total carbon stock (tC)= carbon stock (t/ha) * area of site (ha)

Lye Valley is 24 hectares

5.3.3. Estimating the Value of Carbon Stocks

This was used to highlight the value of carbon stock based on a healthy peatland which is both retaining the current carbon stock and also accumulating peat. Wet fens create an average addition of 1mm per year accumulated peat. The carbon in 1mm can be estimated and added to the value each year.

The value was estimated using the UK governments document highlighting the approach to valuing greenhouse gas (GHG) emissions in policy appraisal, which "includes a monetary value that society places on one tonne of carbon dioxide." Estimations were made based on 2021 values in Table 5.3. but include a real annual growth rate of 1.5% (BEIS, 2021).

Year	Low series	Central Series	High Series
2020	120	241	361
2021	122	245	367
2022	124	248	373

Table. 5.3. Low, central and high values in £ per 1 tonne of Carbon with a real annual growth rate of 1.5% to be used in UK policy when estimating a monetary value on emissions (BEIS, 2021).

5.3.3.1. Formula

Value of carbon stock (£)= current price of carbon per tC/ha (£) * Total carbon stock (tC/ha)

Value of annual accumulated carbon** (£/yr) = ((Total carbon stock (tC/ha)/ Average depth of core (cm))/10) * current price of carbon per tC/ha (£)

**based on accumulation rates of 1mm per year

With a real annual growth rate of 1.5%

5.3.4. Estimating the Potential Cost of Carbon Stocks

This will be displayed as expected annual costs resulting from a scenario in which there is no intervention and Lye valley is left to degrade. This was estimated using the UK governments valuation of carbon per tonne as well as carbon stock estimates. Degraded peatland erodes at 2cm per year, as well as this 1mm per year is not being accumulated.

It is worth noting that continued degradation also means that eventually restoration will not be possible so as degradation develops the carbon stock will eventually release, as well as the loss in potential accumulation.

5.3.4.1. Formula

Value of annual eroded peat **(£)= ((Total Carbon Stock tC/ha/ overall average depth (cm))* 2) * current price of carbon per tC/ha (£)

Annual cost of degraded peatland (£)= value of annual eroded peat (£) + value of annual accumulated carbon (£)

**based on 2cm erosion per year

With a real annual growth rate of 1.5%

6. Results

34 cores were extracted, equating to a depth of 2279cm depth and measured 595 samples from this. All samples were analysed for bulk density and loss on ignition at 550°C and 950°C. Estimations are based on averages of cores, transects and the site.

6.1. Statistical Analysis

Box Plot Analysis

Box plots were created to show potential outliers for organic matter content and carbonate content readings. Potential 'outliers' were highlighted as especially high readings and can be seen in table 6.1. On further investigation these readings were in different cores at similar depths. They highlighted areas of ancient peat or tufa stores within the depth profile of the site and were not removed from the data. More details on calculations can be found in Appendix A.

Core	Depth (cm)	LOI 550 %OM
D5	-2.5	78.62903226
D6	-2.5	72.9844413
D2	-2.5	70.72796935
D3	-2.5	61.09610189
D5	-8.5	68.72759857
D6	-8.5	64.75917978
D3	-8.5	62.34347048
D7	-14.5	59.93065874
D6	-14.5	58.60899067
D4	-20.5	65.31385281
D7	-20.5	59.39329431
D2	-20.5	59.29839391
D4	-26.5	61.7631152
D6	-80.5	59.03819918
D8	-92.5	74.17498081
D9	-94.5	76.59777424
D9	-96.5	76.83835439
C8	-96.5	57.21676151
F7	-128.5	67.35701152
D9	-128.5	60.4

Core	Depth (cm)	LOI 950 %Carbonate
C5	-2.5	39.1768319
C6	-2.5	38.2787162
D7	-2.5	36.1506752
E10	-2.5	36.125
E7	-2.5	36.0724382
D3	-2.5	29.6565033
E8	-2.5	28.8647229
D7	-8.5	41.48
C6	-8.5	40.1169536
E10	-8.5	38.3676633
C5	-8.5	31.7555492
E10	-14.5	34.4054244
C5	-14.5	31.7826087
C6	-14.5	31.1709222
C6	-20.5	28.5941887
E10	-20.5	28.3887014
C6	-26.5	27.0010449
C6	-32.5	42.6221359
F6	-76.5	38.7671085
F6	-78.5	33.5782707

Table 6.1. Top 20 highest readings for % organic matter and % carbonate content organised by depth.

ANOVA

An ANOVA test was conducted for organic matter content and carbonate content data. This was undertaken to determine whether cores were significantly different from one another, this helps to understand whether the site is spatially variable in terms of organic matter content and carbonate content, results are stated below.

Organic Matter Content ANOVA

ANOVAs were undertaken first on individual transects to determine variability of cores within a transect. Cores in transects E and F were significantly different to each other in terms of organic matter content, showing variability for organic matter content for these areas of the site. This was not true for Transects C or D where cores did not show to be significantly different from each other.

An ANOVA was then undertaken between transects to determine whether there was variation across the site. Transects were found to be significantly different from each other amongst the site for organic matter content.

Further information on findings can be found in Appendix B.

Carbonate Content ANOVA

ANOVAs were undertaken first on individual transects to determine variability of cores within a transect. Cores in transect C were significantly different to each other in terms of carbonate content, showing variability for carbonate content in this area of the site. This was not true for Transects D, E or F, where cores did not show to be statistically significantly different from each other.

An ANOVA was then undertaken between transects to determine whether there was variation across the site. Transects were found to be statistically significantly different from each other across the site for carbonate content.

Further information on findings can be found in Appendix C.

Findings from the ANOVA show variation between transects for both organic matter and carbonate content, and, in some cases, variability within transects. Findings indicate that the site is heterogeneous in terms of sediment composition. However, due to the large sample size of 34 cores and 595 samples, spatial variation has been considered and well accounted for and results can still be considered as reliable (Valejo *et al*., 2019).

6.2. Spatial Variation

Variation in Organic Matter and Carbonate Content

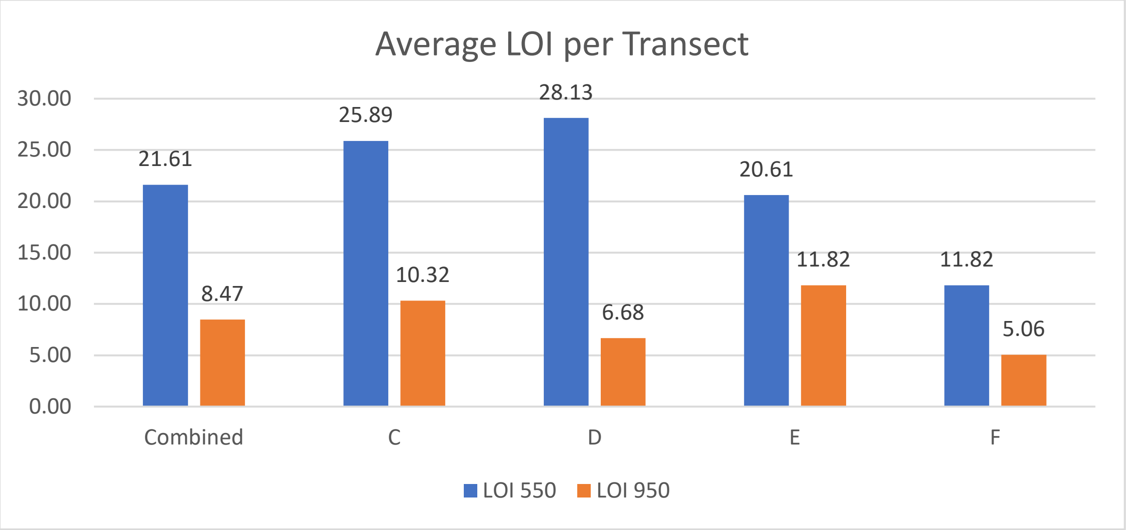


Figure 6.2. Average organic matter and carbonate content (%) per transect at Lye Valley

As can be seen in Figure 6.2. transects were variable for % organic matter content and carbonate content ranging from an average of 11.82%- 28.13% for average organic matter content to 5.06%-11.82% for average carbonate content.

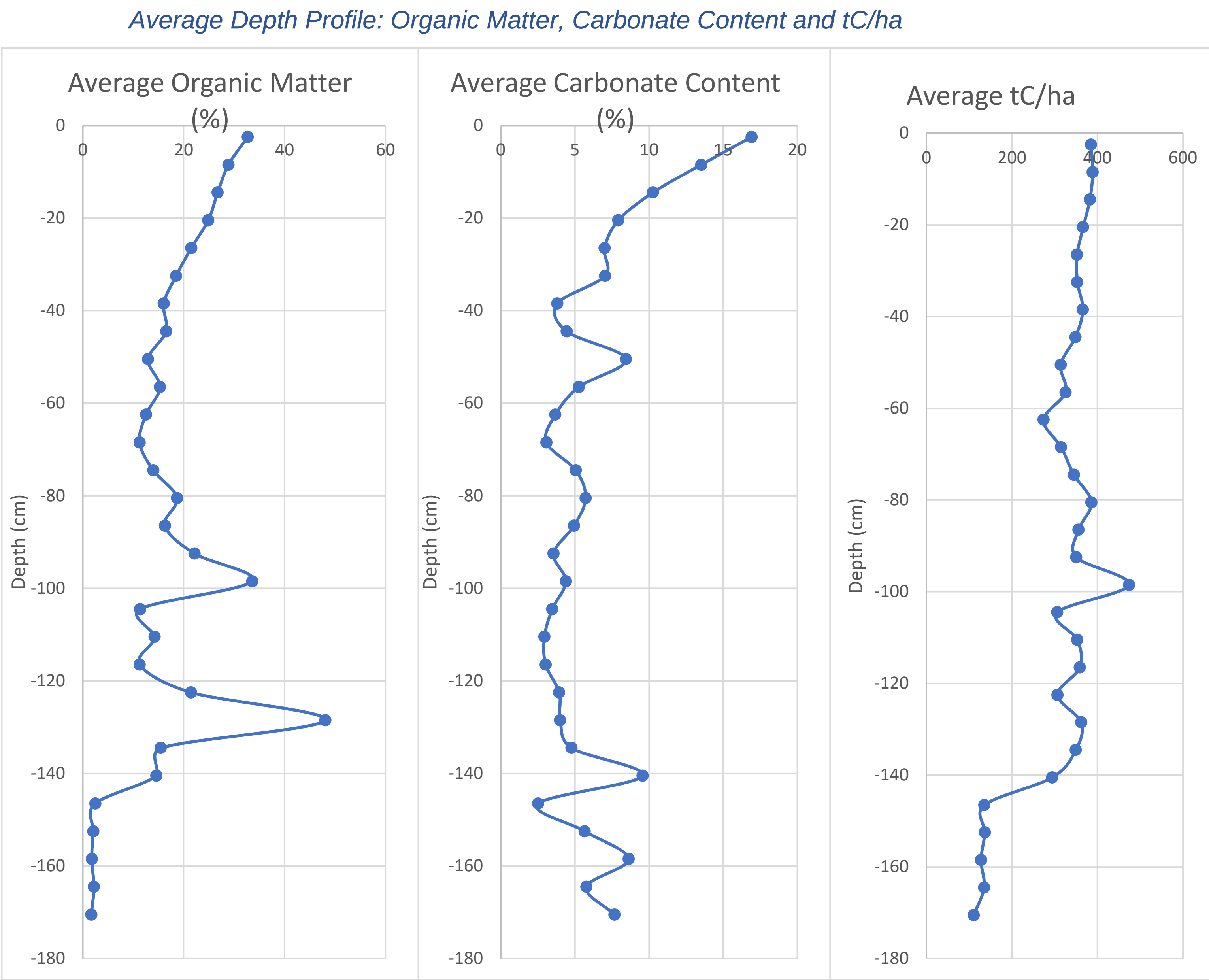


Figure 6.2.1. Average depth profile for (A) % organic matter (B) % carbonate content and (C) tC/ha. Using combined averages for each transect.

As can be seen in Figure 6.2.1., an average depth profile of all transects across the site showed highest %organic matter content in the upper 20cm, at 100cm and 130cm showing newly accumulated as well as ancient peat layers. Average depth profile for carbonate content showed exceptionally high readings in the top 15cm of the core as well as at 50cm and 140cm showing tufa formation at the surface and ancient tufa deposits. Highest carbon content was found at the upper 40cm, 100cm and 130cm and the lowest readings lower down in the profile between 150cm and 170cm.

Variation in tCha per Core and Transect

Figure 6.2.2. Average tC/ha estimates per core, showing variation between and within transects

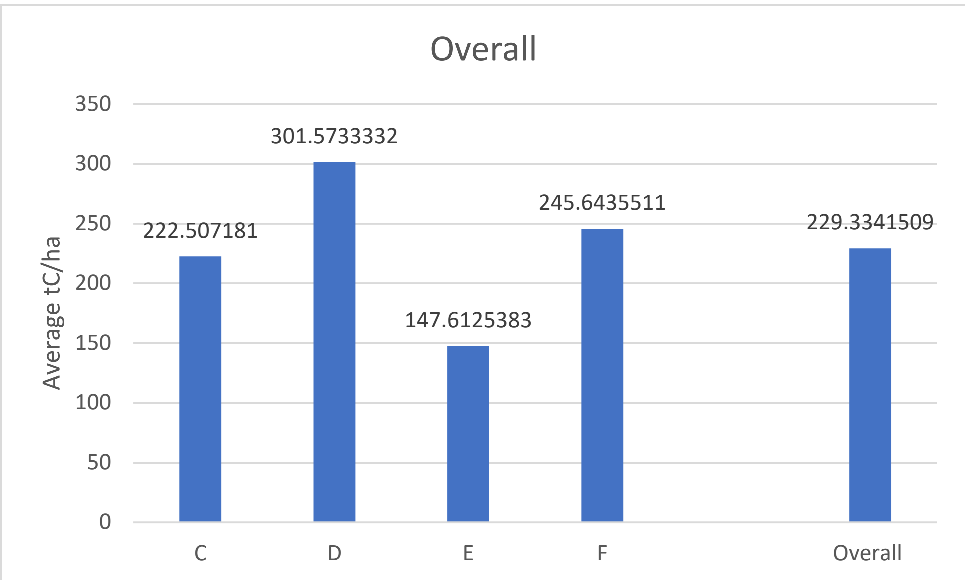


Figure 6.2.3. Averag

The graphs in figures 6.2.2. and 6.2.3. display what the estimated carbon stock would be based on individual cores or transects. The site is heterogenous in terms of sediment composition and depth and a high sample size was necessary to incorporate the variation across the site.

		Tonnes of Carbon per Hectare		
Transect	**Depth (cm)**	**Minimum**	**Maximum**	**Range**
C	59.07142857	67.3147984	472.323619	405.008821
D	81.38888889	143.987939	585.268734	441.280794
E	40.3	33.0630314	257.386152	224.323121
F	80.25	134.608583	464.337627	329.729043
Average	65.25257937	94.7435881	444.829033	350.085445

Table 6.2.4. Variation in data used to calculate average tonnes of carbon per hectare

Estimated tCha was highly variable both within and between transects, with an average range of 350 tCha across the site, this is likely due to variation in depth of cores that were able to be extracted. Table 6.2.4. shows Transect D had the highest average at 301.57tCha and the highest average depth at 81.4cm. Transect E on the other hand had the lowest average at 147.61tCha and the lowest average depth at 40.3cm. Overall the site had an average of 229.334 tCha.

6.3. Estimated Carbon stock

Estimated Carbon per ha (t C/ha)	Site Size (Ha)	Carbon Stock Estimation (t C)	Healthy peatland scenario: Annual accumulated (t C)	Degraded peatland scenario: Annual eroded (t C)
229.3341509	24	5504.019622	8.43494568	168.698914

Table 6.3. Estimated total carbon stock, estimated annual accumulated carbon in a healthy peatland scenario and estimated eroded annual carbon in a degraded peatland scenario for 24ha Lye Valley

Table 6.3. shows that with an average of 229.334 tCha, the 24 ha site holds an estimated carbon stock of 5504 tC.

In a healthy peatland scenario peat will accumulate 1mm per year on average. For the 24 ha site this means, if healthy, Lye Valley would accumulate an estimated 8.4 tC/year.

Alternatively, in a degraded peatland scenario peat erodes an average of 2cm per year. If Lye Valley is left to degrade this would lead to estimated annual emissions of 168.7 tC/year for the 24 ha site.

If restored and made healthy Lye Valley would both accumulate 8.4 tC, as well as avoid emissions of 168.7 tC per year. This means the potential benefits of restoration would lead to reduced emissions of 177.13tC/year.

Further information on calculations can be found in Appendix D.

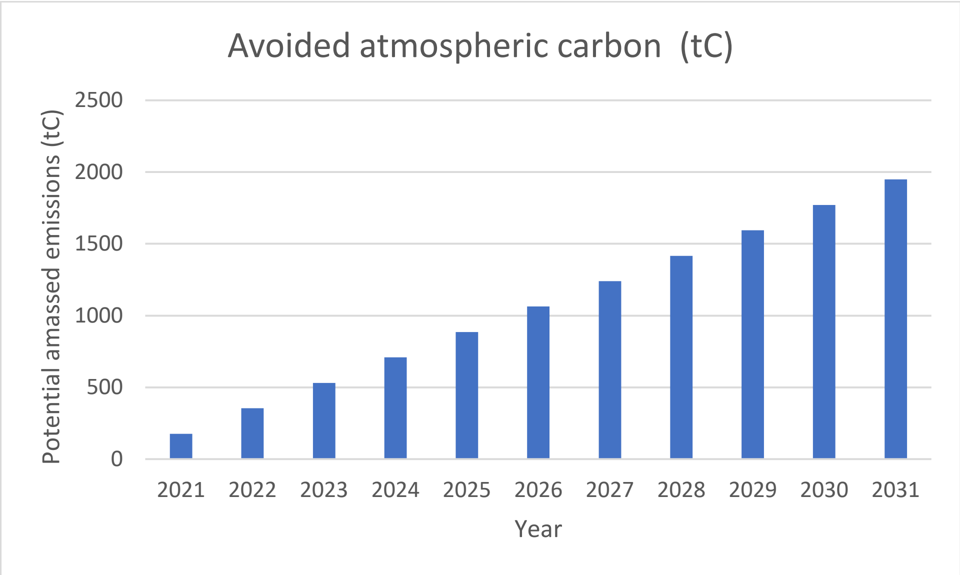


Figure 6.3.1. Potential net emissions (tC) over time, in a healthy peatland scenario, including avoided emissions and accumulated carbon

If restored and enhanced this 24ha area of Lye valleys could stop 1948 tC (Figure 6.3.1.) from entering our atmosphere in the next ten years. Per year this is equivalent to average annual carbon emissions resulting from the use of 412 cars (Carbon Independent, 2007).

On the contrary, this also displays potential additional carbon in atmosphere in a degraded peatland scenario for the 24 area of Lye Valley. It includes emissions resulting from eroded peat as well as the inability to accumulate carbon.

6.4. Estimated Value of Carbon Stocks

Carbon Estimation (t C)	Market Value of tC 2021 (£)	Carbon Value (£)	Annual accumulated (£)
5504.019622	£122 - £367	£671,490.39-£2,019,975.20	£1,029.06-£3,095.63

Table 6.4. Estimated value of total carbon stocks and annual accumulated carbon

Using the UK governments standardised guidance for valuing GHG emissions, the value of the carbon stock for the 24ha site was estimated to be between £671,490.39- £2,019,975.20 for 2021 with a real annual growth rate of 1.5% (Table 6.4.).

The value of annual emissions resulting from 1mm of accumulated peat is £1,029.06-£3,095.63 for 2021 with a real annual growth rate of 1.5%.

6.5. Estimated Potential Cost of Carbon Stocks

	Healthy peatland scenario: Annual accumulated	Degraded peatland scenario: Annual eroded	Total Annual Cost (t C)
(t C)	8.43494568	168.698914	177.133859
Value (£)	£20,581.06-£61,912.50	£1,029.06-£3,095.63	£21,610.33-£65,008.13

Table 6.5. Estimated costs of carbon in a degraded peatland scenario including estimated annual eroded peat and loss of accumulation potential

The cost of 2cm of annual erosion in a degraded peatland scenario is estimated at £20,581.06-£61,912.50 for 2021 with a real annual growth rate of 1.5% (Table 6.5.). This means the potential costs of leaving Lye Valley to degrade includes loss of accumulation as well as erosion would lead to annual costs of £21,610.33-£65,008.13 for 2021 with a real annual growth rate of 1.5%.

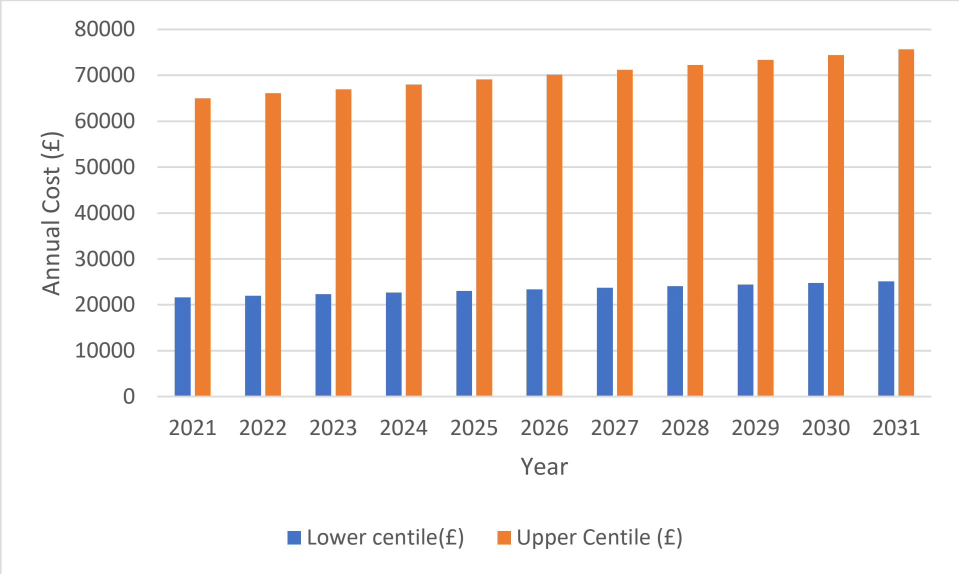


Figure 6.5.1. Upper and lower estimates of annual cost in a degraded peatland scenario, year upon year, with 1.5% annual inflation (BEIS, 2021)

Figure 6.5.1. shows potential annual costs caused by leaving Lye Valley to degrade. This includes costs for the entire 24ha site and is based on erosion rates and loss of accumulation capabilities. Costs are based on UK government upper and lower centiles of carbon which experience an annual growth rate of 1.5%.

7. Discussion

7.1. Summary

The aim of this research was to develop an understanding of the average organic matter content, carbonate content and bulk density of the soil profile of Lye valley through extensive soil coring. Using these findings, estimations were made on carbon stocks and the expected emissions resulting from either leaving Lye Valley to degrade or investing in its restoration. This involved financially valuing stocks, including expected annual increased value in a healthy restored peatland scenario, and expected costs resulting from a degraded peatland scenario. The purpose of this research was to encourage funding for restoration and conservation of Lye Valley and give policy makers a greater understanding of the value of the site allowing them to make informed decisions on its future and assist with distributing a considered budget.

The analysis confirmed that the site is heterogeneous in terms of sediment composition, with spatial variation in organic matter, carbonate, and carbon content in the soil profile. The results indicate that Lye Valley has a high carbon stock of 229.334 tC/ha, meaning the 24-ha site holds an estimated carbon stock of 5504 tC. This holds a value of between £671,490.39- £2,019,975.20 for 2021 with a real annual growth rate of 1.5%. In a healthy peatland scenario, peat will accumulate 1mm per year on average. For the 24-ha site this means, if healthy, Lye Valley would accumulate an estimated 8.4 tC per year. In a degraded peatland scenario peat erodes an average of 2cm per year. If Lye Valley degraded this would lead to estimated annual emissions of 168.7 tC. If restored and made healthy Lye Valley would both accumulate carbon, as well as avoiding emissions due to erosion. This means the potential benefits of restoration would lead to reduced net annual emissions of 177.13 tC per year. The equivalent of annual average emissions of the use of 412 cars (Carbon Independent, 2007). This would lead to saved annual costs of £21,610.33-£65,008.13 for 2021 with a real annual growth rate of 1.5%.

7.2. Interpretation and Implications

7.2.1. Spatial Variation

In line with the hypothesis ANOVA results confirmed that the site is heterogenous in terms of sediment composition, and results were statistically significantly different for organic matter and carbonate content when comparing results between the four transects. ANOVAs were also undertaken for cores within individual transects to determine subtler variations between subsections of the site, for carbonate content, 3 of the 4 cores (D, E and F) did not show to be significantly different from each other within the individual transects and for organic matter this was only true for 2 of the 4 cores (C and D). This indicates that there may be a greater homogeneity in terms of spatial distribution of carbonate content when compared to organic matter content within alkaline fens.

Box plots of organic matter and carbonate content did not show any true outliers and instead showed exceptionally high readings within cores. These high readings were then organised by depth and displayed similarities across the site indicating tufa and peat layers within the soil profile and displaying the acrotelm and catotelm layers that are typical of peatlands.

The 20 highest organic matter content readings were found almost entirely from cores in transect D and range from 57-79%. They were found almost entirely in the upper 30cm of multiple cores in transect D and at between 80-100cm and 130cm. The highest reading of 79% was found in core D5 at a depth of 2.5cm. This shows that certain areas of the site have consistently high levels of organic matter content, it also allowed us to reject the possibility that these high readings were down to error, as these findings were consistent within similar depths at multiple cores in adjacent areas. Further research could be done on these areas to investigate why these areas may have been more efficient at storing or producing higher organic matter contents.

The 20 highest readings for carbonate content were more spread throughout the site with high readings found within every transect. Highest carbonate content readings ranged from 27-43%. The highest readings were found in similar depths throughout the site and tended to be concentrated within the top 35cm. This again shows that carbonate content is more evenly spatially distributed throughout the site when compared with organic matter which has concentrated areas of high organic matter content.

These results build on existing evidence of spatial variation in peatland and the need to further assess and map carbon stocks (Glenk *et al*., 2014). While previous research has focused on bogs, these results demonstrate that fens also have a high spatial variation, this is particularly true for organic matter content and less true for carbonate content which has proved to be more stable and evenly distributed throughout the site. This shows that it is important to get a high sample size and use systematic sampling to incorporate spatial variation in fens to reduce probability of sampling error and ensure findings are representative of the true sediment composition of sites (Jianwie li, 2019).

7.2.2. Organic Matter Content

Average organic matter content for each transects ranged from 11.82%- 28.13% with an overall average organic matter percentage of 21.61%. This is within the range expected for peatland ecosystem, which are classified as having greater than 20% organic matter content (IPS, 2021). This is of high organic matter as many of our productive agricultural soils have only 3-6% organic matter content (Fenton *et al*., 2008).

Highest average organic matter content was found in transect D at 28.13% and the lowest average was found in transect F at 11.82%. Readings for individual samples ranged from 1.1% in core F8 at 68.5cm and 78.6% in core D5 at 2.5cm. This again indicates the high spatial variability of organic matter within Lye Valley and indicates that findings within blanket bogs may indeed be applicable to alkaline peat fens.

Peat layers were identified by high readings of more that 20% organic matter and were found in the upper 20cm of the soil profiles as well as around 100 and 130cm, showing both newly accumulated and ancient peat layers and highlighting the acrotelm and catotelm layers that have been found in other peatlands (Morris *et al*., 2011).

7.2.3. Carbonate Content

Average carbonate content for each transect ranged from 5.06%-11.82% with and overall average of 8.47%. Highest average reading was found in transect E at 11.82% and lowest in transect F at 5.06% which was also found to be lowest for organic matter content. Readings for individual samples ranged from 0.4% in core C4 at 38.5cm and 42.6% in core C6 at 32.5cm. Very little research has been done on percentage carbonate content in calcareous fens, but findings are in line with a study carried out in a Minnesota calcareous fen in 1998 which found carbonate separating into three zonations; a carbonate bearing surface zone of greater than 10% carbonate, followed by a depleted carbonate zone of less than 10% carbonate and finally a lower zone of greater than 10% carbonates.

In our study carbonate levels were higher than 10% in the upper 15cm of the soil profile, before dropping and again reaching 10% at 140cm. The zonation is thought to be caused by fluctuations in the water table which causes precipitation at high water levels and dissolution at low water levels (Almendinger and Leete,1998).

7.2.4. Depth

Depth of individual cores ranged from 8.5cm (E5) to 174.5cm (F6). With an average of 65cm. Average depth for transects ranged from 40.3cm (E) to 81.4cm (D). This is relatively low in comparison to other investigations which show an average of 1.37m (NatureScot, 2020). These findings were from a large study looking at 195 sites, and findings had a large range of < 1 metre up to a maximum depth of 11.0m. However, averages are based on peatlands in Scotland which are comprised mostly of upland peatlands and may not be representative of lowland peatlands in Oxfordshire.

7.2.5. Carbon stock

Carbon stock estimations based on averages of individual transects varied from 148 tCha for transect E to 302 tCha for transect D with an average of 229 tCha for the site.

Minimum tCha estimate were found in transect E where averages for individual cores ranged from 33 tC/ha for E5, due to its low depth of 8.5cm, to 257 tCha for core E10. Though transect F had the lowest average organic matter content, Transect E had the lowest average estimation for tC/ha due to having the lowest average depth for of 40.3cm. Maximum average tC/ha was found in transect D, which showed high readings of >200tCha for 8 of its 9 cores. The lowest reading was in core D5 at 144 tC/ha this was again due to it being a shorter core of 38.5cm depth. Alternatively, the core with the highest reading was D9 which showed estimations of 585.3 tC/ha, this was due to it being one of the deepest cores at 148.5cm depth. Higher tC/ha estimations within the transect are due to a combination of highest average depths and also because this area had already been found to have the highest overall average as well as the highest individual readings of percentage organic matter content.

Highest readings for tC/ha were found at 100cm and in the upper 20cm which is consistent with organic matter content. Based on findings the average of 229.34 tC/ha was used to estimate the stock of the site which for the 24 ha is estimated at 5504 tC. This is lower than previous averages found in Scotland which estimated peat soils to have between 350-510 tC/ha and may be due to the low average depth (Morison *et al*., 2010).

Total annual sequestration resulting from peat accumulation is estimated to be 8.4 tc or 0.35 t CO_2 ha^{-1} yr^{-1}. This is also relatively low in comparison to estimate on near natural upland fens which are estimated to sequester 5.44 t CO_2 ha^{-1} yr^{-1}, however, this is based on upland rather than lowland fens (Evans *et al*., 2017).

Total annual emissions resulting from eroded peat was estimated at 168.7 t C yr or 7.02 tCO_2 ha^{-1} yr^{-1}. This is higher than those stated within the UK emission inventory which estimates semi natural peatland in the UK which are impacted by human activity contribute to an average of around 2.8 tCO_2 ha^{-1} yr^{-1} (Evans *et al*., 2017). This indicates that emissions within alkaline fens may be more significant than blanket bogs, which most of the current data is based on, and therefore may require more attention for restoration. However, this is based on average annual erosion of 2cm per year, which again is mostly based on data gathered in blanket bogs in Scotland.

Differences found from currently available estimates may reflect the lack of representation in current data for lowland alkaline fens. The data contributes a clearer understanding of the soil composition of Lye Valley. These findings also contribute to a greater understanding of Oxfords natural assets and can inform potential outcomes of various land management options via cost benefit analysis. It also contributes insight to limited data available for carbon sequestration in alkaline fens. Findings are limited by the lack of data on accumulation and erosion rates for lowland alkaline fens and assume that carbon represents 50% of organic matter, this is a commonly used estimate but carbon content in peat organic matter can also be variable within and between sites (Chambers *et al.*, 2011).

7.3. Limitations

Most published literature on peatland restoration is dedicated to blanket bogs (Baird *et al*., 2019). One of the aims of this research is to add to limited data on carbon sequestration in fen peatland, however, as much of the existing data in the field is based on blanket bogs estimations use values discovered in previous studies such as annual accumulated and eroded peat which may not be accurate for fen peatland. Carbon stocks estimates can be used, and estimations can be tweaked in the future to accommodate any new scientific findings in terms of accumulation and erosion rates in fen peatlands.

Recent radiocarbon dating of soil cores in Lye valley undertaken by Professor Adrian Parker of Oxford Brookes University established cores dated back to 14,000 years. Estimates on tonnes of Carbon per hectare are based on average carbon density and average depth. The average depth was calculated at 65cm which is relatively low particularly for an area with soil dating back to 14,000 years; data collated from 195 projects showed average peat depth to be 1.37m (NatureScot, 2020). The findings may be reflective of average site depth, as peat depth can be incredibly variable both within and between peatlands (Parry *et al*., 2012). Alternatively, it could be due to data collection difficulty in reaching deep peat layers due to previous site contamination such as sewage pipes installation and its use as the local dumping ground. The corer may have been reaching obstructions rather than the bottom of the soil profile. Transect E for example had an average depth profile of just 40.3cm with some cores at just 18cm. If this is the case carbon estimations could be well undervalued.

Even if they are not an undervaluation and findings represent the full soil profile, carbon stock estimates are still very high, and still support the aim of the study to encourage restoration of the site.

Peatland carbon stocks have been found to have high spatial and temporal heterogeneity (Glenk *et al*., 2014). Including variation in the amount of carbon as a fraction of organic matter percentage (Chambers *et al*., 2011). As such, carbon mapping in unresearched peatlands is so important in understanding our natural capital in carbon stocks and identifying hotspots (DEFRA, 2013; Glenk *et al*., 2014; Reed *et al*., 2014). The generalisability of results was expected to be hindered by spatial variability within the site, these limitations were reduced by including a large sample size and use of systematic sampling of 34 cores including 4 transects and 595 samples, this method has been found to provide higher accuracy and be an optimal choice for large scale heterogenous sites (Jianwie Li, 2019).

For a more accurate estimation findings could be added to by further coring and altering the average. The high sample size having incorporated large areas of the site, have considered spatial variation and the results are a valid informed estimation.

Even though spatially variable, estimations of carbon stocks are valuable in understanding greater spatial variation of carbon stocks between different locations and to contribute to effective provision allocation (DEFRA, 2013; Glenk *et al*., 2014; Reed *et al*., 2014). Research and interest into peatland as carbon storage environments is still relatively new, having only been included in the UKs GHG inventory in 2020 (DEFRA, 2021). Because of this, data such as carbon mapping is useful in terms of understanding how our natural assets can be managed to reach carbon targets, which is already being collected by Natural England in their National Natural capital Atlas (Natural England, 2020). Uncertainties in estimations reflect the early stages of peatland science and the need for further investigation on variability for different peatland environment.

7.4. Recommendations

Funding is recommended to restore and enhance of Lye Valley. Not only because of its potential in future carbon sequestration and climate mitigation but also due to the avoided emissions that would be caused by neglecting to restore the site. It is recommended that this funding is given the upmost importance, as leaving the site to further degrade can mean a lost opportunity for successful restoration and the eventual emissions of 5504 tC (Bain *et al.,* 2011).

The other potential option of taking a hands-off approach would result in degradation of Lye Valley fen as peat would continue to dry out and erode. Without management, the area would succumb to succession, eventually becoming woodland. Trees disturb peat during root formation and continue to draw water, drying out peat and allowing ancient carbon stores to oxidise. Woodland accumulates at around 3.7-3.9 tC ha yr (Sandwood Enterprise, 2013). Though this is higher than annual accumulations estimated for Lye Valley (0.35 t C ha yr), Lye Valley is considered a secure carbon store, and when healthy, will continue to accumulate carbon indefinitely. Woodland on the other hand is a more fragile, reactive carbon store, where stocks will likely be sequestered for decades as opposed to millennia (IUCN, 2020c). Professor Adrian Parker of Oxford Brookes University has recently sent soil cores from Lye Valleys south fen for radiocarbon dating and found records span 14,000 years, showing that stocks have been accumulating for centuries. For this reason, total carbon stocks in peatland are much higher per hectare than woodland and a thin peat layer of just 30cm has an equivalent carbon store hectare by hectare to a tropical rainforest, however, peat is often much deeper than this (Lindsay *et al*., 2019). Lye Valley in particular is a very rare habitat in comparison to woodland and represents 12.7% of the last remaining habitat of its kind in England (FoLV, 2020). The impact on loss of biodiversity, including rare species can also be argued as a motive for peatland restoration and management as opposed to hands off conservation. For this reason, UK Forestry Standard do not support planting on peatland and in some cases even advise the removal of existing plantations on peatland to allow peatland restoration (IUCN, 2020c). Therefore, it is recommended that considering the established value of the site for carbon sequestration and biodiversity, land management focus should be in restoring the rare fen habitat, rewetting peat and managing succession.

Friends of Lye Valley include those with professional and local knowledge who are aware of the sites values as well as its issues. It is recommended that any funding and restoration efforts would include them within the future for the improvement of the site. Involvement of local ecological knowledge has been found to be a key factor in successful restoration and helps to ensure conservation needs are met alongside enhancement of local livelihood and wellbeing (Wheeler *et al*., 2020; Szalkiewicz *et al*., 2020). It is also recommended that scientific communication is used in order to spread knowledge on the value of the site to other members of the local public who are not currently aware of the extent of the ecosystem services that are provided to them and how they may be impacted by the degradation of the site in the future. Positive perceptions of landscapes and knowledge of their ecosystem services help to ensure successful management of ecosystems (Cebrián-Piqueras *et al*., 2020).

Furthermore, upon understanding the value of the site and its need for restoration is it advised that the entire site is considered for higher status protection. This will help to ensure prioritisation of enhancement of the site as well as protection against activities that may harm the ecological value of the site through legal obligation (Selman, P., 2009).

Further research is needed to establish average accumulation and erosion rates for lowland alkaline fens across the UK to gain more accurate predictions to be used in cost- benefit analysis when deciding areas to spatially target for future management plans of peatlands. Most research on peatland has been undertaken on blanket bogs, leaving lowland alkaline fens underrepresented in current data. Because of this, averages on carbon emissions and stocks used within emissions inventories may be under or overvaluing these sites, which will impact the focus that they deserve in future management plans.

Spatial variability of peatlands paired with differing definitions and calculation methods highlight the need for standardised approaches to carbon mapping of peatlands to ensure data can be generalised and findings from different studies can be appropriately compared in the future.

8. Conclusion

This project focused on Lye Valley, an alkaline peat fen in Headington, Oxford, which is currently under threat due to urban development. The peat is currently drying out and eroding due to impacts on its natural hydrology, leading to oxidisation of up to

14,000 years' worth of accumulated carbon (Webb, 2014). Peatlands are the UKs greatest store of terrestrial carbon, however, when degraded they become carbon emitters and globally, degraded peatlands are responsible for 25% of CO_2 emissions from the land use sector (Reed *et al*., 2014; Joosten *et al*., 2012; Moxley *et al*., 2011). To achieve Oxfords aims to reach net zero emissions by 2040, much effort will be needed including finding sustainable methods of carbon sequestration and reducing carbon emissions (OCC, 2021a). Despite these ambitious aims, the natural asset of its rare peatland habitat, which are known to store the greatest percentage of terrestrial carbon are not mentioned within the GHG Emission Report, Net Zero Oxford Plan, Zero Carbon Plan, Sustainability Strategy, Low Emission Strategy or Carbon Management Plan (OCC, 2021b).

This project involved estimating the peat carbon stock in Lye Valley in order to prove the lands value as a carbon storage ecosystem and highlight the potential emissions that will be incurred if the site continues to degrade. The purpose was to provide information for cost-benefit analysis and encourage funding for the restoration of the site.

The results indicate that Lye Valley has a high carbon stock of 5504 tC with an estimated value over £2 million. In a healthy peatland scenario, Lye Valley would accumulate an estimated 8.4 tC per year. In a degraded peatland scenario, Lye Valley would emit an estimated 168.7 tC annually. If restored and made healthy Lye Valley would both accumulate carbon, as well as avoiding emissions due to erosion. This means the potential benefits of restoration would lead to reduced annual emissions of 177.13 tC per year. The equivalent of annual average emissions of the use of 412 cars (Carbon Independent, 2007). This would lead to saved annual costs of up to £65,000 per year.

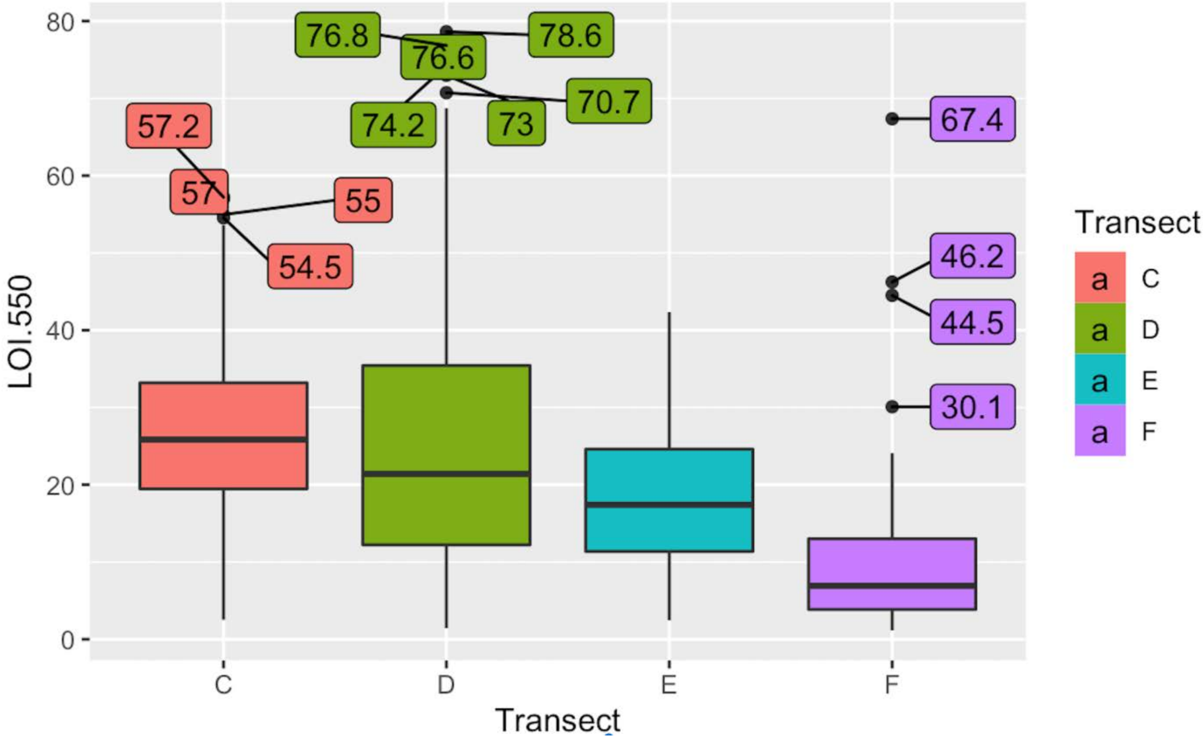
The site was confirmed to be heterogeneous, and organic matter content was highly variable within the depth profile and within and between transects, this was less true for carbonate content which proved to be more stable and evenly distributed throughout the site. This is in line with other findings indicating spatial heterogeneity of carbon stocks in peatlands (Agus *et al*., 2011). This suggests that current data may be applicable to Alkaline Fens in England even though they are currently underrepresented within national data which has focused on upland peatlands in Scotland (Lindsay at al., 2010).

Estimations suggest that in a degraded state Lye Valley would emit 7.02 tCO_2 ha^{-1} yr^{-1}. This is higher than the average stated within the UK emission inventory which estimates semi natural peatland in the UK which are impacted by human activity contribute to an average of around 2.8 tCO_2 ha^{-1} yr^{-1} (Evans *et al*., 2017). Since estimations are skewed towards upland peatlands in Scotland, this suggests that lowland peatlands may have a greater impact on emissions than upland peatlands which has also been suggested in previous studies (Worral *et al*., 2011).

These findings provide insight on the carbon fluxes within alkaline peat fens, for which data is currently limited. It is recommended that funding is put towards restoration and enhancement of Lye Valley. Not only because of its potential in future carbon sequestration and climate mitigation but also due to the avoided emissions that would be caused by neglecting to restore the site. It is recommended that this funding is given the upmost importance, as leaving the site to further degrade can mean a lost opportunity for successful restoration and the eventual emissions of 5504 tC (Bain *et al*., 2011). This will help Oxford in reaching net zero emissions targets by 2040.

Appendix

Appendix A: Boxplot Results



These are the results of the boxplots. 'outliers' were then organised in order of depth in the table below:

Depth (cm)	Core	LOI 550(%OM)
-2.5	D2	70.72796935
-2.5	D3	61.09610189
-2.5	D5	78.62903226
-2.5	D6	72.9844413
-8.5	D3	62.34347048
-8.5	D5	68.72759857
-8.5	D6	64.75917978
-14.5	D3	56.63302091
-14.5	D6	58.60899067
-14.5	D7	59.93065874
-20.5	D2	59.29839391
-20.5	D4	65.31385281
-20.5	D7	59.39329431
-26.5	D4	61.7631152
-44.5	C6	57.00516351
-80.5	D6	59.03819918
-92.5	D8	74.17498081
-94.5	D9	76.59777424

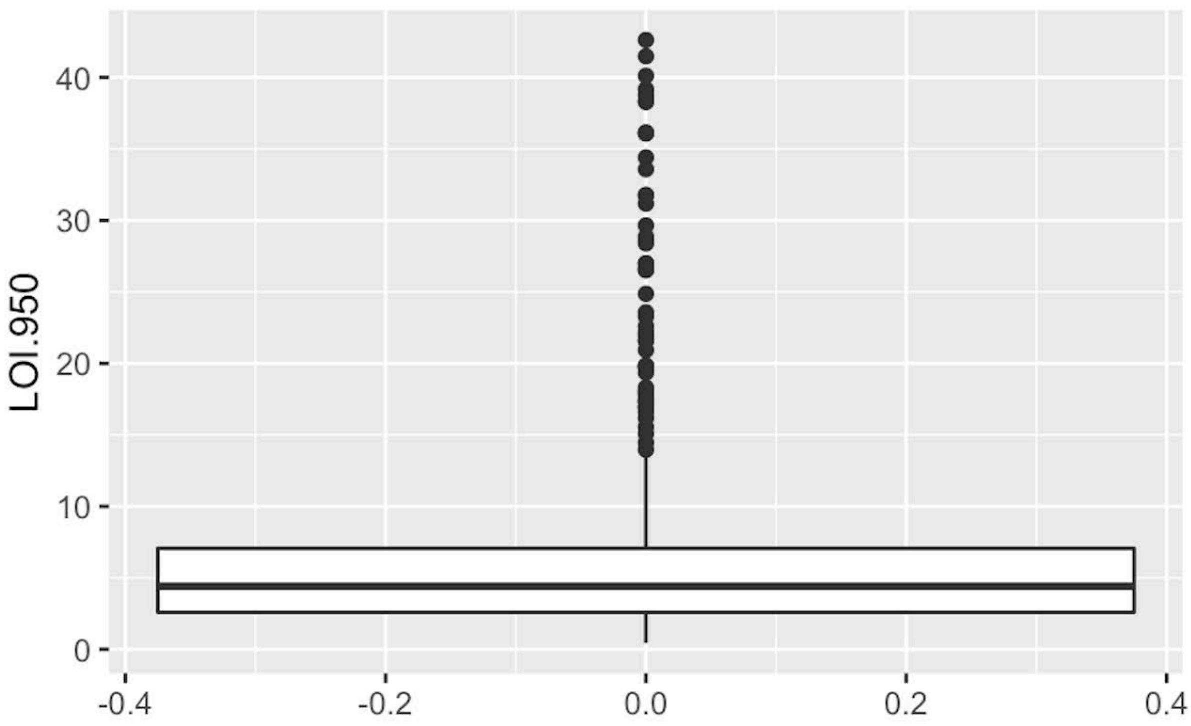
-96.5	C8	57.21676151
-96.5	D9	76.83835439
-128.5	D9	60.4
-128.5	F7	67.35701152

These are outliers that were found by creating a boxplot of all LOI^{550} data combined. Majority of high readings are in transect D and at similar intervals (in upper 20cm and again at 80- 100) - therefore I think these are reliable and display layers of high organic matter in the soil profile- also shows the high variability within the depth profile and between different areas of the site.

Stats summary per transect for LOII 550

LOI 550						
Transect	**Min**	**1st Quartile**	**Median**	**Mean**	**3rd Quartile**	**Max**
C	2.514	19.464	25.843	27.435	33.186	57.217
D	1.429	12.216	21.398	26.468	35.434	78.629
E	2.452	11.363	17.4	19.016	24.601	42.355
F	1.141	3.86	6.915	9.279	13.012	67.357
Combined	1.141	8.75	16.042	19.973	27.56	78.629

950



When creating a boxplot for 950 over 50 samples were indicated as ‘outliers’ this suggests the data is not well described by a normal distribution.

Stats summary per transect for LOI 950

LOI 950						
Transect	**Min**	**1st Quartile**	**Median**	**Mean**	**3rd Quartile**	**Max**
C	0.4387	3.5935	5.2695	8.923	9.0554	42.6221
D	0.4488	2.2365	3.3453	5.3542	5.4435	41.48
E	1.37	4.855	10.093	11.394	12.849	38.368
F	1.202	2.272	3.856	5.065	5.7	38.767
Combined	0.4387	2.5862	4.4082	6.8181	7.0595	42.6221

Appendix B: ANOVA results for LOI550

ANOVAs were undertaken to understand whether there is variation in % organic matter readings both within and between transects.

Transect C

	Df	Sum Sq	Mean Sq	F Value	P Value
Core	6	1925	320.9	2.241	0.0458
Residuals	94	13457	143.2		

P-value can be rounded up to 0.05 and a Tukey post hoc test showed that cores within transect C were not significantly different from one another

Transect D

	Df	Sum Sq	Mean Sq	F Value	P Value
Core	8	4521	565.1	1.73	0.0949
Residuals	164	53559	326.6		

P- value= 0.0494 and cores within transect D are not significantly different from one another in terms of organic matter content

Transect E

	Df	Sum Sq	Mean Sq	F Value	P Value
Core	9	2840	315.57	4.503	0.000137
Residuals	63	4415	70.08		

Cores within transect E are significantly different from one another with p-value < 0.05. Tukey post hoc test showed E8 is significantly different from E2 and E3, E4 and E9. Core E8 was a very small core however of just 6 samples all with high readings of between 24-42%OM if could be that the short core was pulled out due to an obstruction and a deeper core could have led to transect E not being considered significantly different.

Transect F

	Df	Sum Sq	Mean Sq	F Value	P Value
Core	7	2782	397.5	7.339	1.22e-07
Residuals	161	8719	54.2		

P value = 1.22e-07. Therefore cores in transect F are significantly different from each other in terms of organic matter content. A tukey post hoc test revealed F4 was significantly different from F6 and F5 was significantly different from F6, F7, F8, F9 and F10.

I then compared transects against each other to see whether the areas of the site are significantly different in terms of organic matter content.

Combined

	Df	Sum Sq	Mean Sq	F Value	P Value
Core	3	32316	10772	59.81	<2e-16
Residuals	512	92218	180		

Tukey post hoc test showed that E and F were significantly different from each other and all other cores in terms of LOI550 (%OM content). Only C and D were not significantly different from one another, This shows high variability amongst the site and possibly difficult to suggest a clear answer- therefore I may show a minimum to maximum possibility for carbon stock

Appendix C: ANOVA results for LOI 950

ANOVAs were undertaken to understand whether there is variation in % carbonate content readings both within and between transects.

Transect C

	Df	Sum Sq	Mean Sq	F Value	P Value
Core	6	2916	486.1	7.521	1.34e-06
Residuals	94	6075	64.6		

P value = 1.34e-06 so cores are significantly different from each other in terms of carbonate content. A tukey Post hoc test revealed C6 is significantly different from C8 and C4. C4 was also significantly different from C5

Transect D

	Df	Sum Sq	Mean Sq	F Value	P Value
Core	8	4521	565.1	1.73	0.0949
Residuals	164	53559	326.6		

P value= 0.0949, so cores were not significantly different from each other in this transect for carbonate content.

Transect E

	Df	Sum Sq	Mean Sq	F Value	P Value
Core	9	625	69.45	0.864	0.562

Residuals	63	5064	80.38		

P values= 0.562 so cores were not significantly different from each other in this transect for carbonate content.

Transect F

	Df	Sum Sq	Mean Sq	F Value	P Value
Core	7	149	21.22	0.847	0.55
Residuals	161	4032	25.04		

P value= 0.55 so cores were not significantly different from each other in this transect for carbonate content

Combined

	Df	Sum Sq	Mean Sq	F Value	P Value
Core	3	2862	953.9	19.29	7.29e-12
Residuals	510	25215	49.4		

P value = 7.29e-12 so cores are statistically significantly different from each other in terms of carbonate content. A tukey post hoc test showed that the transects were split into 2 groups, transects E and C and transects F and D. The two groups are statistically significantly different from one another.

Appendix D: Calculations

Carbon stock

Carbon Density (g/cm3) = Bulk density (g/cm3)* %Corg)/100
Average carbon stock (g/cm2) = Average Carbon Density per Core (g/cm3) * depth of core (cm)

This is first completed as an average for each core, then as an average for each transect and then as an average for the site overall. Results of the calculations are below:

Core	Carbon stock in core (g/cm2)	Depth (cm)
C2	1.814968257	44.5
C4	2.220631902	68.5
C5	1.620650794	56.5
C6	2.380671395	68.5
C7	2.142196146	62.5
C8	4.723236195	98.5
C9	0.673147984	14.5
D1	2.768538265	56.5
D2	3.650059113	92.5

D3	2.660476028	92.5
D4	2.002051754	68.5
D5	1.439879392	38.5
D6	2.843233785	80.5
D7	2.056260976	62.5
D8	3.868413338	92.5
D9	5.852687336	148.5
E1	1.650360374	32.5
E2	1.632523524	38.5
E3	1.039726423	26.5
E4	1.611873016	38.5
E5	0.330630314	8.5
E6	1.042222608	26.5
E7	1.188066597	32.5
E8	1.290802638	32.5
E9	2.401186814	74.5
E10	2.573861519	92.5
F3	1.608694544	38.5
F4	3.203840617	74.5
F5	1.359711046	32.5
F6	4.643376268	174.5
F7	4.25933023	134.5
F8	1.492016813	74.5
F9	1.738428738	68.5
F10	1.346085833	44.5

Transect	**Average (g/cm2)**	**Average T/ha**	**average Depth**
C	2.22507181	222.507181	59.07142857
D	3.015733332	301.5733332	81.38888889
E	1.476125383	147.6125383	40.3
F	2.456435511	245.6435511	80.25
Overall	2.268524723	226.8524723	65.25257937

The overall average is then used as the estimate for tC/ha for the site and can be multiplied by the area in hectares to obtain total carbon stock

Carbon per hectare	**Site size (ha)**	**Total Carbon Stock (t C)**

(tC/ha)		
226.8524723	24	5444.459335

Annual accumulated and eroded

Value of annual accumulated carbon** (£/yr) = ((Total carbon stock (tC/ha)/ Average depth of core (cm))/10) * current price of carbon per tC/ha (£)

Value of annual eroded peat **(£)= ((Total Carbon Stock tC/ha/ overall average depth (cm))* 2) * current price of carbon per tC/ha (£)

Total Carbon Stock (t C)	Average Depth of Core (cm)	Total Carbon in 1mm (tC)	Total Carbon in 2cm (tC)
5444.459335	65.25257937	8.34366915	166.873383

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