An assessment of the societal impacts of water level management on lowland peatlands in England and Wales

Report to Defra for Project SP1218: Managing agricultural systems on lowland peat for decreased greenhouse gas emissions whilst maintaining agricultural productivity

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Road Sign on the Ouse Washlands near Welney, Norfolk
(Photo - S. Page)

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Executive Summary

Across the UK, lowland peatlands occupy a relatively small proportion (15 to 16%) of the overall peatland area, rising to 19% in Wales and 44% in England. Lowland peatlands comprise both base-rich fens and more acidic, base-poor raised bogs, with fen peatlands occupying the largest area (2887 km^2 in England; 66 km^2 in Wales). Only 16% of lowland peatlands in England are found on deep peats (> 40 cm depth); the remainder occupy shallow peats, a good proportion of which, particularly in the Fens, are classed as 'wasted' (i.e. degraded by a combination of oxidation and wind erosion and increasingly dominated by the underlying mineral material). Lowland peatlands, particularly in England, have been subject to a high degree of land-use pressure. Extensive areas of fen peatlands have been drained for agriculture, giving rise to some of the most productive farmland in the UK, e.g. in the Fens of eastern England. Other large areas, for example in the Somerset Levels and Norfolk Broads, have been modified, to varying degrees, by drainage for grazing and other land uses.

Lowland peatlands play an important role in climate regulation in the UK, acting both as sinks and sources of greenhouse gases. They also deliver a range of ecosystem co-benefits. This scoping study considers the benefits and disadvantages arising from historic and current water level management of lowland peatlands in England and Wales. Direct and indirect societal impacts, both positive and negative, are reviewed to establish the current state of knowledge regarding the extent of these impacts, their causes and potential solutions. Key uncertainties and priorities for future assessment are identified. Information was obtained from the published and grey literature and through direct enquiries made to stakeholder organisations and individuals.

Peat is an organic material that contains very little solid matter and is around 90% water by volume when saturated. Drainage of previously saturated peat soils sets in motion a series of events resulting in reduction in peat volume and lowering of the land surface. Peat subsidence is a function of several processes, namely peat consolidation, compaction and shrinkage, and the oxidation of previously water-saturated organic material under aerobic conditions. The first three processes lead to an increase in peat bulk density over time and concomitant changes in peat hydrology. Oxidation, acting alone, does not increase peat bulk density, but does result in greenhouse gas emissions, thereby connecting peat subsidence to climate change. Other processes can also contribute to lowering of the peat surface, including wind erosion, peat off-take during crop harvest, peat extraction, and burning. Contemporary rates of subsidence for drained lowland fen peatlands under arable agriculture in the UK are typically in the range 1 – 2 cm yr^{-1}. At Holme Fen in Cambridgeshire, 128 years of drainage has resulted in a subsidence of around 4 m. Wind erosion makes a smaller contribution to peat loss and subsidence. In the Fens, wind erosion typically occurs during the spring months when the soil has been ploughed but is without a crop cover, with estimated losses translating into a peat surface lowering of 0.03 to 0.25 cm yr^{-1}.

Land subsidence resulting from the drainage of lowland peatlands can result in an array of negative impacts for infrastructure. While some of these have been previously recognised, most emphasis to date has been on identifying and addressing the symptoms of subsidence, rather than addressing the causes or gauging the associated economic or social costs. The most direct consequence is a change in hydrology, since subsidence brings the peat surface within the reach of local river flood levels or, in coastal areas, of high tide levels. Large areas of the Fens are below sea level (40% of Lincolnshire; 50% of Cambridgeshire) but drainage has provided some of the most fertile agricultural land in the UK, producing a third of England's fresh vegetables. Maintaining agricultural production, whilst also ensuring protection from flood risk, has necessitated significant investment in embankments and coastal flood defences, drainage pumps and sluices, which are managed by a combination of Internal Drainage Boards (IDBs), the Environment Agency and local authorities. During 2015-16, IDBs in England invested £61 million in water level management work, with additional investment from the Environment Agency to maintain fluvial and coastal flood defences. An unknown portion of costs

associated with maintenance of watercourses and flood defences are attributable to peat subsidence, including repairs to embankments that have slumped or deformed and deepening/clearance of drains.

Peatland drainage and associated subsidence also have consequences for maintenance of other categories of infrastructure. Peat shrinkage affects thousands of kilometres of the UK's road network, as well as sections of the rail network. Roads crossing peat soils in the Fens suffer regular deformation, cracking and pot-holing, resulting in high repair costs for local authorities. Even where Fenland roads are located on silty ridges, subsidence of the peat either side of the ridge has left roads well above the adjacent landscape, necessitating investment in crash barriers to improve road safety. Several railway lines cross lowland peatlands. Reported issues include track deformation, resulting in reduced engine power, increased journey times and regular repairs of the track bed, and ground vibration boom from high speed trains, which requires investment in mitigation measures to reduce dynamic amplification. Where houses and other buildings have been constructed on peats, subsidence can cause cracks, tilting and differential settlement. Compared to the Netherlands, however, there has only been limited urban and rural development on lowland peat soils in the UK, thus subsidence damage to properties appears to be a relatively minor problem. In the Fens, most settlements are located on mineral islands or ridges, rather than on peat, and have relatively stable foundations. Communication and energy supply networks are also at risk of damage from peat subsidence, as evidenced by tilting of telegraph poles and the differential movement of energy supply pipelines.

In addition to direct impacts on infrastructure, current water and land management practices on lowland peatlands incur a range of other societal benefits and costs. In England, around 2400 km^2 of drained lowland peatland are farmed for food production which brings with it benefits for the rural economy, employment and food security. It is estimated that Fenland agriculture and food-related industries employ 80,000 people and generate around £3 billion a year for the regional economy. But peatland drainage does not always result in benefits. Lowland peatlands contain a wealth of archaeological interest; however, drainage and peat wasting have exposed buried artefacts to aerobic decay, degradation and loss. Examples of peatland archaeology include the world's oldest surviving trackway in the Somerset Levels as well as human remains (so-called bog bodies). It is estimated that as many as 10,000 archaeological monuments (74% of the total resource) have been destroyed completely in the last 50 years as a result of peatland drainage and peat loss. Mitigation measures to prevent further loss will require landscape-scale maintenance of high water levels. Peatland drainage and land use change have also resulted in the demise, or in some cases the transformation, of peatland cultural values. Drainage of the Fens led to the loss of a unique cultural heritage associated with the exploitation of the former wetland's rich natural resources. Nevertheless, for today's communities, the unique drainage history of the Fens, along with their important farming and food production history, provide a strong sense of tradition and place. Peat drainage and loss also result in loss or reduction of other valued ecosystem services – carbon storage and biodiversity support. Total current greenhouse gas emissions from English peatlands are estimated to be 10 Mt CO_2e yr^{-1}, with lowland peatlands drained for agriculture contributing 80% of this emission. Halving the drainage depth across all peatland under intensive agricultural use in the UK, most of which is in England, could reduce emissions by around 70%. A large proportion of remaining, undrained lowland peatlands are protected as Sites of Special Scientific Interest and both lowland fens and bogs are included as priority habitats in the UK Biodiversity Action Plan. The main threats to their biodiversity interests are water management, including drainage and excessive water abstraction from underlying aquifers, and pollution from agricultural run-off. In the Fens, peat subsidence has left areas set aside for nature conservation isolated as 'wet' islands perched several metres above adjacent drained fields. This incurs management costs for maintaining an appropriate wetland hydrology.

Mitigating the risks posed by current water management regimes in lowland peatlands will require consideration of appropriate actions to reduce hazards, reduce exposure, and reduce vulnerability.

Measures to reduce hazards focus on raising the peatland water table to counteract subsidence; this would deliver benefits in terms of reduced greenhouse gas emissions, reduced maintenance costs for transport routes and other infrastructure, protection of archaeological heritage, and improved hydrological security for wetlands managed for nature conservation. Measures to reduce exposure could include diverting traffic away from roads without strong foundations, strengthening transport routes that cross peatlands, limiting further infrastructure development on peat soils, and wider uptake and implementation of on-farm soil conservation measures to reduce erosion losses. Measures to reduce vulnerability include designing future infrastructure to take account of both the low load bearing capacity and subsidence of peat substrates and the increased risks of fluvial and coastal flooding under future climate change scenarios. The magnitude of risks will be determined by the characteristics of a particular location (e.g. elevation, proximity to river/coast), vulnerability of assets and people (e.g. presence of high value agricultural land, infrastructure, future impacts of climate change), and the mitigation and adaptation measures already in place, and their effectiveness.

Implementing appropriate mitigation measures will reduce risks but it will not be possible to offset or eliminate all of them. Measures need to be judged according to their specific costs and benefits (social, economic, environmental) over appropriate timescales. For example, the rate of peat subsidence could be reduced or even stopped by raising water levels. This would provide benefits in terms of reduced costs for water management, reduced greenhouse gas emissions and so on, but would challenge various agriculture-related functions and interests. Taking all lowland peatlands out of agricultural production would significantly impact on UK food production, as well as have implications for livelihoods and regional economies. Climate change also needs to be considered in any assessment of the costs and benefits associated with peatland drainage. Climate change projections indicate that the UK is likely to experience hotter, drier summers and wetter, warmer winters. These conditions will promote and possibly enhance current rates of subsidence; they could also increase the risk of peat loss by wind erosion and, during extended droughts, increase the risk of damage to infrastructure. In addition, lowland peatlands located at or below sea level, such as the Fens, the Somerset Levels and the Norfolk Broads, could be at increasing risk of coastal flooding and saline intrusion and incursion, both as a result of sea level rise and the increased risk and height of storm surges. This level of increased risk could incur additional costs for the IDBs, the Environment Agency and local authorities with responsibility for land drainage and flood risk management.

This scoping study provides a broad assessment of the principal environmental, economic and social impacts arising from the drainage of lowland peatlands in England and Wales. There remain some key uncertainties and knowledge gaps which could lead to underestimation of the total scale of the impacts. In view of this, it would currently be difficult to model the returns (costs and benefits) delivered from implementing most of the proposed mitigation measures. Nevertheless, we are confident in presenting an initial conclusion that the costs associated with drainage are largely 'hidden' and/or are not directly connected to drained peatlands and their management. Key uncertainties relate to costs associated with infrastructure, both in terms of maintenance and higher initial costs associated with construction on soft and subsiding substrates, and on society, particularly in terms of the costs of providing and maintaining land drainage and flood defences. While some infrastructure impacts arising from peatland drainage have been recognised in previous studies, most of the emphasis has been on identifying and addressing the symptoms of subsidence and little consideration has been given to addressing the causes. A more detailed assessment would allow: i) an improved understanding of the effect of alternative water and land management measures on subsidence and greenhouse gas emissions; ii) an insight into the key financial values, enabling an accurate cost-benefit analysis; and iii) an understanding of what will happen, for example in terms of damage to infrastructure or loss of high value agricultural soils, if nothing is done, thereby providing the basis for a business as usual scenario against which to compare various policy options.

1. Introduction

Across the whole of the UK, lowland peatlands occupy a relatively small proportion (around 15 to 16%) of the overall peatland area, with the larger part comprising upland blanket bogs (JNCC 2011). In Wales, 19% of the total peatland area is classed as lowland, whilst Scotland and Northern Ireland have smaller proportions at 6% and 17%, respectively (Evans et al. 2017). In England, however, the proportion of lowland peatland is much higher, at around 44% (Figure 1). Lowland peatlands can be broadly classified as either i) fens, which are mostly base-rich and receive some minerotrophic water input usually through drainage from surrounding mineral soils, ground or surface waters, or ii) raised bogs, which are base-poor, acidic and dependent entirely on precipitation for their water supply.

Fen peatlands occupy the largest area, covering 958 km^2 in England, a figure that rises to 2887 km^2 if wasted peats[1] are also included, and 66 km^2 in Wales (Blackstock et al. 2010, Natural England 2010, JNCC 2011). Raised bogs occupy an estimated 353 km^2 in England (Natural England 2010, JNCC 2011), but much of this area is in the uplands, with Baird et al. (2009) reporting only 60 km^2 of remaining lowland raised bog. Whilst lowland peat occupies a relatively large proportion of the total peat area in England, only 16% is found on deep peat, i.e. on peat with a depth greater than 40 cm (Natural England 2010, Evans et al. 2017) and the remaining 84% comprises shallow (<40 cm thick) peats, a good proportion of which are wasted. Where they occur, these wasted peats are derived predominantly from fen peats and are most extensive in the Fens of eastern England; in total they occupy around 1930 km^2.

Compared to their upland counterparts, lowland fen and bog peatlands in England have been subject to greater land-use pressure (Evans et al. 2017a). Extensive areas of fen peatlands have been drained for agriculture (horticulture, arable and intensive grassland), giving rise to some of the most productive farmland in the UK, e.g. in the Fens of eastern England. Other large areas, for example in the Somerset Levels and Norfolk Broads, have been less affected by arable agriculture, but have been modified, to varying degrees, by drainage for grazing and other land uses. Overall, it is estimated that 39% of fen peat in England is under cultivation, and that 22% of the remaining deep fen peat is under agriculturally-improved grassland. Formerly extensive areas of lowland raised bog in England have also been lost through conversion to various land uses. Around 16% has been affected by peat extraction, including large areas in the north and east of the country and in the Somerset Levels; some 15% has been converted to improved grassland; and around 17% has been afforested, although this is mostly focused in the uplands (JNCC 2011). In Wales, a considerable proportion of lowland fens are in a comparatively unmodified condition (Blackstock et al. 2010). In the same country, lowland raised bogs occupy a current area of around 18 km^2, less than half of the original estimated extent, with the remainder lost through drainage and conversion to grassland (Blackstock et al. 2010). Of this area, 10 km^2 is classed as unmodified, mostly concentrated in mid-Wales.

Lowland peatlands play an important role in climate regulation in the UK, both as sinks and sources of greenhouse gases (Evans et al. 2017a). They also deliver a range of ecosystem co-benefits that are discussed more fully in Mulholland et al (2020). In this scoping study we consider the benefits and disadvantages arising from historic and current water level management of lowland peatlands in England and Wales. Direct and indirect societal impacts, whether they are positive or negative, are reviewed to establish the current state of knowledge. We identify the key uncertainties and the priorities for future assessment. Information has been obtained from the published and grey literature and through direct enquiries made to a range of stakeholder organisations and individuals.

[1] Peat degraded by a combination of oxidation and wind erosion and increasingly dominated by the underlying mineral material. Remaining thickness of the peat layer is less than 40 cm.

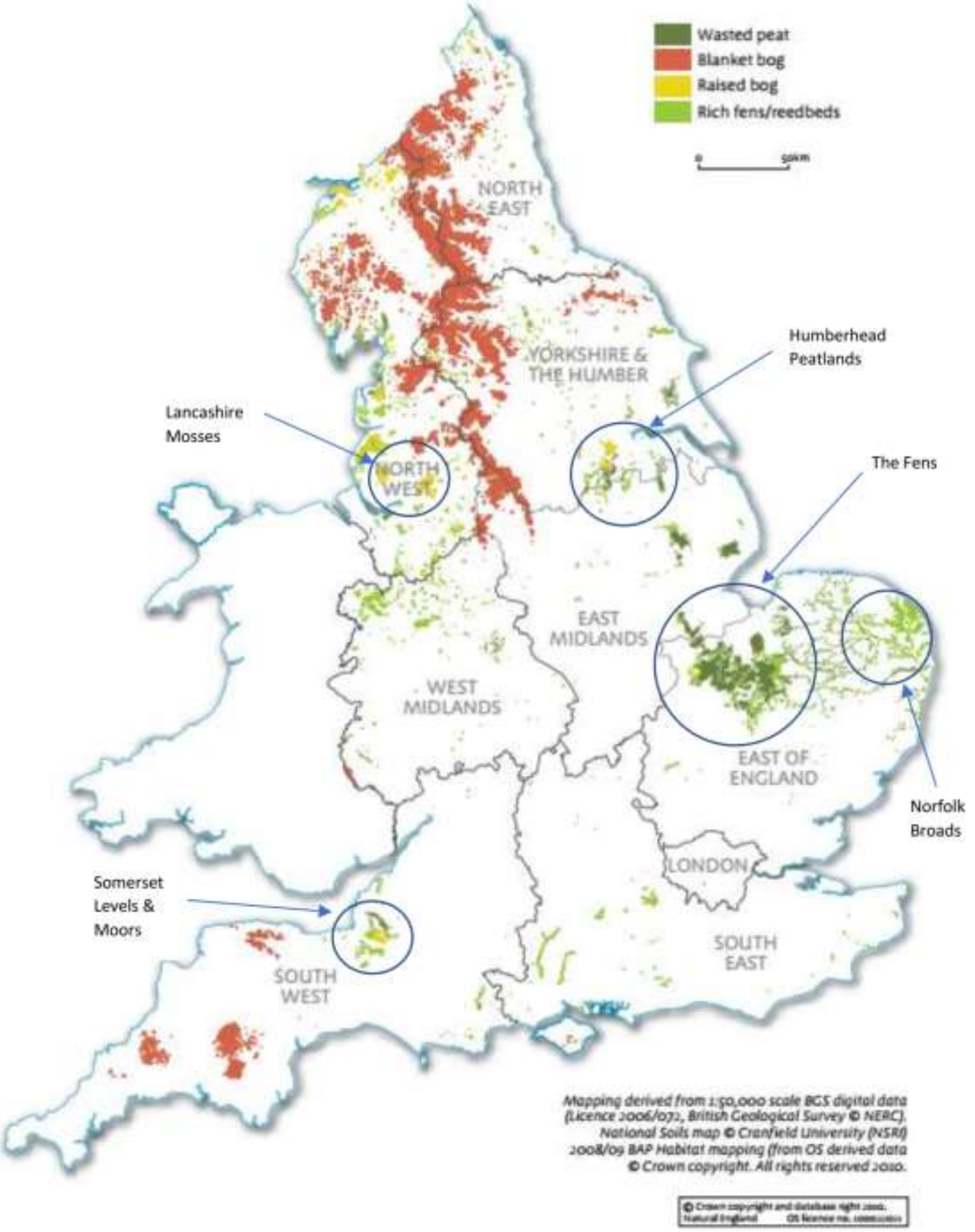


Figure 1: Peat distribution map for England showing the main areas of lowland peatland referred to in this report (Source – Natural England 2010, derived from various sources, see above).

2. Aims

The aims of this scoping study are to:

1) Review both UK and international literature on the impacts of lowland peat drainage on infrastructure to determine the current state of knowledge regarding the extent of impacts, causes and potential solutions, key uncertainties, data sources and priorities for future assessment.
2) Consider the range of other less tangible societal impacts resulting from the current management of lowland peatlands, including both beneficial and negative impacts.
3) Inform the socio-economic evaluation undertaken in Work Package 4 of the project.

N.B. In writing this report, it has not always been possible to separate the direct and indirect impacts of peatland water level management. It is challenging to separate the effects and costs arising from construction on peat soils (e.g. where insufficient account has been taken of the physical nature of the substrate) from those arising from on-going peatland drainage. For example, the condition of a road traversing a peatland may deteriorate either because the construction methods did not account for the low load-bearing capacity of the substrate or because of the on-going effects of land subsidence. Separating the effects and costs arising from these two linked, but essentially different, phenomena would likely be challenging but is something that should be considered in any further analysis that might follow on from this scoping study.

3. Peat Surface Movement and Peat Loss

Peat is an organic material that, unlike mineral soil, contains very little solid matter and is around 90% water by volume when saturated. Drainage of previously saturated peat soils sets in motion a series of events that results in reduction in peat volume and lowering of the land surface (e.g. Stephens & Speir 1969; Schothorst 1971; Egglesman 1986). This process of peat subsidence is a function of several processes, namely peat consolidation, compaction and shrinkage, and the oxidation (decomposition) of previously water-saturated organic material under aerobic conditions (den Haan et al. 2012; Hooijer et al. 2012).

Consolidation is the physical process of compression of saturated peat below the water table owing to loss of buoyancy of the top peat but also as a result of loading at the peat surface (e.g. through use of heavy machinery or added soil) which increases the downward pressure on the peat below. The amount of subsidence attributable to consolidation will depend on the type and thickness of peat and the drainage depth.

Primary consolidation is caused by loss of water from pores in the peat following drainage and can occur rapidly depending on the speed with which water is removed from the peat by drainage.

Secondary consolidation is a function of the resistance of the solid peat material itself to the compression caused by de-watering. This is a slow process that may continue in the long term but makes up only a small fraction of total consolidation (Berry 1983; Mesri & Aljouni 2007). Both primary and secondary consolidation processes increase peat bulk density (where bulk density is the weight of dry soil in a given soil volume).

Compaction and shrinkage are additional physical processes that bring about a volume reduction of peat in the aerated zone above the water table. Compaction results from pressure applied on the peat surface, e.g. by heavy equipment. Shrinkage occurs through contraction of organic fibres as the peat dries as a result of negative suction. These two processes cannot usually be separated and are considered together as ‘compaction’. Both lead to an increase in peat bulk density.

Oxidation is a biological process that occurs because of microbial decomposition of organic matter in the aerated zone above the water table. It results in the release of gaseous CO_2 (carbon dioxide) to the atmosphere and, to a lesser extent, of DOC (dissolved organic carbon) into drainage waters and subsequent CO_2 and CH_4 (methane) efflux at the water surface arising from DOC decay. After drainage, initial subsidence is largely due to compaction but, with time, it is increasingly due to oxidation. The contribution of oxidation to total subsidence varies quite widely, from 35% to 100% (Couwenberg et al. 2010). In a study of Dutch peatlands, 52% of subsidence was ascribed to oxidation (Schothurst 1977), but more recent experimental studies suggest that at least 70% of current peat subsidence in the Netherlands is due to oxidation (Den Haan & Kruse 2006). For drained fen peatlands in Switzerland, Leifeld et al. (2011) estimated an oxidation contribution of between 28% and 64%, with this wide range of values attributed to differences in hydrological conditions, land management (e.g. tillage will increase soil aeration, and fertilizer application will increase the rate of organic matter mineralisation), and peat physical and chemical attributes. Over time, oxidation will gradually lead to an increase in the mineral matter content in the upper (aerobic) section of the peat column with a concomitant reduction in the rate of oxidation. In peats with a low mineral content (e.g. < 2% dry weight), this slow down over time is likely to be very small. Oxidation, acting alone, does not increase peat bulk density, but it does result in greenhouse gas emissions (CO_2), thereby connecting subsidence to climate change. If drainage is maintained, i.e. if the water table is managed to maintain a freeboard, oxidation will cause a loss of mass from the peat profile.

Changes in peat bulk density resulting from drainage bring about changes in peat physical properties, including changes in peat pore structure (Rezanezhad et al. 2016), hydrological processes, including water infiltration, hydraulic conductivity (permeability) and runoff production (Holden et al. 2006; Liu & Lennartz 2019), and water chemistry (Holden et al. 2004). With subsidence, peat bulk density increases, whilst hydraulic conductivity and specific yield decrease as the pore space in the upper drained peat compresses; these changes directly affect water flow rates through the peat and also the peat soil moisture, which is one of the main controls of soil carbon and nitrogen dynamics and the flux of the greenhouse gases CO_2, CH_4 and N_2O (nitrous oxide) at the soil surface (e.g. Kasimir-Klemedtsson et al. 1997; Price 2003; Kluge et al. 2008; Taft et al. 2017; see also Section 4.1).

In some situations, other processes can also contribute to the lowering of the peat surface (section 3.3). These include *wind erosion* and transport of particles from the peat surface, peat *off-take* during crop harvest (e.g. removal of peat particles on roots or other parts of the crop), *peat extraction (digging)* for fuel, and *burning*. None of these processes will result, directly, in changes in peat bulk density, although burning has been shown to increase bulk density under certain circumstances (e.g. Dikici & Yilmaz 2006).

3.1 *Long-term Rates of Peat Subsidence*

Rates of peat surface subsidence can be high in the first few years following drainage, as the peat consolidates owing to increased overburden resulting from a loss of buoyancy. This relatively rapid subsidence is caused largely by the physical compression and shrinkage processes associated with loss of water from the peat profile. Following this primary stage, a secondary phase of irreversible shrinkage and compaction of the peat, together with peat decomposition, results in a slower, long-term rate of subsidence (Hooijer et al. 2012). At typical agricultural water-table depths (e.g. ~0.6–0.8 m below the peat surface for most horticultural and arable crops), rates of secondary surface lowering, which are due largely to oxidation, usually vary from 1–2 cm yr^{-1} in temperate climates, to 3-5 cm yr^{-1}

in tropical areas (see Table 1; derived from Evans et al. 2018), with higher rates occurring when water tables are lower and where the peat has a high organic and low mineral content.

Over a period of 128 years, a total peat subsidence of 3.91 m (~ 3.0 cm yr^{-1}) resulting from drainage for agriculture was recorded in the Fens of eastern England (Hutchinson 1980), as measured against the Holme Post (Holme Fen, Cambridgeshire) (Figure 2). Over the initial 27-year period, subsidence was about 9.6 cm yr^{-1}, before levelling off to a reduced rate of 1.1 cm yr^{-1} over the last measurement period of 16 years. In his study, Hutchinson speculated that other locations in the Fens that had been drained for much longer periods and that had been more intensively cultivated, would have experienced greater peat subsidence. This long-term subsidence rate is supported by a more recent assessment at Methwold Fen, Norfolk (just over 50 km east of Holme) by Dawson et al. (2010) who undertook soil and topographic surveys. They measured an average lowering of between 1.1 and 1.4 cm yr^{-1} over a 22-year period. In the drained grasslands of the Somerset Levels, Brunning (2012) reported a subsidence rate of 0.6 cm yr^{-1}. The absolute rate of subsidence will depend on location-specific dynamics of groundwater level management and may be strongly related to the last adjustment (usually lowering) of the groundwater level, as well as climate, land use and peat chemistry.

Figure 2: The Holme Post at Holme Fen, Cambridgeshire. In 1851, a metal post was driven into the peat so that its top was level with the ground. The top of the post is now some 4 m above the land surface, and at 3 m below sea level, Holme Fen is the lowest point in Britain. (Photo – S. Page).

Studies of cultivated, drained peatlands in Europe, the USA and Canada have recorded annual rates of surface lowering in the range 0.75–3.3 cm yr^{-1} under arable, 0.37–1.91 cm yr^{-1} under forest (commercial forest stands), and 0.06–3.40 cm yr^{-1} under grassland (Table 1). These rates can translate into substantial long-term (decadal) subsidence values; e.g. more than 5 m within a century in the Sacramento Delta, California, USA (Deverel & Leighton 2010); 2.5 m in 60 years in the Florida Everglades, USA (Stephens & Speir 1969) and between 1 and 2.3 m over 140 years in Switzerland (Leifeld et al. 2011). In tropical peatlands, year-round high temperatures promote even higher rates of loss, e.g. 2.8 m over 28 years in Johor, Malaysia (Wösten et al. 1997). As mentioned above, rates of subsidence will be strongly influenced by the history of management of the groundwater level.

Land-use type	Location	N sites	Duration (years)	Mean WTD (cm)	Subsidence (cm yr^{-1})	Reference
Arable	Canada (Ontario)	1	3	102	3.30	Mirza & Irwin (1964)
Arable	Canada (Quebec)	1	10	ND	2.50	Mathur et al. (1982)
Arable	Canada (Quebec)	1	38	ND	2.07	Millette et al. (1976)
Arable	Germany	2	12	98	2.15	Eggelsmann & Bartels (1975)
Arable	Italy	1	4	50	0.75	Zanello et al (2011)
Arable	Switzerland	15	141	110	1.26	Leifeld et al (2011)
Arable	UK (England)	7	30	ND	1.37	Richardson & Smith (1977)
Arable	UK (England)	117	22	ND	1.48	Dawson et al. (2010)
Arable	UK (England)	1	53	120	1.56	Hutchinson (1980)
Arable	USA (California)	13	8	90	1.25	Deverel et al. (2010, 2016)
Arable	USA (Florida)		20	ND	1.45	Shih et al. (1998)
Arable	USA (Florida)	15	88	ND	1.82	Aich et al. (2013)
Arable	USA (Florida)	1	76	ND	1.40	Wright & Snyder (2009)
Arable	USA (Florida)				3.00	Stephens et al. (1984)
Arable	USA (Indiana)	3	6	75	2.26	Jongedyk et al. (1950)
Forest	Finland	273	60	ND	0.37	Minkinnen et al. (1999a)
Forest	Finland	4	30	ND	0.48	Minkinnen et al. (1999b)
Forest	UK (Scotland)	101	29	55	1.91	Shotbolt et al. (1988)
Grassland	Germany	1	40	80	0.83	Kluge et al. (2008)
Grassland	Germany	1	66	80	0.67	Eggelsmann & Bartels (1975)
Grassland	Germany	1	35	ND	0.50	Eggelsmann (1976)
Grassland	Netherlands	8	6	64	0.53	Schothorst (1977)
Grassland	Netherlands	1	88	15	0.06	Schothorst (1977)
Grassland	New Zealand	66	80	ND	2.56	Fitzgerald & MacLeod (2004)
Grassland	New Zealand	10	40	ND	3.40	Schipper & MacLeod (2002)
Grassland	New Zealand	119	12	ND	1.90	Pronger et al. (2014)
Grassland	Norway	11	28	ND	2.00	Gronlund et al. (2008)
Grassland	Norway	5	31	ND	1.04	Gronlund et al. (2008)
Grassland	Poland	18	38	53	0.17	Grzywna (2017)
Grassland	UK	ND	10	ND	0.62	Brunning (2002)
Grassland	USA (California)	34	28	ND	2.20	Deverel et al. (2010)

Table 1: Literature derived values for peat subsidence rates in northern peatlands (from Evans et al. 2018).

3.2 *Short-term Peat Surface Movements*

Measurement of short-term (hours to weeks) peat surface movements have demonstrated that drained peat soils can exhibit significant elastic volume changes, i.e. seasonal shrinking and swelling, in response to changes in soil moisture and temperature (Schwärzel et al. 2002; Teatini et al. 2004; Camporese et al. 2006) that is sometimes referred to as 'bog-breathing' (German: *mooratmung*). It is therefore possible to distinguish between short-term, mostly seasonal, reversible movements of the peat surface and long-term irreversible subsidence. In a study of drained peatland in NE Italy, Teatini et al. (2004) demonstrated a constant ratio between peat surface uplift and water table rise, equal to 0.3-0.4 mm cm^{-1}. Similar surface movements were also observed during winter in relation to temperature change, with a surface uplift due to ice formation and associated expansion of the order of 1 cm on nights when the temperature was below freezing. This uplift quickly dissipated as temperatures rose during the following day. Knowledge of short-term peat surface deformations is important since they can produce both reversible and irreversible changes in peat pore structure and hence the density and hydraulic properties of peat soils. In turn, these can influence peat water storage capacity and permeability (see further on this in Section 4.1 below) (Price & Schlotzhauer 1999; Price 2003).

Shrinking and swelling movements of the peat surface are currently being measured at several peatland sites in the UK (including at a number of flux tower sites) and in SE Asia (Evans et al. unpub. data). In common with the studies cited above, initial results indicate elastic change of the peat surface in response, primarily, to change in water-table level (a proxy for soil moisture). Differences in elasticity between sites with different land use and, specifically, drainage histories may provide some indication of the condition of the peatland – i.e. its degradation status – and its potential for restoration, given that restoration of sites that have undergone subsidence may be more challenging because of changes to peat structure, hydraulic gradients and water storage capacity (Ingebritsen et al. 1999; Price 2003). The capacity of a peatland to swell may indicate that the peat retains a high water storage capacity, which may be important for successful hydrological restoration.

3.3 *Other Causes of Peat Loss and Surface Lowering*

3.3.1 Wind erosion

Estimating the quantity of peat being transported and lost from the UK's upland and lowland organic soils by wind erosion has, until recently, received very limited attention, despite references to so-called 'fen blows' in some of the earlier literature (e.g. Thompson 1957; Pollard & Millar 1968; Hutchinson 1980). Fen blows are most likely to occur during the early spring months (February through April) when the bare peat surface is dry, is without a crop cover and is exposed to high wind velocities (Figure 3). Agricultural management of peatlands can intensify this process; e.g. the movement of machinery over the peat surface can promote wind erosion. While a few studies have acknowledged this loss pathway (e.g. Dawson & Smith 2007; Taft et al. 2017), there has, until recently, been no direct quantification of the flux, but rather a reliance on reference values of > 3 t ha^{-1} yr^{-1} reported by Böhner et al. (2003) for lowland mineral agricultural soils in the UK and of 0.46-0.48 t ha^{-1} yr^{-1} reported by Warburton (2003) for upland blanket bog. In the first study of aeolian losses from lowland peatland in the Fens of eastern England, Cumming (2018) demonstrated that the aeolian flux for land under salad crops and vegetables was in the range 2.3 to 12.8 t ha^{-1} yr^{-1}. The highest flux occurred during spring months when the soil had been ploughed in preparation for planting but was without a crop cover. A potentially large, but still unquantified, proportion of this flux will not be lost from the site, but rather will be re-deposited at field margins (e.g. in the tall vegetation growing alongside ditch margins and in hedge and tree rows; Chappell & Warren 2003). Nevertheless, the net effect across the bulk of the cultivated land will be a loss which will contribute to land surface lowering, albeit at a lower rate than that currently attributable to peat oxidation. For example, from a study of one field, Cumming (2018) estimates a loss of 0.15 to 1.3 kg m^{-2} yr^{-1} that could translate into a lowering of 0.03 to 0.25 cm yr^{-1}. This contemporary loss rate may be lower than occurred at times in the past given that some farmers have established hedges and tree rows at field margins to reduce cross-field wind speeds. Thompson (1957), for example, noted that fen blows could result in drainage ditches being brimful of peat after a severe blow. He also commented that the increase in planting of sugar beet and other root crops after World War I had likely increased the amount of wind-blown peat since harrowing during the spring months left the peat surface very susceptible to aeolian erosion.

Figure 3: A ‘Fen Blow’ across Hod Fen Drove, Cambridgeshire.
(Image obtained from https://www.geograph.org.uk/reuse.php?id=2334642).

3.3.2 Peat off-take during crop harvest

No quantitative data are available to calculate the contribution of harvest to peat loss, and this loss pathway will likely not apply to all crops. Farm operators in the Fens cut, clean and package salad and vegetable crops in the field, resulting in minimal peat loss. In addition, leafy crops such as lettuce that might capture wind-blown peat tend to be excluded from harvest and left on the field if they are too dirty. There may, however, be a net export of peat from the field for root crops such as sugar beet.

3.3.3 Peat extraction

From at least pre-Roman times onwards, peat digging for fuel has been a relatively widespread practice on both upland and lowland peatlands across the UK and, along with the drainage required to facilitate peat extraction, has also made a contribution to the lowering of the peat surface. Archaeological evidence for pre-Roman peat cutting comes from sites in the Fens and the Somerset Levels (Rotherham 2009). In later centuries, medieval peat excavations for fuel were so extensive that they were responsible for creating a series of lowland lakes (the Broads) within the fen peatlands of Norfolk and Suffolk (Lambert et al. 1960). Thompson (1957) notes that there were also extensive diggings in parts of the Cambridgeshire fens which resulted in substantial local lowering of the peat surface, especially in the vicinity of villages in the deep peat districts. Most, if not all, of these workings ceased between the First and Second World Wars, but at the time of writing in the 1950s, Thompson noted that many inhabitants of the Fens could still remember when peat was the common fuel of the poor people. The contribution that pre-industrial scale peat extraction made to land surface lowering across lowland peatlands in the UK is not known, but according to the accounts of both Rotherham (2009) and Thompson (1957) it was an important and widespread activity that likely resulted in considerable loss of peat. Rotherham notes, for example, that the peat consumed by a single household for fuel, litter (for animal bedding) and other purposes could be around 8,000 turves per year, with peat stacks as high as cottages. Turves were also cut and supplied to local towns and cities; the colleges of medieval Cambridge, for example, were fuelled by the fenland turbaries, while use of the Yorkshire Fens (the Humberhead peatlands and adjacent sites) supported a major industry that not only supplied turves for heating, but also to power local industries such as salt-making (Rotherham 2009).

The history of peat excavation in the Netherlands gives us some idea of the potential scale of this activity. The Dutch mined peat from the late Middle Ages and continued until the early years of the Industrial Revolution. Peat provided an energy source for production of glass, bricks, tiles, ceramics, and for brewing and baking. Peat digging became so widespread that large areas of land started to go below the water table as the peat surface was progressively lowered; during the 17^{th} century, several villages were 'swallowed' by man-made peat lakes and by the end of the 19^{th} century, peat had been removed from an estimated 10% of the total land surface of the Netherlands (de Dekker 2011). Erkens et al. (2016) estimate that this has led to a lowering of the Dutch coastal plain by an average of 1.9 m. At least 66% of this volume reduction is the result of peatland drainage, but some 34% was caused by the excavation and subsequent combustion of fuel peat.

From the mid-19th century, small-scale peat cutting on lowland peatlands in the UK was largely replaced by industrial-scale extraction to provide material for animal bedding and, increasingly from the 1930s onwards, for horticultural uses. Peat extraction has now ceased on sites such as the Humberhead peatlands and the Lancashire and Cumbrian Mosses, with the focus of peatland management now turned to ecosystem restoration. Small-scale extraction does still continue, however, in the Somerset Levels, albeit at a reduced intensity from earlier decades.

3.3.4 Burning

Agricultural conversion of peatland in the Netherlands provides one of the earliest accounts of the use of fire on lowland temperate peatland. During the 16^{th} and 17^{th} centuries, and continuing on a smaller scale into the 19^{th} century, farmers burnt the top layer of the peat surface to create a fertile ash within which grain crops such as buckwheat and rye could be cultivated (Verhoeven 1992). More recently, Rojstaczer and Deverel (1995) note that peat subsidence in the San Joaquin delta may have been accelerated by burning of crop residues. In the UK, Thompson (1957) noted that burning was once a regular practice among Fenland agriculturalists who set fire to the peat surface as a means of increasing fertility (ash production) and destroying weeds. More recently, and up until the imposition of government controls in the 1990s, burning of crop stubbles was a widespread practice that could have resulted in some peat loss if practiced on organic soils. While both prescribed and wildfires occur on upland organic soils in the UK (e.g. on heathlands and some blanket bogs, Garnett et al. 2000) there have also been occasional wildfires on lowland raised bogs, e.g. extensive fires on Glasson Moss in the 1970s and a fire on Cors Fochno in the early 1980s. There are no published accounts of combustion losses of peat during these events, but they are likely to be considerably lower than the values recorded for fires on tropical peatlands in SE Asia, where depth of burn values can be in the range 30–50 cm for high intensity fires (Page et al. 2002; Ballhorn et al. 2009), and for fires in drainage-impacted temperate forested peatlands in the USA, with burn depths in the range 0–30 cm (Poulter et al. 2006). By comparison, the fire at Cors Fochno occurred during the winter and did not consume any peat. Neither was the *Sphagnum* consumed, although it died owing to heat rupture of the plant cells (Mike Bailey, Natural Resources Wales, pers. comm.).

4. Direct Impacts of Peatland Drainage on Hydrology and Infrastructure

Peatland drainage and associated land subsidence can result in an array of negative impacts with environmental, economic and social implications. In the UK, these range from an increased risk of flooding through to changes in the hydrological properties of peat soils; and from the deformation of critical infrastructure, including transport and communication routes, through to less visible consequences, such as metal corrosion of drainage culverts. While some of these impacts have been recognised, most of the emphasis to date has been on identifying and addressing the symptoms of subsidence, with less consideration given to addressing the causes or gauging the associated economic or social costs.

4.1 *Hydrological Impacts and Increased Flood Risk*

The most direct and practical consequence of subsidence is that lowering of the land surface will change the hydrology of the area. Subsidence may bring the peat surface within the reach of local river flood levels or, in coastal areas, of high tide levels, which will eventually allow river or sea water to flood the area unless there has been significant investment in embankments, drainage pumps and sluices (water gates). In agricultural peatlands that have been drained for long periods, including much of the Fens of eastern England, the topography has been effectively reversed, such that silt-bedded rivers are now higher than the adjacent peatlands. Across large parts of the Fens, subsided peatlands are now below sea-level. In combination with sea level rise, on-going peat subsidence in low-lying coastal areas will lead to an increase in flood frequency, inundation depth and duration, increased frequency of saline inundation for coastal peatlands, and, ultimately, land loss (Day et al. 2007).

If, and exactly when, peat subsidence results in flooding and the loss of agricultural production will depend on local hydrological conditions and drainage options. In the Netherlands and in the Fens of eastern England, drainage by pumping has been possible and the peatlands have remained productive even where the land is now well below sea level - e.g. 2.7 m below sea level at Holme Fen in England and 6.7 m below sea level at Zuidplaspolder in the Netherlands, although in the case of the latter location the low land level is due to a combination of former peat excavation and drainage-induced subsidence.

Nevertheless, and largely because of subsidence, some areas of temperate peatland that were formerly drained for agriculture have now been abandoned or put to other land uses due to decreasing agricultural productivity, the increased costs of drainage and the concomitant risks of riverine and coastal flooding. On the Sacramento-San Joaquin delta in California, for example, subsidence has resulted in levée failure, flooding and salt-water incursion, giving rise to an increasing amount of marginal or non-farmable land (Drexler et al. 2009; Deverel et al. 2010). The delta produces one third of the USA’s table vegetables, which means that there are economic as well as environmental considerations. Rehabilitation initiatives here include trying to buy out farmers prior to rewetting the land to create permanent shallow and deep-water flooding (e.g. Miller et al. 2008), and conversion of conventional drained agriculture to flooded, wet cultivation systems like rice paddy to reduce further peat oxidation (Lund et al. 2007, cited in Hatala et al. 2012; Kirk et al. 2015). In the Florida Everglades, complex restoration initiatives have been implemented to improve soil accretion, as well as water quality and biodiversity (e.g. Wetzel et al. 2017). In the Netherlands, peatlands have been rewetted alongside the introduction of reduced intensity agricultural land management for nature conservation purposes, although lower rates of land subsidence are an additional benefit (e.g. Schrier-Uijl et al. 2014). In all these cases, peatland exploitation has resulted in long-term, essentially irreversible changes in local environmental and hydrological conditions such that alternative land uses (e.g. nature conservation or wetland agriculture) have been put in place or may need to be implemented in the future to reduce rates of subsidence.

In England and Wales, protecting people, valuable farmland, properties and critical infrastructure from river and tidal flooding is the responsibility of the Environment Agency, Internal Drainage Boards (IDBs) and local authorities. The Environment Agency have responsibility for managing the risk of flooding from 'main rivers' (larger rivers and streams) and the sea. They maintain coastal defences and carry out maintenance, and improvement or construction work, including for flood defence. Lead local flood authorities (unitary and county councils), district councils and IDBs have responsibility for flood risk management work on other 'ordinary' (usually smaller) watercourses.

The IDBs are local independent public bodies, many of which were founded in the 18th century (Ely Group of IDBs 2016). They provide specialist local management of water levels in watercourses and the surrounding landscape to provide land drainage and irrigation, and to reduce the risk of flooding. They also have responsibility for maintaining the environmental interest of Sites of Special Scientific Interest (SSSIs; statutory sites protected for their nature conservation value) and other designated environmental areas. IDBs operate across 1.2 million hectares, including all the larger blocks of lowland peatland in the Fens, the Trent valley and Yorkshire (Humberhead peatlands), Somerset Levels and Moors, and the Norfolk Broads. Some one million hectares of agricultural land and more than 50,000 farms occur within IDB districts, including the majority of England and Wales' lowland peatlands and highest-grade farmland (ADA 2017). Urban areas within IDB districts, at least part of which will be on peat soils, contain 870,000 homes, industrial premises, and critical infrastructure, including power stations producing 53% of England and Wales' electricity generating capacity. There are also 1,500 km of railway and 208 km of motorway (ADA 2017). Total road length within IDB areas and, specifically, on peat soils is not known.

In addition to the direct consequences of land surface lowering, subsidence also affects the water storage capacity of peat through an increase in bulk density and a reduction in pore volume. With increasing bulk density, both peat hydraulic conductivity and specific yield increase. Liu & Lennartz (2019) note that, as bulk density increases from 0.01 to 0.2 g cm^{-3}, the hydraulic conductivity reduces rapidly; but at higher bulk densities, which might be more characteristic of wasted peats (e.g. from 0.2 to 1.0 g cm^{-3}), hydraulic conductivity remains constant, albeit with a large variance. In a natural, undrained condition, near-surface peat from a *Sphagnum*-dominated ombrotrophic peatland (e.g. a raised bog) has a low bulk density and a specific yield[2] of 20 to 65% in the uppermost 20 –30 cm. In contrast, fen peats, which are derived from grasses and sedges rather than mosses, have a higher bulk density and a lower porosity resulting in specific yields that are lower, e.g. typically between 10 and 20% (Gilman 1994). Following drainage, the effect of peat subsidence on the water balance in both fen and bog peats will be to lower permeability and specific yield and reduce water storage, while saturation will occur at a lower volumetric moisture content (e.g. Silinis & Rothwell 1998; Price &

[2] Specific yield is the volume of water released from storage by an unconfined aquifer per unit surface area of aquifer per unit decline of the water table.

Schlotzhauer 1999; Kellner & Halldin 2002; Kennedy & Price 2005; Stratford & Acreman 2014; Bourgault et al. 2018). Holden et al. (2004) note that these changes will affect catchment hydrology with the potential for both reductions and increases in total runoff. A decrease in flood and annual runoff may occur as a result of the drainage-induced decrease in peat hydraulic conductivity, but also through increased evaporation related to changes in vegetation and the presence of drainage channels, which both store water and increase evaporation. Conversely, flow increases can be caused by direct precipitation into drainage channels, temporary flow increases brought about by channel straightening, widening and vegetation clearance, decreased evapotranspiration from drained but uncultivated land, and increased drainage of previously closed wetland systems. Lower peat hydraulic conducitivity can also reduce infiltration rates and make overland flow more likely, thereby increasing flood risk. Thus, generalising the impacts of agricultural land drainage can be complex and not easily predicted, with some effects being cancelled out by others.

4.2 *Case Studies: The Fens and the Somerset Levels*

The Fens of eastern England occupy 4000 km^2 across Lincolnshire, Cambridgeshire, Norfolk and a small part of Suffolk. This area was once the largest wetland in England interspersed by settlements on islands of higher ground. Fed by the floodwaters of four large rivers, the Great Ouse, Nene, Witham and Welland, the fen peats started to form and built up to a thickness of 3 to 4 metres under near constant waterlogging and over many thousands of years. Initial efforts to drain the Fens took place during the Roman and Medieval periods, followed by more comprehensive drainage efforts starting in the middle of the 17th century that were focused on drainage for agriculture. Rivers were diverted to run through a series of new 'cuts' (human-made, straight river channels) (Figure 4) to drain the land, river embankments were constructed to protect it from flooding, and winter flood water storage areas (washlands) were engineered, such as the Ouse Washes. These large-scale engineering works, that were initially dependent on gravity drainage, proved effective for a period, but as the peat dewatered and dried, it also compacted and oxidised resulting in a rapid lowering of the land surface. By the end of the 17th century, peat subsidence meant that much of the reclaimed land was below the level of the rivers and was once more under water. Hundreds of wind pumps were erected to lift the water out of the fields and more river sluices were installed to prevent flooding at high tide, followed by more intensive drainage efforts from the 18th century onwards. Further embankments, drains, channels, and sluices were built, and wind pumps were replaced by more powerful steam engines, later to be succeeded by diesel and electric pumps in the 20th century. Over time, drainage was focused increasingly on flood alleviation in addition to enabling agriculture.

As a consequence of their long history of drainage, a large portion of the Fens now lies below sea level and is reliant on pumped drainage (e.g. 40% of Lincolnshire and 50% of Cambridgeshire; in total, some 3,100 km^2 are below sea level). But the Fens also provide some of the most fertile agricultural land in the UK. Ninety per cent of Fenland farms are on Grade 1 or 2 farmland with these farms supplying about 7% of England's total agricultural production, including 33% of England's fresh vegetables (NFU 2019). The most fertile soils are on the deep peats which occupy an estimated 600 km^2; these are mainly farmed for high value vegetables, salad crops and potatoes. A larger area (estimated to be around 1400 km^2) is occupied by wasted peat soils where most or all of the original peat cover has been lost, exposing a heavy clay marl (skirt soil) (Figure 5). These soils have a lower agricultural value; they are more difficult to work, have a lower, more variable fertility, and are mainly used for cereals, oil seeds and some sugar beet.

Figure 4: The Twenty Foot River (Drain) near Whittlesey was constructed in the mid-17th century. (Photo - S. Page)

Figure 5: Arable land on shallow, wasted peat in the Fens of eastern England. In the foreground, ploughing has brought the underlying mineral soil to the surface. (Photo – T. Newman).

In order to protect valuable Fenland agricultural land and properties from river and tidal flooding, protection is provided by 100 miles of sea and riverine flood defences maintained by the Environment Agency. Thirty-six IDBs plus the Middle Level Commissioners collectively manage some 4000 miles of ditches, along with pumping stations and other control structures. Problems are caused by ongoing peat subsidence which causes damage to river embankments necessitating regular additional maintenance. For example, the Environment Agency is currently engaged in a £27 m project to raise and strengthen a 30 km stretch of the Middle Level Barrier Bank at the Ouse Washes to address lowering of the bank crest level caused by settlement of the underlying peat and marine clays (Environment Agency n.d.) (Figure 6). This bank is effectively the dam wall which, during periods of winter flood storage, holds up to 90 million cubic metres of water inside the washland. Similar problems of embankment (levee) damage caused by peat subsidence have also been reported in the Sacramento-San Joaquin delta in California. Subsidence there has led to instability of the 100-year-old levee system, resulting in a number of breaches (Deverel et al. 2016).

Figure 6: Environment Agency sign explaining engineering works to strengthen the Ouse Washes Middle Level barrier bank, Cambridgeshire. (Photo – S. Page)

Over the past two decades, the Somerset Levels and Moors have experienced several episodes of severe flooding. Extensive drainage of the Levels began in the 1600s and has resulted in widespread peat subsidence. RMS (2007) note that this is likely to have contributed to observed changes in maximum high tide levels in the Bristol Channel, which are estimated to be at least 1.0 m higher than 400 years ago. They calculate that the observed increase in maximum tidal heights is due to a combination of global sea level rise (0.2 m) and other factors including localised peat shrinkage (0.2 m) (with the latter presumably resulting in subsidence of non-embanked adjacent areas – also note that, according to the subsidence rate reported by Brunning (2012) of 0.06 cm yr^{-1}, this could be an under-estimate). In their report on a long-term plan for the Somerset Levels and Moors, the Adaptation Subcommittee of the Committee on Climate Change Adaptation note that Sedgemoor District, located in the Levels, had by far the highest number and proportion of properties in significant flood risk areas in 2011 (at 5,400) of the four local district council areas in Somerset (CCCA 2014). Within this District, 11% of all properties are at a significant flood risk, compared to 1-2% for the other three county council districts and 1% nationally. Furthermore, the annual rate of property development in significant flood risk areas in Sedgemoor District increased from 1.2% a year between

2001 and 2008 to 3.2% a year between 2008 and 2011. This was more than double the average annual rate for England (1.2%), resulting in almost 900 new properties being built in areas of significant flood risk in Sedgemoor District over the decade to 2011. Whilst flooding in the Somerset Levels has several causes, peat subsidence is likely to make an ongoing contribution to enhanced flood risk because around 70% of the peatland is drained for intensive livestock grazing, cultivation and also direct peat extraction (CCCA 2014). Whilst some peatland restoration has already occurred, the CCCA (2014) note that 'further restoration of the remaining area of degraded peat would help to improve water management, primarily by reducing carbon-rich soil losses to the rivers. Restoration would also help to increase the resilience of vulnerable peat soils to the increasing frequent and severe extreme weather events we can expect in the future with climate change'.

Following severe flooding over winter 2013/14, the Somerset Levels and Moors Flood Action Plan (2014) was published. This is a £100 million 20-year plan that, amongst other considerations, recognises that a range of land management activities will be important in reducing the risk of future devastating floods, including improving soil management and reducing erosion, harvesting rainwater on farms, intercepting overland flows, slowing the flow in watercourses, restoring and creating wetland areas that absorb and store water, and woodland planting and management. It also proposed to pilot a locally operated payment for ecosystem services scheme to deliver a reduction in local flood risk and carbon flux through conservation of peat soils.

4.3 *Impacts on Infrastructure*

Regarding impacts on infrastructure, the critical negative properties of peat soils are their limited load-bearing capacity and their sensitivity to oxidation and hence subsidence. Both low load-bearing capacity (where, in the case of a road, load comprises the road foundations, the road surface and the traffic) and subsidence can result in major economic losses arising from structural damage to, and high maintenance costs for, infrastructure including *inter alia*, roads, railways, pipelines, buildings, electricity and telephone cables, drainage and sewerage structures (Gambolati et al. 2006; PBL 2016; van Asselen et al. 2018). As a result of the long term lowering of the peat surface discussed above, key infrastructure including roads and railways is now elevated above the surrounding landscape, and in some cases is 'floating' on peat which continues to subside, leading to deformation. A review of the impacts of soil-related threats to critical UK infrastructure (Pritchard et al. 2013a) identified peat shrinkage as one of six main problems, affecting thousands of kilometres of the road network, as well as sections of the rail network.

4.3.1. Roads

Road construction over peat presents a range of challenges owing to low load bearing capacity (low strength), high water content, high compressibility and subsidence. These can lead to problems of stability and long-term settlement. There are several options available for road engineers to reduce subsidence, including:

a) Excavation and removal / replacement of the peat to allow construction on the underlying mineral substrates.

b) Construction on the peat preceded by preloading, i.e. loading the peat with a load in excess of that required to allow the peat to settle, then removing the excess to leave a sufficient load for road construction on a strong foundation. Preloading has to take place slowly enough for the underlying peat to respond and allow sufficient time for the compressed peat to consolidate and gain strength rather than shear. It is considered an effective means to eliminate, in advance of construction, both primary consolidation and a portion of the secondary compression that follows the loading of a soft substrate and is the most technically and environmentally advantageous and economical solution for peat substrates, especially where the peat is underlain by a soft clay (Mesri & Ajlouni 2007).

c) Use of lightweight fill to reduce the loading stress, which has the advantages of not requiring underlying peat to be strengthened and lower rates of future settlement. Pritchard et al. (2013a) report that for the construction of embankments (e.g. for roads and railways), some countries have employed lightweight fill materials such as polystyrene blocks, sawdust, brushwood and peat bales although the disadvantage is that these types of materials have a low load-bearing capacity. This can be done in combination with (b) above.

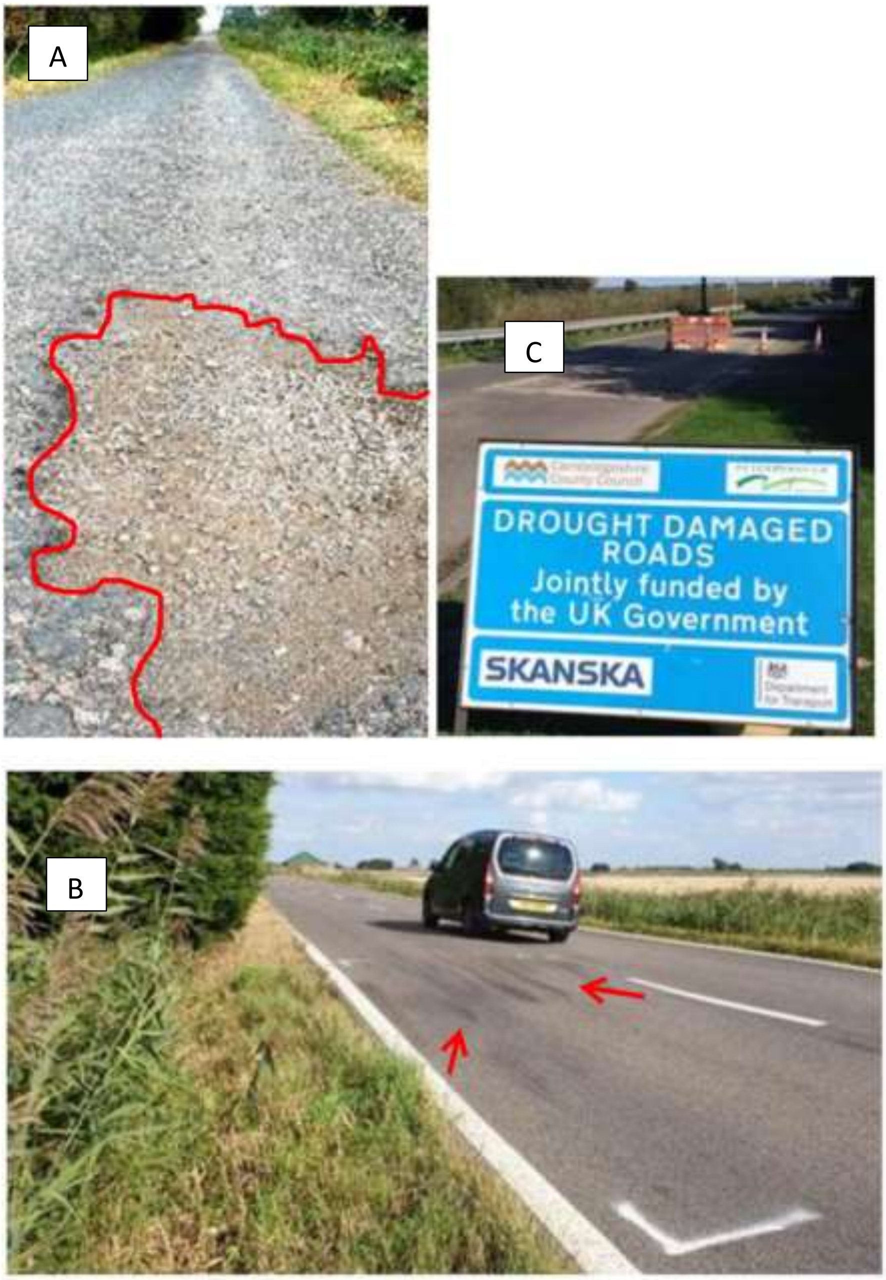
d) Construction of a road embankment on a raft constructed from timber, concrete, galvanised steel or geotextile.

(See Munro (2004) for more detail on road construction on peat soils).

All highways constructed over the last 50 or so years in the UK have followed specific design standards, including for axel loadings according to the Design Manual for Roads and Bridges (http://www.standardsforhighways.co.uk/ha/standards/). Nevertheless, if construction takes place on soft ground, additional costs may be incurred. As an example, construction of the recently completed Ely southern bypass required deeper foundation supports than originally expected on sections crossing fen peat. This, along with other issues, reportedly led to an increase in costs of £13 million to the build of the bypass (Ely Standard 2018). At time of writing this document, it has not been possible to ascertain whether peat subsidence had also to be considered in the design of the road and whether this incurred an additional cost. Investing more in the planning and construction phase may reduce maintenance and repair costs in the longer term. In the Netherlands, the cost-savings associated with mitigation measures for construction on peat have been estimated. These measures include building roads in such a way that subsidence is partly mitigated (by using lighter building materials etc.) in an effort to reduce repair costs (van Woerden 2018). As a salutary example of the need to take account of substrate conditions, a bridge on the four-lane A20 motorway near Tribsees in northern Germany collapsed in 2017, only 12 years after construction. This stretch of highway traversed a peatland but the bridge foundations were not sufficiently strong (deeply founded) for the soft ground. The road was closed, forcing traffic through small local towns with delays and potential negative impacts on tourism for resorts on the Baltic coast. A temporary replacement bridge has now been constructed at an estimated rental cost of 100,000 Euros per month; meanwhile, work to build a permanent bridge is underway (John Couwenberg, University of Greifswald, pers. comm.).

In their report on soil movement in the UK, Pritchard et al. (2013a) noted that several East Anglian highways authorities (including those in the Fenland counties of Lincolnshire, Norfolk and Cambridgeshire) had reported that soil subsidence caused significant damage to their highway network, most notably during periods of drought. As a result of the drought of 2003, Lincolnshire County Council recorded damage estimated at £7 million affecting over 200 road sections. More recently in 2010-11, drought conditions caused damage to 154 sites, predominantly in the south-east of the county (The Geological Society 2014). In 2011 this led to an (unsuccessful) bid to government for additional road funding (BBC News 2012; Mike Coates pers. comm., cited in Pritchard et al. 2013a), and local media reports of cracked road surfaces, particularly on Fenland roads (Figure 7). In 2017, a heavily deformed and ditch-lined section of road in Lincolnshire was dubbed 'Britain's worst road'(www.thesun.co.uk/news/5126166/britain-worst-road-guantlet-south-fens-lincolnshire/) (Figure 8), and in Cambridgeshire alone the Department for Transport recently invested £3.5 million towards the repair of subsidence-affected roads (Peterborough City Council n.d.).

A further problem for peatland roads is that the subsidence of the drained peat on either side of the road has left these highways elevated by one or more metres above the rest of the landscape. These raised sections often have steep banks leading down to water-filled drainage channels. This can give rise to slope instability resulting in road closures and high remediation costs, and an increased accident risk. Some road courses through the Fens follow the silty ridges formed by roddons (former river channels) and are therefore less susceptible to ground movement. However, subsidence of the surrounding peatland has left these highways well above the adjacent landscape (The Geological Society, 2014). In some places, this has necessitated installation of crash barriers to improve road safety and reduce the risk of cars from leaving the road on potentially dangerous elevated sections alongside deep drainage channels (authors' pers. obs).



Figures 7A & 7B: Damage to road surfaces near Holme Fen, Cambridgeshire. (Photos – S. Page); **Figure 7C**: Repairs underway on a peatland road in Cambridgeshire during recent summer drought conditions. (Photo – R. Morrison).

Figure 8: Article on 'Britain's worst road', The Sun, December 2017
(Image: www.thesun.co.uk/news/5126166/britain-worst-road-guantlet-south-fens-lincolnshire/)

As an indication of the scale of the problem, Norfolk County Council have approximately 4,000 km of their road network located on subsidence-prone soils (Robert Noakes, pers. comm. cited in Pritchard et al. 2013a). Some of the most subsidence-prone roads are unclassified roads that have not been subject to modern engineering development and have 'evolved' from older roads, possibly dating back hundreds of years. These roads may originally have been built on rafts of brushwood, so that they literally float on the peat (Waltham 2000). In the Somerset Levels, increased heavy goods vehicle (HGV) traffic has been identified as a concern for damage to road surfaces in peatland areas (Somerset Levels HGV Management Study n.d.). Besides public roads, there are also many miles of private farm roads on peat soils, particularly in the Fens, which require regular maintenance. On Anglesey, the main A55 dual carriageway required resurfacing within a few years of construction where it crosses the Cefni Marshes. In Northern England, part of the M62 crosses peatland on the edge of the Lancashire mosses. It is understood that deformation of this section of the highway has caused drainage problems and damage to the road surface necessitating regular re-surfacing approximately every 3 to 5 years (Mike Longden, Lancashire Wildlife Trust, pers. comm.). We have not been able to obtain confirmatory information or costs from Highways England. In this regard, indirect costs, e.g. as a result of speed restrictions or road closures and diversions, should also be considered.

4.3.2. Railways

Several railway lines in England and Wales have been constructed across peatlands. These include the UK's first passenger line between Liverpool and Manchester that was opened in 1830. Designed and built by George Stephenson, his biggest engineering challenge was traversing the lowland raised bog at Chat Moss to the west of Manchester. Following an initial attempt to drain the peatland, he used hurdles of timber and heather to provide a base for a stone and clay embankment which sank into the peat until it reached equilibrium. This embankment is still in use today, albeit having required the addition of secondary foundations during electrification works in 2012/13 (Railway Engineer 2012) and undergoing regular maintenance (tamping work – i.e. repacking of ballast under the tracks) to address track deformation (Figure 9).

Figure 9: Tamping work on the railway track crossing Chat Moss. Over time, railway tracks settle with the passage of traffic; this is more likely to happen where the track passes over soft ground. The track may not settle evenly, resulting in track deformation. Tamping (i.e. packing - or tamping - the track ballast under the tracks) makes the tracks more durable, thereby ensuring good track alignment, smooth running and also preventing derailment.
(Image source: https://twitter.com/TheGNRP/status/793397016143495172)

The East Coast railway line crosses the western edge of the Fens near Holme Fen, Cambridgeshire. It was opened in 1850 and built on a low embankment of faggots and peat sods and was constructed slowly to allow settlement into the peat until it could bear the load of the ballast and the trains. Waltham (2000) reports that a hundred years after its construction, it was still subsiding by 1 to 2 cm yr^{-1}, but that it now appears to be stable and resting on a buried mass of fill that reaches to the underlying clay. Pritchard et al. (2013a) provide other examples of rail infrastructure built on soft peat substrates in eastern England – at Stilton Fen, Cambridgeshire and Thandestron Bog, Norfolk. They state that at 'Stilton Fen, track displacements are caused by passing trains (180 km/h), and the embankment at Thandestron bog is often subject to slope failure and large settlements'. In 2019, Network Rail reportedly dedicated £10 million of their annual maintenance budget to addressing issues in the East Anglian region alone (East Anglian Daily Times 2019). It has not yet been possible to ascertain how much of this budget was required to address problems of track deformation arising from peat subsidence.

Pritchard et al. (2013a) also cite a study undertaken by Hendry et al. (2010) at Brackagh Bog, Northern Ireland, which showed that large displacement occurred on tracks passing over a peat bog. The train drivers reported a reduction in power as they passed over the peat section owing to track deformation; this resulted in increased journey times. One proposed solution for the problems caused by subsidence of railway tracks is to inject polyurethane foam under the track bed. The company Uretek UK (now Geobear) believes that their "PowerPile" technology could be used to stabilise railway lines built on soft ground (Eureka Magazine, 2009). Reduced speeds are also in force across sections of railway that cross soft peat soils in the Netherlands (G. Erkens, Deltares/University of Utrecht, pers. comm.).

An additional phenomenon associated with railway track sections passing over soft substrates relates to ground vibration and associated noise (ground vibration boom) that occurs when train speeds exceed the velocity of Rayleigh waves in the underlying ground. Madshus and Kaynia (2000) report observations by railway companies in France, Germany, Switzerland, the Netherlands and the UK of substantial increases in the vertical movement of the track as train speeds approach the Rayleigh wave speed in the ground, resulting in large dynamic amplifications. At the time of writing, the authors commented that there was limited information on this issue in the literature, and that the severity of the problem did not seem to be widely known. More recently, the issue has been highlighted in planning for the new high-speed HS2 railway line. Krylov and Lewis (2016) assessed locations along the proposed route that were likely to experience ground vibration boom from high-speed trains. The track section crossing Chat Moss was identified as presenting conditions that would require mitigation measures to reduce the risk of ground vibration boom, e.g. reduced train speeds, strengthening of track foundations or installation of in-filled isolating trenches and wave barriers. The additional costs of implementing these measures are not known.

4.3.3. Buildings

Structures built on peat soils without adequate foundations will likely experience subsidence-related problems such as cracks, tilting and differential settlement. In the Netherlands, it is estimated that the extra costs and damage to urban infrastructure caused by consolidation of peat soils in the period up to 2050 will amount to between 1.7 and 5.2 billion euros, and that the extra costs related to the restoration of inadequate foundations will add up to at least 16 billion euros (at current price levels). The cost of damage to infrastructure and buildings in rural areas is estimated to reach a maximum of 2 billion euros by 2050 (at the current price level; 1 billion euros for infrastructure and 1 billion euros for buildings) (PBL 2016). There has been much less urban and rural development on peat soils in the UK than in the Netherlands; accordingly, there is a much lower risk of subsidence and other forms of water-related damage to properties. Waltham (2000) reports that some older buildings in the Fens were constructed to take account of the soft substrate: older farmhouses in Holme Fen, for example, and Ramsey St Mary's church were built on timber piles[3] driven down into the underlying clay. These piled buildings have remained relatively stable, even as the surrounding drained peat has subsided, although the church has now to be entered via a flight of steps which themselves showing evidence of on-going subsidence damage (Figure 10). In his article on the English peat fens, Thompson (1957) presents two striking photographs of subsidence impacts on Fenland houses (Figure 11). For more recent buildings, there is anecdotal but only very limited verifiable evidence of subsidence damage in the Fens or, for that matter, other lowland peatland areas in England. For example, GeoInvestigate (2014) report damage to a house in the vicinity of Chat Moss which required underpinning to a depth of 3.9 m, whilst a house in the vicinity of Holme Fen has reportedly been condemned due to subsidence damage.

Figure 10: Subsiding steps at the Church entrance and collapsing gravestones in the churchyard at Ramsey St Mary's, Cambridgeshire. Built in 1859, the church was constructed on peat and soft clay using a foundation of wooden piles. It has remained relatively stable, although the spire had to be removed in 1920. By contrast, the surrounding land has subsided by several metres, leading to damage to churchyard monuments and necessitating the demolition of the Vicarage.
(Photos: S. Page)

[3] It is worth noting that in the Netherlands, buildings constructed on soft substrates using timber pile foundations may subside because of direct damage to the piles, e.g. as a result of bacterial or fungal attack or negative shaft friction (which occurs when concrete piles are situated in soft soils, resulting in a downward force that increases loading on shaft piles and reduces the bearing capacity of the piles), rather than due to land subsidence *per se* (G. Erkens, Deltares/University of Utrecht, pers. comm.).

Figure 11: Images from Thompson (1957): Left - A house built on peat some 100 years previously with its foundations on clay. The peat level has subsequently been lowered by about 2 m by subsidence leaving the house entrances above ground level. Right - Two Fenland cottages leaning away from each other as a result of peat subsidence.

There are some key differences between lowland peatlands in England and those in the Netherlands which might explain the (seeming) striking differences in building damage and costs associated with peat subsidence in the two countries. Firstly, in England, and particularly the Fens, most rural settlements are located on pockets of mineral ground (fen 'islands'), with only a few isolated dwellings and farms constructed on peat or, more often, on silty roddon ridges. Thus many properties will have relatively stable foundations, although there may be problems caused by ongoing subsidence of the surrounding peat. Secondly, there are no larger urban areas on peat soils. Ely, for example, is a city of 20,000 people, but is located on a clay island. In the Netherlands, a large proportion of the estimated costs for urban areas stem from the need to rehabilitate buildings with inadequate foundations (PBL 2016). Gouda, for example, is a city of 72,000 inhabitants that is located on soft peat and clay. Many of the houses here were constructed between the 16th and 20th centuries but have inadequate and/ or shallow foundations. As a result, they are subsiding, due mainly to consolidation, and resulting in structural damage and maintenance costs (van Asselen 2018). Given that there are fewer settlements built on peat substrates in lowland England and Wales, it follows that there will also be a much lower risk of damage to other infrastructure in the built environment, e.g. to pavements, sewer systems and underground utilities, although we have not been able to obtain data to support this contention. Thirdly, some of the damage to buildings founded on wooden piles in the Netherlands, such as in Amsterdam, and other European countries (e.g. Estonia; Kalm 2007) arises from fluctuations in the groundwater level, although this damage is also subsidence-related. Because of subsidence, the groundwater level has had to be lowered in order to maintain the freeboard; however, this also causes an increased risk of low groundwater levels and aeration of the piles. When timber piles are waterlogged and in an anaerobic condition they will not be affected by decay, but if water tables fluctuate, e.g. as a result of groundwater abstraction or drought, then the exposed piles will be exposed to oxygen, giving rise to decay. The weakened piles cause subsidence of the foundations and building damage. Since some older buildings constructed on peat soils in the UK also have wooden pile foundations, it is possible peat de-watering poses a similar risk. The degree of risk may in part be dependent on the type of wood: piles made of oak can be more resistant to the effects of aeration than those made of pine (G. Erkens, Deltares/University of Utrecht, pers. comm.).

4.3.4 Other Infrastructure

Where infrastructure passes across or through peat soils, there may be a requirement for regular maintenance. This applies to power and communications infrastructure. For example, the gas pipeline crossing Chat Moss was not constructed in such a way as to secure it to the underlying mineral layer. As the peat mass changes over time (e.g. due to peat oxidation and subsidence) the pipeline is moving towards the surface, necessitating constant monitoring by the operator, Cadent (Mike Longden, Lancashire Wildlife Trust, pers. comm.). Telegraph poles crossing parts of Chat Moss and the Fens can also be seen leaning at varying angles (Figure 12).

Figure 12: Subsidence damage to telegraph poles crossing drained peatland near Holme Fen, Cambridgeshire. (Photo – S. Page)

In addition to the direct consequences associated with subsidence, Dawson et al. (2010) and Pritchard et al. (2013a, b) note that the oxidation of peat can have secondary impacts on infrastructure systems. Where, for example, fen peats in eastern England are underlain by sulphate-rich fen clays, drainage can lead to the production of acid sulphate soils with pH as low as 2. This can facilitate the formation of ochre containing sulphate-reducing bacteria that can clog up sub-irrigation systems, corrode metallic structures (e.g. culverted drainage), pollute waterways and potentially limit crop yields.

5. Other Societal Impacts

Current water and land management practices in the lowland peatlands of England and Wales incur a range of other less tangible societal impacts. These include both benefits (e.g. for rural employment, food security, flood storage capacity) and detriments (e.g. costs of land-drainage and flood defence, loss of high-value agricultural soils, loss of carbon sink and biodiversity support functions, damage to archaeological sites, loss of cultural value, and the risk of saline intrusion into coastal floodplains with rising sea levels).

5.1 *Benefits for the Rural Economy, Employment & Food Security*

In England, around 240,000 hectares of drained lowland peat are farmed for food production (Morris et al. 2010). The National Farmers' Union (2019) estimate that farming in the Fens (Figure 13) directly employs around 27,000 people, and, in total, it is estimated that Fenland agriculture and food-related industries employ 80,000 people and generate around £3 billion a year for the regional economy. In Somerset, the agricultural sector employs some 10,000 people and is estimated to be worth around £200 million per annum (Somerset County Council 2016). In the District of Sedgemoor, which encompasses a large part of the Somerset Levels and Moors, the GVA (gross value added, i.e. the value of goods and services produced in the area) attributed to the agricultural, forestry and fisheries sector is £33.8 million (i.e. ~17% of the total GVA for Somerset, with most derived from agriculture) (2014 data based on 2011 prices; Somerset County Council 2016).

UK policy on food security aims to 'guarantee households' access to affordable nutritious food' (Morris et al. 2010), but national food security is in long-term decline, with the country importing 48% of all food consumed (Global Food Security 2019). In this regard, agriculture in the Fens makes an important contribution since it accounts for approximately 10% of the national areas given to potatoes, sugar beet and vegetables (Graves & Morris 2013), with more than one fifth of England's potatoes and a third of fresh vegetables grown in this region. UK Government efforts to address dietary issues (e.g. in 2018 only 29% of adults and 18% of children were reportedly receiving the suggested daily dietary requirement of five portions of fruit and vegetables; NHS 2019) along with the projected increase of the UK population by half a million people annually (ONS 2017) will likely put further demand on the supply of vegetables from the agricultural industry in the Fens. Morris et al. (2010) provide more information on agricultural production on lowland peatlands in England and the impact that taking this land out of production, e.g. for wetland restoration, would have on food production and security. They conclude that taking all of England's 240,000 ha of agriculturally-managed peatland out of production would account for about 2% of the total lowland agricultural land area, over 3% of its total value, and around 5-8% of the area of specialist crops (e.g. salads and vegetables). This could affect national supply if relocation elsewhere in the UK were not possible.

Figure 13: Fenland vegetable farming on deep peat soils near Ely, Cambridgeshire.
(Photo - S. Page)

5.2 *Provision of Flood Protection and Flood Storage Capacity*

In their natural state, floodplain fens, when not separated from the main river channel by bunds or flood embankments, can have an important role in reducing flooding. They do so by providing storage areas into which out-of-bank flows can be temporarily stored, thus reducing the velocity and the height of a flood wave. In a meta-analysis of 28 studies, Bullock and Acreman (2003) found that floodplain wetlands (including both peat and non-peat systems) delayed or reduced flooding in 23 cases. In a modelling study, Acreman et al. (2003) have also shown that removing flood embankments and re-connecting a river channel with its floodplain can have substantial effects on flood flows, reducing downstream peak flows by 50-150%. All floodplains, whether they contain peat or mineral soils or both, should behave in a similar way in this respect; as noted by Acreman et al. (2003), their study has generic value. However, it is also worth noting that the hydraulic roughness of some floodplain fens may further attenuate flood flows. For example, wooded floodplain fens (a type of carr woodland) may hold up flows more than grazing meadows or other, less hydraulically-rough, vegetation (Thomas & Nisbet 2007). Woody debris from floodplain trees may additionally partially clog river channels and this too can have an effect on flooding (e.g. Dadson et al. 2017). The overall effect of trees on flood water storage and river hydraulics is still being actively researched within the context of 'natural flood management'.

In drained peatlands, such as the Fens of eastern England and the Somerset Levels, the land surface is now one or more metres below river level, thus water is pumped uphill from the peatland and into the adjacent river system. In theory, this low-lying land bounded by embankments could offer capacity for water storage on the field surfaces at times of heightened flood risk. But realising this potential at a landscape scale would have negative consequences for current drained land uses, particularly agriculture and habitation. In addition, given the relative positions of land and rivers, if inundation were to occur it could persist for long periods of time and would require energy-intensive pumping of water ‘uphill’ out of the fields and into the watercourses. This was the situation during the 2013-14 winter floods on the Somerset Levels. Heavy rainfall led to the River Parrett bursting its banks resulting in inundation of 12,200 hectares, much of it agricultural land, flood damage to about 165 properties, with many more indirectly affected, and disruption to train services on the Bridgewater to Exeter line (Parsons Brinckerhoff/Somerset Rivers Authority 2014). Floodwaters remained on the land for several weeks until temporary heavy-duty pumps were installed to propel the water back uphill into the River Parrett.

In the Fens of eastern England, most flood storage is focused in specific areas of washland, which can be purposefully flooded when river levels are high, thereby protecting areas of high value agricultural land on surrounding shallow and deep peat soils. The Ouse Washes, for example, occupy 2,500 ha between the Old and New Bedford Rivers in Cambridgeshire and Norfolk and play an important role in floodwater storage during the winter months and occasionally during the spring and summer (Figure 14). Being either permanently wet or underwater during the winter months, they also provide an internationally significant habitat for wintering and breeding wildfowl and waders. The smaller Nene Washes (1500 ha), east of Peterborough, play an equivalent role in flood storage and the provision of wildlife habitat.

New areas of flood storage may be provided as part of fen wetland restoration projects. The Great Fen project, for example, is being designed to create new water storage areas that will provide flood risk alleviation during heavy rainfall events (Great Fen, undated). We are not aware of any holistic study that quantifies the economic and social benefits that the current washlands of eastern England provide, e.g. in terms of flood protection for high value agricultural land and housing, or whether consideration has been given to promoting the creation of more extensive areas of winter washland on agricultural land (i.e. on field surfaces). As previously noted, however, this could necessitate active pumping to move water back off the land once the flood risk was diminished; prolonged flooding could also have negative impacts on soil structure and crop production. We have also been unable to ascertain the role that the network of watercourses managed within the IDB network plays in winter flood storage. We understand that, at least in some districts, winter water levels are kept low in order to provide increased capacity for flood water storage, but it is not known if this flood storage capacity within the drainage system is ever used. If this capacity needs to be maintained, it could have implications for initiatives to raise winter field water levels to reduce peat soil carbon loss and GHG emissions. Mulholland et al. (2020) provide a more thorough discussion of flood risks and costs under current and future land management options for lowland drained peatlands.

5.3 *Costs of Land-drainage and Flood Defences Borne by Society*

As previously discussed, subsidence has caused the land surface of extensive areas of drained peatland to fall below the level of the rivers, which are now embanked, often channelized and intensively managed to mitigate flood risk. Water levels in field ditches are lowered using pumped drainage to move the water uphill and against gravity into adjacent rivers. This pumped drainage is managed by the Internal Drainage Boards (IDBs) who also operate a series of inlets, weirs and sluices to manage water levels within their districts and to control water levels at high and low tides. At the field scale, e.g. in the Fens but also in the Somerset Levels, farmers employ a series of sub-surface drainage pipes and tiles along with field ditches to achieve suitable conditions for crop growth and management. Water can only be drained into the field ditches under gravity, requiring ditch water levels to be below the groundwater level of the field. As a result of ongoing peat subsidence, both large and small field drains have to be deepened over time in order to stay operational.

Figure 14: Flood water gauge board on a road crossing the Ouse Washes near Welney, Cambridgeshire. (Photo – S. Page).

Internal Drainage Boards have the power to raise funds locally for water level management through Agricultural Drainage Rates paid by agricultural land occupiers, special levies paid by local authorities on behalf of non-agricultural land occupiers, and a contribution from the Environment Agency. IDBs can also seek funding for capital works through Flood Defence Grant-in-Aid from Treasury and voluntary funds.

During 2015-16, IDBs in England invested £61 million in water level management work, including £19.8 million for maintenance of watercourses, £8.5 million for pumping stations, sluices and water level control structures, £8.8 million for new and improvement works, £7.7 million for contributions to the Environment Agency, including main river maintenance, and £0.9 million for environmental works and activities (ADA 2017). In the Fens area alone, there are 286 pumping stations (NFU 2008) which pump water up into the rivers and out into the Wash. The energy requirement for pumping has, presumably, risen over time as the land surface has subsided (see Mulholland et al. (2020) for further information on the energy use associated with pumping).

Where watercourses pass over and through peat substrates, IDBs may need to implement more frequent dredging every 5 or more years to maintain water flow and drainage. It is assumed that this is required both to remove material that has slumped into the watercourse from banks and because, over time, peat subsidence lowers the adjacent land surface, increasing the need for improved drainage. The additional cost of maintaining watercourses through peatland areas is not known. In addition to dredging, the IDBs also undertake regular, at least annual, weed cutting. The intensity of vegetation management, which is required to provide efficient water conveyance, means that there is limited capacity for accommodating environmental features (e.g. stands of aquatic or emergent vegetation).

The Environment Agency have responsibility for managing the risk of flooding from 'main rivers' (larger rivers and streams) and the sea (see Section 4.1). Over the financial period 2017-18 to 2018-2019, they report an increase in funding for the costs of culvert and waterway maintenance from £14.7 m to £25.9 m (Environment Agency 2019). The cost of maintenance of waterways by IDBs is given as £660 per km of waterway (Environment Agency 2015), with the most significant costs listed as de-weeding and dredging. It is unclear how much of these costs can be attributed to subsidence-related channel infilling, e.g. through bank slumping.

In eastern England, the Environment Agency is not only responsible for maintaining 96 miles of river embankments but also 60 miles of sea defences (NFU 2008). With a rising sea level and increased risk of more intense and more frequent storm surge events, there is a need for a continued programme of investment in these structures in order to continue to provide protection of the low-lying hinterland.

As an example of the costs involved in installing and maintaining land drainage, a study of cultivated fen peatlands in Switzerland calculated that the investment costs for the agricultural drainage system were approximately 12,000 euros per hectare, with an additional 5000 euros per hectare for a complete system that included the pumping station; these total costs were amortised over periods of 30 to 50 years (Ferré et al. 2019).

5.4 *Loss of High Value Agricultural Soils*

A consequence of the long history of drainage and cultivation of lowland peat soils is that peat thickness is reducing at rates of between 1.4 to 1.6 cm yr^{-1} (Table 1). In extensive areas of the Fens, former deep peat soils have become completely, or almost completely, depleted of their organic material and are now influenced by the underlying mineral substrates. These wasted peats are estimated to occupy an area of 1930 km^2 across England, comprising two thirds of all the original fen peat in England. And whilst the largest extent is in the Fens, wasted peats also occur on the fringes of other large peatland areas such as the Somerset Levels (Natural England 2010; Figure 15). In the latter half of the 19^{th} century, the British geologist Sydney Skertchly undertook a study of Fenland geology as part of a memoir for the Geological Survey of England and Wales (Skertchly 1877). Over 200 years after the drainage of the Fens had begun, he mapped the remaining peat area, accompanied by geological cross-sections and thickness data points (although, unfortunately, most of the cross-sections 'miss' the peat areas and so are of limited value in reconstructing the scale of peat wastage at specific locations). His work was presumably undertaken, at least in part, in response to the rapid rate of peat wastage that was being observed around that time (e.g. at Holme Fen; Figure 2). Using this study and more recent soil survey data combined with information on peat subsidence rate and bulk density, Eihenbaums (2011) estimated that there had been a loss of 2.12 billion m^3 of peat from the Fens, compared with the likely original maximum peat aerial extent and thickness.

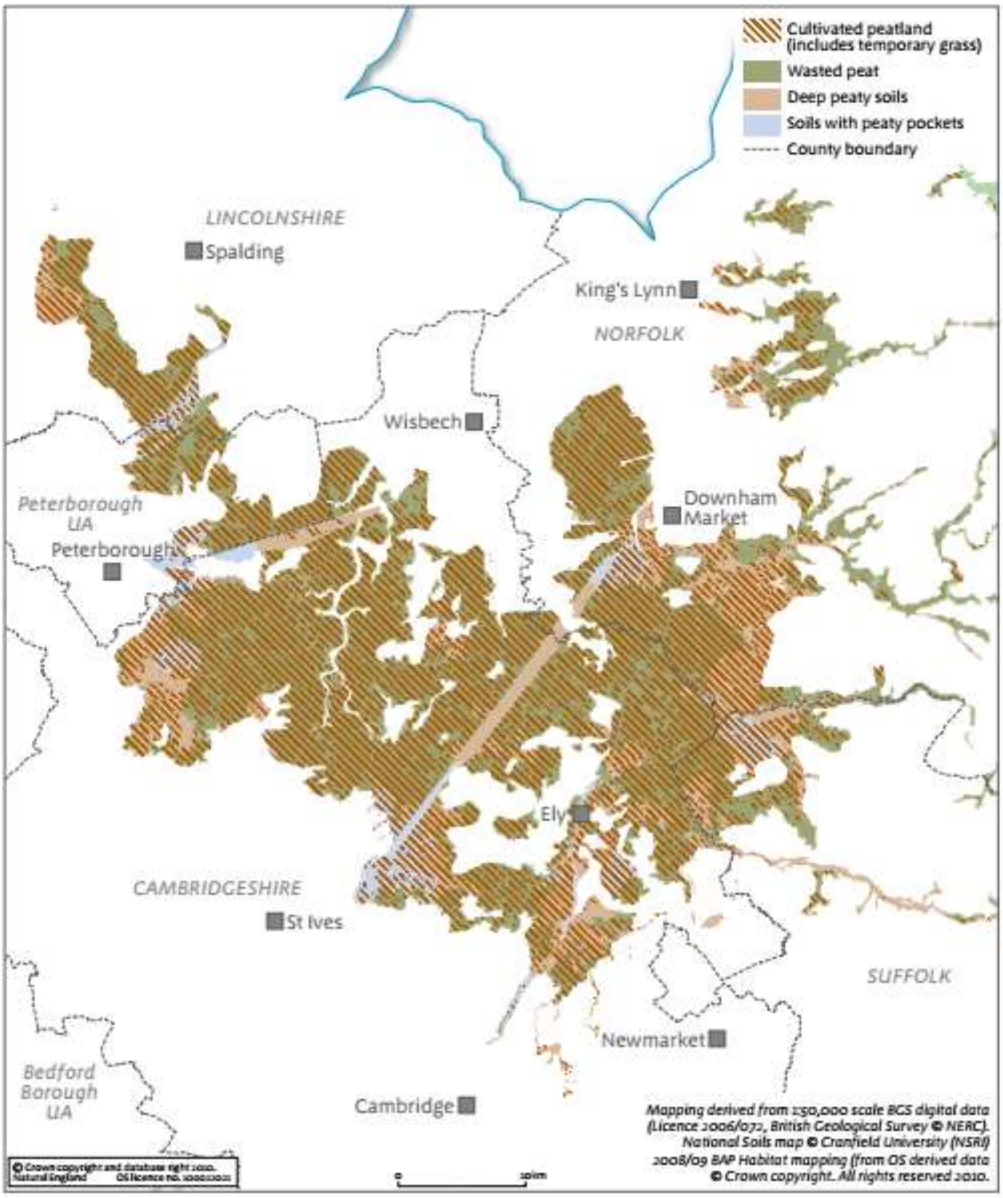


Figure 15: Most of the peat soils in the Fens are under agriculture, but deep peat soils now occupy a small area compared with the extensive area of wasted peat
(Source – Natural England, 2010; data derived from various sources, see above).

Depleted or wasted peats in the Fens are often referred to as skirt or skirtland. They have a lower agricultural value than the deep peat soils and are less suitable for the cultivation of high value vegetable crops (Rob Parker, G's Fresh, pers. comm.). Farmers need to adjust their cropping to take account of the changed soil conditions (i.e. lower fertility and greater tendency for waterlogging), and usually switch from high value vegetable or salad crops to lower value cereal or oil crop rotations. The economic consequences of peat wastage are dealt with in more detail in Jones et al. (2020) but in summary, farmers on deep peat soils have a vested interest in prolonging the life of those soils through soil conservation measures given the reduction in financial returns once peat depth is depleted. The loss of peat soils will also impact on the farming of vegetables that have a specific regional identity, notably Fenland celery which is only grown on deep peat soils and has Protected Geographical Indication (PGI) status from the European Commission.

5.5 *Loss of Archaeological, Historical and Geological Features*

Lowland peatlands contain a wealth of archaeological interest but drainage, and the accompanying loss of peat, risk exposing buried artefacts to aerobic decay and their gradual degradation and loss. Examples of peatland archaeology include the Sweet Track in the Somerset Levels, said to be the world's oldest surviving trackway, and a number of human remains (so called bog bodies), including Lindow Man, which dates from the Iron Age or early Romano-British period and was discovered in Lindow Moss, Cheshire.

In 2000, English Heritage commissioned a desk-based study on monuments at risk in England's wetlands (Van de Noort et al. 2002). This addressed the effect of hydrological changes on the waterlogged organic archaeological and palaeo-environmental remains in wetlands, alongside the impacts of peat extraction, forestry and urban and industrial expansion onto wetlands on this resource. England's wetlands contain some of the best archaeological sites in England, including those of the Somerset Levels and Moors, the East Anglian Fens, the Shropshire mosses, and the Humber peatlands. According to the authors, the greatest threat to the wetland archaeological resource arose from the drainage of the land for agriculture and the subsequent drying out of the archaeological remains, along with peat wastage. As a result of both drainage and other land uses (including peat extraction), van Noort et al. (2002) estimated that a considerable number of monuments, perhaps as many as 10,000 (74% of the total resource), had been destroyed completely in the last 50 years.

In a subsequent report commissioned by the UK IUCN Peatland Commission, Gearey et al. (2010) noted a 'lack of understanding of the impact of management practices on peatland as a historic environment'. Their review considered the main threats to peatlands as historic landscapes; these included de-watering as a result of peatland drainage or water abstraction, and agricultural reclamation. The review highlighted the plight of several important peatland archaeological sites, including Star Carr in North Yorkshire. This Mesolithic site provides unique evidence of human-landscape interactions since the end of the last glacial, but it has experienced significant deterioration and loss of artefacts as a result of drainage, hastened by the construction of a series of field drains in 2000. As a result, archaeological remains now lie above the waterlogged peat layer and are undergoing significant deterioration (High et al. 2016). In addition to the loss of waterlogging, the oxidation of underlying sulphur-rich mineral substrates has reduced the sediment pH (to as low as pH 2). The high concentrations of sulphur along with acidification are a further cause of negative geochemical changes, e.g. promoting demineralization of bone and depletion of cellulose in wood (High et al. 2016). Sites in the Fens, such as Flag Fen, and in the Somerset Levels have experienced similar problems as a result of peat loss and desiccation. This led Brunning et al. (2000) to state that one of the only archaeological sites in the Levels that still appeared to be secure was the Sweet Track which was protected by pumping to maintain high water levels on the Shapwick Heath National Nature Reserve (NNR).

In a later study, Brunning (2012) focused on the Somerset peatlands and identified at least 53 important prehistoric archaeological monuments including trackways and lake villages dating back to the Neolithic and Iron Age. While most of these are being maintained *in situ* at waterlogged sites they face an increasing range of problems caused by low water tables and peat wastage, particularly during the drier summer months. As a result, all the waterlogged scheduled monuments in the Somerset Moors and Levels are now classified as being at high risk of destruction. Brunning (2012) suggests that mitigation measures will require a landscape-scale approach to protecting the peat soils in a suitable condition, e.g. a summer water table that is a maximum of 40 cm below the field surface maintained by ditch or sub-surface irrigation at 40 m spacing. This would not interfere with traditional pasture farming but would require capital funds to install the irrigation. Insufficient summer water to feed such a system could pose an additional constraint. In the Netherlands, for example, considerable groundwater table lowering between ditches has been observed during the summer months due to evapotranspiration. As a consequence, a much narrower ditch spacing of 4 to 8 m is required to maintain high water levels, although even this may not be sufficient to prevent some lowering during dry periods (G. Erkens, Deltares/University of Utrecht, pers. comm.).

It is important to note that the archive within peatlands not only includes archaeological and historic remains but also a record of the palaeoenvironment in the form of plant and animal remains, such as pollen grains and testate amoebae. These can provide information about the environment around archaeological sites as well as contributing to an understanding of peatland, vegetation and wider landscape development processes and change, and of human cultural history. Some of the earliest, detailed knowledge of the post-glacial vegetation history of the British Isles was obtained from pollen analysis of peat samples collected at Wicken Fen (Godwin 1940).

Peatland archaeology sites and projects provide opportunities for public engagement both through tourism opportunities, for example at Flag Fen near Peterborough (Figure 14), and hands-on community archaeology, such as the Must Farm project which is another peatland Bronze Age site located a short distance from Flag Fen (http://www.mustfarm.com). In a 2014 review, English Heritage concluded that 'participating in heritage can contribute to people's personal development, and there is emerging evidence of a positive relationship between heritage participation, wellbeing and health' (English Heritage 2014).

Figure 14: Remains of part of the wooden causeway that was preserved in peat at the Flag Fen archaeological site, Cambridgeshire. The wooden remains are kept moist by misting with water to prevent deterioration and decay (Photo – S. Page).

5.6 *Loss of Cultural Value and Sense of Place*

"You walk the roof of the world here.
Only the clouds are higher and they are not permanent.
Trees are too distant for the wind to reach
And mountains hide below the horizon.
The wind labours through reed
As though they were the final barrier.
Houses and farms cling like crustations
To the black hull of the earth.
Here, you must walk with yourself
Or share the spirits of forgotten ages".
(Edward Storey; www. literarynorfolk.co.uk/fens.htm)

Early written accounts of England's wetlands often portrayed them in negative terms – as dangerous, vast and desolate swamps – inhabited by people who were seen as equally wild and dangerous (Huisman 2017). Fear and dislike of these environments were sometimes mentioned by land owners as part of their motivation to drain and 'reclaim' the wilderness (Rotherham 2013). In the 16th century, the country between Lincoln and Cambridge was described as 'a vast morass' while even in the 19th century, Thorne Moors (part of the Humberhead peatlands) were described as "This tract ….. [which] presents to the eye a dreary expanse' (Rotherham 2013). Yet lowland peatlands, and particularly fen peatlands, were important for the local communities that lived in and beside them. They provided fish, eels, wildfowl, reeds and rushes (for thatching, flooring, candles), peat turves and brushwood for fuel and other uses, and summer pastures and hay for cattle. Some, such as the lowland fens of South Yorkshire, were also important hunting lands (Rotherham 2011). In the Fens of eastern England, there was a close interdependence between human communities and the natural resources provided by the landscape. In turn, the variety of fenland uses (grazing, cutting, turf digging) shaped the local ecology, creating a diversity of habitats. Following widescale drainage, most of these wetland landscapes were transformed and lost, along with much of the unique fenland cultural heritage, and by the 19th century, the loss of wetland began to evoke feelings of nostalgia rather than aversion (Huisman 2017).

Today, traditional livelihood activities including reed and sedge cutting, are only being continued at a few sites, mostly in the Broads, and often as part of conservation management (The Broads Authority 2019). Nevertheless, the contemporary scenery of the drained peat landscapes does provide some distinctive features that are valued by residents and visitors alike. The 'big skies' rising above the flat, wide landscapes (Figure 4) are regarded by many as uplifting and have provided inspiration for writers and artists over the centuries, including the Fenland writer and poet, Edward Storey, and the novelists Charles Kingsley and Graham Swift.

"Overhead the arch of heaven spread more ample than elsewhere, as over the open sea; and that vastness gave, and still gives, such cloudlands, such sunrises, such sunsets, as can be seen nowhere else within these isles." (Charles Kingsley; Hereward the Wake).

For today's Fenland communities, the unique drainage history along with the important farming and food production history provide a strong sense of tradition and place (Ouse Washes Landscape Partnership 2018).

"The Fens as a landscape is the product of its people just as the people themselves are shaped by the land." (Graham Swift).

The cultural characteristics of similar lowland peat landscapes in the Netherlands have been recognised by the Dutch Government. Five areas have been assigned National Landscape protection in order to protect core qualities such as their wide, open character, typical historic land reclamation patterns, and the characteristic grassland landscape with its high water table (de Mulder et al. 2019).

5.7 *Loss of Carbon Sink Capacity*

Peat actively forms when more organic matter is added in the form of plant litter than is lost via peat decay (Page & Baird 2016) and peat carbon storage will be ensured as long as the peat remains water saturated. Any disturbance that results in lowering of the peat water table allows oxygen to enter the peat column, disturbing the balance between peat accumulation and decay, and resulting in oxidative microbial degradation of the peat and release of stored carbon to the atmosphere. Present day peat accumulation and decay rates are controlled largely by climate but with an increasing role played by direct human activity. At a low level of intensity, human exploitation of a peatland resource may be considered sustainable, if the hydrological functioning of the peatland remains more or less natural and net carbon accumulation is maintained. But more intensive uses, and particularly those that require drainage, result in the loss of the peatland carbon storage function and, critically, the release of greenhouse gases to the atmosphere, with implications for global warming (Page & Baird 2016). The increased depth of the water table leads to more decay (aerobic decay may be 10-1000+ times the rate of anaerobic decay) while much less plant litter is added to the peat because of crop off-take. The effect is that the peatland switches from a sink (a net accumulator of carbon) to a net source. In the Fens of eastern England, Eihenbaums (2011) estimated that the loss of peat resulting from several centuries of drainage, and presumably also peat extraction, had resulted in a total carbon loss of some 317 Mt. For the more extensive lowland peatlands in the Netherlands, the carbon loss due to drainage and extraction is estimated to be 830 Mt (Erkens et al. 2016).

Total current greenhouse gas emissions from English peatlands are estimated to be around 11 Mt CO_2e yr^{-1}, which is 3% of total English greenhouse gas emissions (Evans et al. 2017a). By comparison, Van den Bos (2003) estimates that annual emissions from drained peatlands in the Netherlands are somewhat smaller, in the range 4.6-6.5 Mt CO_2 yr^{-1}, but their contribution to the country's total greenhouse gas emissions is similar at 2.0-2.9%. In England, the largest sources of emissions are lowland peatlands drained for agriculture (> 80% of total emissions; Evans et al. 2017a, b). In these peatlands, water table depth has been identified as playing an over-riding role in emissions. Evans et al. (2017a) found that a 10 cm increase in mean water table depth was responsible for an increase in greenhouse gas emissions of over 3 t CO_2 ha^{-1} yr^{-1}. While conservation-managed fen had a mean water-table that fluctuated around the surface by +/- 20 cm and a net uptake of 2.8 t C ha^{-1} yr^{-1} (i.e. it functioned as a carbon sink), intensive agriculture on fen peat soils had a mean water table depth of 90 cm and a net loss of 7.7 t C ha^{-1} yr^{-1} (i.e. it functioned as a carbon source). Evans et al. (in prep.) estimate that halving average drainage depths across the 370,000 ha of peat under cropland and intensive grassland in the UK (most of which is in England) could reduce their emissions by around 70%. In addition, ONS (2019) report that the carbon benefits of restoring all UK peatlands are estimated to outweigh the cost by five to ten times. For example, the estimated cost of restoring all lowland peatland under horticultural and arable crops would be £2861 million, but the present value of carbon benefits is £35,628 million (ONS 2019). Taking all lowland peatlands out of agricultural production would, however, significantly impact on UK food production (Section 5.1).

5.8 *Loss of Biodiversity Support Functions*

Lowland raised bogs and fens support an array of specialised flora and fauna and are a priority for nature conservation. But over the last century, these habitats have undergone a dramatic decline and are now amongst the rarest and most threatened in the UK. Prior to large scale drainage and reclamation, peatlands stretched almost continuously along the east coast from East Anglia to North Yorkshire, encompassing the fenlands of Cambridgeshire and Lincolnshire, the lower Trent Valley, and north to the fens and raised bogs of the Humberhead Levels. These wetlands must have supported a very diverse array of wildlife, which was also a valued resource for local communities (Rotherham 2013; Purseglove 2016). In the Fens, less than 1% of the original fen habitat has survived as tiny remnants in an otherwise drained and intensively managed landscape. Extensive areas of lowland peatland habitat in other regions have been similarly affected by habitat loss and degradation. Ninety-eight percent of the raised bog 'mosslands' of Lancashire, Greater Manchester and North Merseyside have been lost as a result of drainage, agricultural conversion and peat extraction.

Both lowland fens and raised bogs are included as priority habitats in the UK Biodiversity Action Plan and are also listed under Annex I of the EU Habitats and Species Directive. A large proportion of remaining sites are protected as SSSIs: in England, this includes 85% of the remaining lowland raised bog (8,270 ha of a total area of 9,690 ha) and 59% of lowland fen, marsh and swamp (13,281 ha of a total area of 22,323 ha); in Wales, 94% of lowland raised bog has SSSI status (1,683 ha of a total area of 1,800 ha) and 30% of lowland fen, marsh, swamp, flush and spring (1,960 ha of a total area of 6,600 ha) (JNCC n.d.).

The main threat to remaining lowland peatland habitats, both in terms of habitat loss and degradation, are water management, including drainage, excessive water abstraction from underlying aquifers resulting in lower phreatic groundwater levels, and pollution from agricultural run-off. Many lowland raised bogs have also been damaged by peat extraction, although this has now ceased at most sites.

In the Fens, drainage and the lowering of the land surface in the surrounding agricultural landscape have left areas set aside for nature conservation, such as the National Nature Reserves (NNRs) at Wicken Fen and Woodwalton Fen, as isolated 'wet' islands perched several metres above the level of the surrounding drained fields and above the level of the regional water-table. In order to keep these wetlands wet, it has been necessary to bring or pump water onto them and to waterproof their boundary banks in order to retain the water within the reserve (Lock et al. 1997). During dry summers, fen remnants in the Netherlands can no longer maintain their high (i.e. shallow) groundwater tables because of their elevated position in the landscape. As a result, groundwater levels within the remnants are too low, resulting in subsidence and GHG emissions. A further issue is that water brought on site is often of a low quality (i.e. is nutrient-enriched) which may damage oligotrophic habitats and species (G. Erkens, Deltares/University of Utrecht, pers. comm.). As a result, these essentially short-term solutions for small, isolated sites cannot provide long-term sustainability of biodiversity. In recognition of this, the National Trust, who manage Wicken Fen NNR in Cambridgeshire, have a 100-year strategy (the Wicken Fen Vision) to extend the area of the reserve to 5,300 ha from its current size of 758 ha (which is already an extension of the original NNR) by purchasing additional, adjacent land holdings. The Vision area lies within a single IDB and the intention is to raise water levels through reduced pumping and the use of sluices to allow wetland habitats to regenerate (www.wicken.org.uk). Some miles north of Wicken Fen, the Great Fen project (Figure 15) has a similar ambition. This 50-year project aims to create 3,700 ha of wetlands that will join the two fen NNRs at Woodwalton Fen and Holme Fen which are otherwise too small and isolated in their own right to effectively support their populations of fen species. On a smaller scale, there are nature conservation and wetland restoration projects underway at other fenland sites, e.g. the Hilgay Wetland Creation Project in Norfolk and the Willow Tree Fen restoration project in Lincolnshire (www.fensforthefuture.org.uk).

Figure 15: A viewing hide located next to restoring reed beds; part of the Great Fen project, Cambridgeshire (Photo - S. Page).

5.9 *Saline Intrusion*

A major concern in the Netherlands is that peat oxidation, which causes not only a reduction in peat thickness but also in mass, is resulting in the peat layer having a lower weight, thus the downward force (load) on the land surface is reduced. At some point, this downward force becomes smaller than the upward force of the groundwater. In this case, a saltwater-seepage (a 'salt boil') may form on the land surface which can carry brackish salt water up to the surface and contribute to salinization of surface water, mixing with shallow fresh groundwater, and damaging crops, natural vegetation and aquatic systems (De Louw 2010; G. Erkens, Deltares/ University of Utrecht, pers. comm.). This is a particular issue for low-lying coastal areas in the Netherlands where about 25% of the country is located below mean sea level.

Salt boils have not been observed in the UK, but there is evidence that sea level rise and a heightened risk of storm surges could lead to an increased risk of saline inundation of freshwater wetlands close to the coast. These include 3.5% of SSSIs, including both fens and lowland raised bogs located in coastal floodplains. East Anglia is particularly vulnerable to the impacts of storm surge events and evidence of saline intrusion has been recorded in some of the Broadland fens. An increase in salinity has a negative impact on the productivity of reed grass, *Phragmites australis*, and saline influenced sites have also been shown to have lower carbon accumulation potentials, which could indicate that on-going peat accretion in the Broads would not offset projected sea-level rise, thereby increasing the future risk of inundation and saline intrusion (Webster 2016).

6. Mitigation Measures

When considering mitigation of the risks posed by current water management regimes in lowland peatlands it is perhaps informative to follow a similar approach to that employed in the management of flood risk. Namely, consideration of appropriate actions to reduce hazard, reduce exposure, and reduce vulnerability.

Measures to Reduce Hazard – examples of mitigation actions in this category are primarily focused on water management, i.e. raising the peatland water table:

- Raising water levels in agricultural land would reduce the loss (wasting) of valuable agricultural soils as well as reducing greenhouse gas emissions;
- There would be additional benefits in terms of reduced maintenance costs and improved safety for road and rail transport links crossing peatlands, and for other infrastructure (power transmission lines, gas pipelines etc);
- Raising water levels would protect peatland archaeological monuments and their associated heritage and tourism values (Brunning 2012);
- Raising water levels would provide improved hydrological security for existing and planned wetland sites managed for nature conservation and restoration, e.g. the National Nature Reserves in the Fens.

Measures to Reduce Exposure – mitigation actions in this category include:

- Diverting traffic away from roads without strong foundations (PBL 2016);
- Strengthening stretches of railway line passing over peatland by constructing additional secondary foundations – both to reduce track deformation and ground vibration dynamics;
- Limiting further infrastructure development on lowland peat soils, or at least considering which locations are most suitable for development;
- Considering strategic opportunities to raise water tables, e.g. in corridors adjacent to major infrastructure (road and rail transport links), in order to target reductions in road and track deformation;
- Implementing on-farm soil conservation measures to reduce soil wind erosion, e.g. cover crops, hedge and tree rows, and subsidence.

Measures to Reduce Vulnerability – mitigation actions in this category include:

- Designing future roads, buildings and other infrastructure to take account of the low load bearing capacity and subsidence of peat substrates, and the increased risk of fluvial and coastal flooding under future climate change scenarios;
- Laying cables and pipelines on geotextiles to reduce movement and damage caused by peat subsidence (PBL 2016).

The magnitude of the risks posed by ongoing peatland drainage will be determined by

i) the characteristics of a particular location (e.g. its elevation, proximity to a river or coast);

ii) the vulnerability of assets and people (taking into account population density now and into the future, presence of high value agricultural land, infrastructure, transport and communication routes, both now and into the future. Vulnerability could change as a result of changes in spatial planning and also climate change);

iii) the consequences that result from on-going subsidence (e.g. the loss of high value agricultural soils and associated social and economic dependencies, the increased risks of flooding and costs of flood protection, both now and into the future);

iv) the mitigation and adaptation measures that are already in place (e.g. riverine and coastal flood embankments, on-farm measures for managing field water levels and reducing aeolian losses) and their level of effectiveness, both now and into the future under climate change scenarios.

Implementing appropriate mitigation measures will reduce the risks associated with peatland drainage; nonetheless it will not be possible to offset or eliminate them all. Mitigation measures will need to be judged according to their specific costs and benefits (social, economic, environmental) and over appropriate timescales. For example, the rate of peat subsidence could be reduced or even stopped by raising water levels. Implementing measures to achieve this would provide benefits in terms of reduced costs for water management, reduced damage to infrastructure and reduced greenhouse gas emissions, but would challenge various agriculture-related functions and interests.

Climate change is a further issue that will require particular consideration in relation to any assessment of the costs and benefits derived from peatland drainage. Climate change projections indicate that, in the future, the UK is likely to experience hotter, drier summers and wetter, warmer winters (UK Climate Change Risk Assessment 2017). For peat soils these conditions will promote and possibly enhance current rates of subsidence; they could also increase the risk of aeolian peat loss. Drier summers could also exacerbate the types of damage to the road infrastructure reported during the 2011 drought. In addition, whilst UK sea level rise projections for the 21st century are uncertain, they generally range from around 0.25 to 1 m, with a few high-end estimates in the range 1.5 to 2.5 m, depending on greenhouse gas emissions scenarios (Edwards 2017). As a result of drainage, many lowland peatlands in England are now at or below current sea level. For example, much of the peat landscape of the Fens is around 2 m below sea level, and even the adjacent silt-dominated land nearer to the Wash is only around 0.3 m above sea level (Waller 1994). Given this, it is possible that in future decades lowland peatlands such as the Fens, the Somerset Levels and wetlands in the Norfolk Broads will be at increasing risk of coastal flooding and saline intrusion and incursion, both as a result of sea level rise and the increased risk and height of storm surges. This level of increased risk could incur additional costs for the IDBs, the Environment Agency and local authorities with responsibility for flood risk management.

In view of the paucity of data on the direct financial and less tangible costs and benefits associated with peatland drainage, it would be difficult to model the returns delivered from implementing most of the proposed mitigation measures. Some would clearly be challenging to implement without economic or other incentives. For example, raising water tables in peatlands under intensive arable and horticultural production would be problematic given their present-day economic importance. Any such measures would need to consider the implications for food security, along with the interests and livelihoods of those working the land (Morris et al. 2010). In the Netherlands, most agricultural peatlands are under either extensive or intensive livestock production, so there are no ready comparisons with lowland peatlands, such as the Fens, under arable or horticultural land uses. Nevertheless, information on the costs and benefits of high water table management on Dutch peatlands could provide useful contextual data for the assessment of options for locations such as the Somerset Levels, where the main land use is cattle grazing.

7. Sources of Uncertainty, Knowledge Gaps and Priorities for Future Assessment

This scoping study has provided a broad assessment of the principal environmental, economic and social impacts arising from the drainage of lowland peatlands in England and Wales. We have attempted to provide a comprehensive account, but there remain some key uncertainties and knowledge gaps which could lead to underestimation of the total scale of the impacts. Nevertheless, we are confident in presenting an initial conclusion that the costs associated with drainage are largely 'hidden' and/or are not directly connected to drained peatlands and their management.

The key uncertainties relate to the financial costs associated with the impacts of peatland water management on infrastructure, both in terms of the increased costs of maintenance and higher initial costs associated with construction on soft and subsiding substrates, and on society, in terms of the costs of providing and maintaining land drainage and flood defences. While the infrastructure impacts arising from peatland drainage have been recognised in some previous studies, most of the emphasis has been on identifying and addressing the symptoms of subsidence (e.g. engineering solutions such as lightweight fill beneath embanked roads; Pritchard et al. 2013a) and little consideration has been given to addressing the causes. In addition, there has been no comprehensive assessment of the costs to society of maintaining land drainage and flood management in and adjacent to lowland peatlands, nor have the costs of on-going subsidence been accounted for, e.g. in terms of damage to river embankments.

In the process of writing this report, we contacted a number of organisations including utilities companies and public bodies, but with limited success in obtaining the requested information on direct and indirect costs. More research on the economic costs associated with peatland subsidence has been undertaken in some other countries, notably the Netherlands where a recent study has changed the way policy makers are thinking about subsidence (PBL, 2016). In a second recent study, again from the Netherlands, the cost-savings associated with mitigation measures were estimated, e.g. by building roads in such a way that subsidence is partly mitigated (by using lighter building materials etc.) and repair costs can be reduced (van Woerden 2018). Detailed studies such as these would help to provide a much clearer understanding of the costs and benefits associated with peatland drainage and would provide the basis for determining future policy options in relation to agriculture, water management, biodiversity, cultural heritage, climate and other factors.

We recommend that this scoping study should be followed by a more detailed assessment. This would allow, firstly, an improved understanding of the effect of alternative water and land management measures on subsidence and greenhouse gas emissions; secondly, an insight into the key financial values, enabling an accurate cost benefit analysis; and thirdly, an understanding of what will happen, for example in terms of damage to infrastructure or loss of high value agricultural soils, if nothing is done, thereby providing the basis for a business as usual scenario against which to compare various policy options. More detailed analysis would also allow regional case studies to be developed (e.g. for the Fens, the Somerset Levels, the Lancashire Mosses and so on), given that there will be geographical variations in peatland type (fen, raised bog), level of flood risk, current and potential future land uses, costs and benefits, and desired economic, social and environmental outcomes. The Annex to this report provides a list of data sources and stakeholders from the private sector, and regional, national and local government sectors that we believe should be approached to provide the necessary financial and other information to take this scoping study forward. We also recommend that once this evidence base has been developed that it will need on-going and regular assessment, particularly in the light of the UK's changing climate.

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ANNEX

Potential sources of information on the direct and indirect costs relating to infrastructure in drained lowland peatlands. The preceding review indicates that costs are likely to be greatest for categories 1 to 4.

Infrastructure type	Information	Potential source
1. Roads	Cost of repairs to subsidence damage on roads (pot holes, embankment instability etc) Number of accidents relating to subsidence (e.g. because of an uneven road surface) Number of accidents relating to land drainage (e.g. where ditches run alongside the road without protection of a crash barrier) Costs of installing additional safety measures Additional costs of road construction on peat substrates (e.g. use of lightweight fills, deeper foundations etc). Costs of road closures due to subsidence (e.g. in terms of additional journey times etc)	Department for Transport Highways England Traffic Wales Local government authorities (highways)
	Costs of repairs to farm access roads	Farmers and landowners, e.g. in the Fens, Somerset Levels
2. Railways	Costs of repairs to rail tracks crossing peatland Increased costs of building new rail tracks on peat substrates, including measures to minimise ground vibration boom Delays and increased journey times due to reduced train speeds, e.g. for travel over deformed track	Network Rail
3. Land Drainage & Flood Control Structures	Costs of maintaining peatland drains and other waterways (dredging slumped material, deepening to account for on-going subsidence) Costs of pumped drainage and maintenance of pumping stations, sluices and other water management structures Costs of maintaining river flood defence structures on peat soils, e.g. river and	Internal Drainage Boards The Environment Agency Local government authorities (flood management)

	washland embankments; additional costs of maintaining embankments on peat as opposed to mineral soils.	
4. Utilities	Costs of maintaining power (electricity, gas) and telecoms transmission across peat soils (e.g. additional maintenance costs associated with subsidence) Costs of using geotextiles under pipelines passing through peat soils	BT Open Reach Cadent Gas Northern Gas Networks Wales and West Utilities SGN UK Power Networks Northern Power Grid Electricity North West SP Energy Networks Western Power Distribution Scottish and Southern Electricity Networks
5. Buildings	Extent and costs of repairs to homes and businesses due to peat subsidence Costs of additional structural or other modifications required for properties built on peat substrates	Individual home owners House insurance companies Companies providing advice and remediation for subsidence damage Local government authorities (planning departments)
6. Other infrastructure	Costs of maintaining culverts owing to corrosion or clogging by sulphate-reducing bacteria	Local government authorities Farmers and local landowners
7. Conservation of Nature and Cultural Heritage	Costs of maintaining suitable hydrology on peatland nature reserves (pumping to maintain a high water table; use of barrier membranes along reserve boundaries) Costs of pumping to maintain a high water table and other measures to protect archaeological and historic features	County Wildlife Trusts Local government authorities English Heritage Cadw