The Future of UK Vegetable Production – Technical Report

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THE FUTURE OF UK VEGETABLE PRODUCTION

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Working together

1. Introduction to UK vegetable production, imports, and challenges

Horticultural crops are grown extensively across the UK. The diverse soils and temperate climate allow for a wide range of crops to be grown, and over 300 types of field-scale and protected vegetable and salad crops together with fruits and ornamentals are produced in the UK (AHDB 2013). The UK's horticultural sector is made up of a diverse range of businesses, ranging from smallholders growing commercial crops selling through farmers' markets and box schemes, to internationally integrated businesses selling to supermarkets. Organic production systems make up 8-10% of the total production area. Defra Horticulture Statistics (2021a) showed that UK vegetable growing produced around 200-250,000 tonnes of vegetables each year over the period 2010-2020, with a planted area of 110-120 thousand hectares, equating to 55-60 % of the total market supply.

Field vegetables make up approximately 90% of total vegetable production in the UK. Tomatoes are the main vegetable grown in protected cropping systems; the UK is approximately 15% self-sufficient in tomato production. Carrots are by far the most important field vegetable crop, with onions and brassicas also grown widely. A wide range of cabbages are grown together with cauliflower, broccoli (calabrese), brussels sprouts and kale. In the UK, brassicas are mostly grown on water-retentive silt soils, whereas sandy soils are preferred for carrots and onions. The UK is self-sufficient for carrots, and usually for cabbage. The UK is more reliant on other countries or regions for specific foodstuffs at different times of the year, due to a variety of growing seasons across the world. Vegetable imports are mainly from Spain (33%) and the Netherlands (25%) which are mostly of tomatoes, onions, lettuces, cucumbers, and sweet peppers, although imports from North Africa have increased substantially post-Brexit. Seasonality is complex and product specific. The UK depends on diverse supply lines to meet demand for out-of-season products throughout the year, following growing seasons across the world. Year-round access to out-of-season fresh fruit and vegetables has increased in the last 20 to 30 years, together with a more diverse range of vegetables consumed, leading to longer and more complex supply chains for the vegetables found on supermarket shelves.

There is a global problem of insufficient consumption and access to fresh fruits and vegetables, which is one of the leading causes of reduced life expectancy and preventable health cost burdens. In the UK in 2018 only 28% of adults were eating the recommended five portions of fruit and vegetables a day (NHS 2019). However, the commercial horticultural sector currently faces many environmental, economic, and social challenges that have the potential to threaten its sustainability and associated food security, particularly in the UK.

A major challenge is the availability of seasonal labour for crop harvests. Following the UK's exit from the EU, labour shortages are now common in many of the large horticultural businesses that have previously relied on seasonal labour from European Union workers. The House of Commons Environment, Food and Rural Affairs Committee report (2020) said that European Union (EU) workers had accounted for "as much as 99%" of seasonal labour recruited by the edible horticulture sector in 2020". A significant proportion of vegetable crops receive irrigation to maintain market demands for quality, consistency, and continuity of supply. Therefore, water availability is also a growing challenge, especially given predictions of increased temperatures with a reduced proportion of annual rainfall falling during the growing season. Although water demand for irrigation is small in volumetric terms (1-2% of water abstraction in the UK), the majority of catchments in which horticultural production is found have been defined by the Environment Agency as being either over-licenced and/or over-abstracted (J. W. Knox et al. 2020a). As water resources become more limited due to climate change, there is an increase in on-farm reservoir storage of water to allow irrigation requirements to be met from winter abstraction. However, there is an ongoing need to increase water use efficiency in the horticultural sector.

The principal environmental impacts associated with agriculture have been identified as the loss of biodiversity due to habit loss, non-target impacts of pesticides, nitrogen leaching and other nutrient losses, soil erosion, and greenhouse gas (GHG) emissions. Agricultural intensification has been linked to the decline in farmland birds, plant, and invertebrate taxa (Krebs et al. 1999; Wilson et al. 1999). Lillywhite et al. (2007) quantified the environmental footprint of the UK's main horticultural crops (carrot, cauliflower, onion, potato, protected salad leaves) and compared these with fruit and other agricultural products, in terms of land use, pesticides, GHG emissions, eutrophication, water and labour demands. Protected cropping systems (lettuce, strawberry) had much higher environmental footprints largely due to the environmental impacts of the infrastructure required.

Field vegetable crops all had similar overall estimated impacts with higher pesticide use, eutrophication potential, water use and labour demand than cereal crops. Environmental impacts were strongly related to fertiliser use, for example in relation to eutrophication risk and GHG emissions (both as a result of the energy used to manufacture it and emissions of nitrous oxide (N_2O) after field application). The study assumed that all crops were established with plough-based tillage systems and does not consider cultivation on peat. Overall, the study showed that horticultural production was generally more intensive than comparable arable systems; this distinction has increased further over the last decade as reductions in tillage intensity have been occurring rapidly for combinable crops (i.e., crops that are commonly harvested using a combine harvester). Stockdale et al. (2019) characterised and compared the impacts of UK agricultural systems on soil biology (Table 1-1). In this study comparisons were made between field vegetable cropping systems and rotations with only combinable crops, where the results showed poorer soil habitat quality, lower soil organism populations and activity in field vegetable cropping systems because of the increased tillage intensity and requirements to use imported organic materials (Food Standards Agency 2009).

One third of England's fresh vegetables come from the Fens (NFU East Anglia 2019), a low-lying region in Eastern England (ca 4% of England's farmed area, 400,000 ha) where both silt and peat soils are used for field vegetable rotations. Other lowland peat soils e.g., in the Humberhead Levels and Lancashire Mosses are also major centres for field vegetable production. Evans et al. (2017) have estimated that drained and cultivated peat soils are the UK's largest land-use related CO_2 emissions source, and recent work for the UK Inventory suggests that these soils are emitting over 10 Mt CO_2e yr^{-1} (based on 2021 data; Brown et al., 2023). Particulate air pollution (PM2.5) also regularly exceeds the critical health limit of 20 $\mu g/m^3$ under dry conditions due to wind erosion of peat. Although highly productive and a major source of vegetables for the UK, current vegetable production systems on lowland drained peat are effectively extractive, in that they lead to sustained and ongoing loss of soil organic matter, and therefore must be considered unsustainable. This review therefore aims to describe and evaluate the impacts of land use options in lowland peat landscapes together with the scope for sustainable vegetable production, using regenerative farming practices, to deliver food security, climate change mitigation and reversal of biodiversity loss.

Table 1-1 Comparison of typical cropping systems in the UK lowlands in terms of the range of management practices and notes on the implications for soil habitats and soil populations of earthworms and decomposers (as an example) on a light/medium texture soil. From Stockdale et al. (2019). Note that natural (wet) peatlands do not support earthworms or other soil fauna adapted to dry conditions, so do not represent a simple metric of soil health in a peatland context.

	Cropping - field vegetables	**Cropping - combinable crops**
Typical management practices		
Crops	Onions, carrots, potatoes, brassicas, in rotation with cereals	Cereals (winter and spring sown), oilseed rape, beans Some use of cover crops
Tillage	Intensive and often repeated in-season	Rotational ploughing and non-inversion approaches Some direct-drill
Livestock	Rare	Rare
Residue management	Incorporation	Incorporation: cereal straw may be baled and sold
Soil habitats and populations		
Roots	Annual cropping; some fallow periods	Annual cropping; some active growth all year
Rhizosphere	Very simple rhizosphere development; some short duration and incomplete	Simple rhizosphere succession but including crop senescence. Main rhizosphere development phase in spring
Fresh OM inputs	Diverse crop residues OM inputs often restricted by customer protocol	Mainly senesced crop residues (straw/ haulm) Often limited OM inputs available
Earthworms	Few	Some, but mainly topsoil-dwelling. Deep-burrowing species increase as tillage intensity decreases
Decomposers	Low/moderate. Residues may persist for one season	Moderate. Residues sometimes persist for one season

2. Nature and distribution of agriculture on peaty soils, with a focus on veg production

UK peatlands are estimated to occupy approximately 3 million ha, or 12 % of the UK land area (Bain et al. 2011; C Evans et al. 2017). Cropland across the four home nations (England, Scotland, Wales, and Northern Ireland) occupies around 6% (188,000 ha) of these peat soils and, as of 2021, is estimated to emit 5.5 Mt CO2e per year which is a third of the total GHG emissions from UK peatland soils, and 3.9 Mkt CO2e per year from intensive grassland (20% of total, primarily located in lowland peat) (Brown et al. 2021). Cropland on peat is primarily located in lowland areas of England of which 72% of the cropland areas have soils that can be classified as ‘wasted’ (retaining a peat layer of < 40 cm). The remainder is on deeper peat (retaining a peat layer > 40 cm), which is generally classified as the highest grade (ALC Grade 1) agricultural land. While there are various definitions of shallow and deep (or thin and thick) peat, for the purposes of this report we refer to all peat > 40 cm as ‘deep’ to differentiate it from wasted peat.

Wasted peat soils (also referred to as ‘skirtland’ in the Fens) consist of shallow residual organic soils overlying the mineral substrate, where most of the original peat has been lost through a combination of decomposition, compaction, and erosion, to the extent that the remaining peat is less than 40 cm deep, and typically intermixed with mineral soils due to ploughing. With less carbon remaining in the soil, wasted peatlands are a smaller source of CO_2 emissions per unit area than croplands on deeper peat, but nevertheless make a substantial contribution to overall peatland greenhouse gas emissions. Wasted peat soils are of lower agricultural value, and less suitable for the cultivation of high value vegetable crops (Mulholland et al. 2020a).

2.1. Lowland peat areas in agriculture

In order to estimate the total lowland peat areas in agriculture across Great Britain multiple datasets were reviewed: the UKCEH land cover map 2015 (Rowland et al. 2017); the UKCEH Land Cover ® *plus*: Crops maps (referred as LC+ Crops from now on) from 2015 to 2021; the UK peat soils dataset developed by Evans et al., (2017); the NRW upland boundary; the England moorland line; and the Scottish land capability for agriculture (LCA) dataset (Scottish Government 2022). The methodology was as follows: in England and Wales land below the moorland line and upland boundary respectively was considered lowland, while in Scotland land within classes 1-4 of the LCA dataset was defined as lowland; land classified within the UKCEH crop map was overlain with the peat map dataset to provide areas of crops grown on peat soils, then the areas of cropland on peat were clipped to the regions determined to be lowland as described above (although note that little or no cropland on peat occurs outside the lowlands).

Finally, the five main regions for vegetable production on peat were manually delineated: the East Anglian fens, the Broads, the Humberhead Levels, Northwest England (including the Manchester mosslands), and the Somerset Levels (Figure 2-1). Note that using this method land cover information was not available for Northern Ireland so figures in section 2.1.7 are quoted from reporting by the Agri-Food and Biosciences Institute (AFBI). Data was also split by UK regional boundaries; results can be found in appendix 1.

The UKCEH LC+ Crops maps are jointly produced by UKCEH and Remote Sensing Applications Consultants Ltd. (RSAC) and are available on request from https://www.ceh.ac.uk/data/ceh-land-cover-plus-crops-2015. We used all seven years of data available (2015 – 2021). The LC+ Crops provides crop information for all agricultural land parcels larger than 2 ha across GB. The maps are derived from Sentinel 1 Synthetic Aperture Radar (SAR) and Sentinel 2 optical data (Upcott et al. 2022). Fields are classified into one of 15 crop categories, which have been grouped into vegetables, cereals, and grasslands for the purposes of this analysis – See Table 2-1 for the grouping used.

This categorisation needs some caveats. Firstly, the LC+ Crops category ‘Beet’ includes sugar beet and field beet crops as well as beet for direct vegetable consumption. Similarly, maize is primarily grown for agricultural feed and / or biomass for bioenergy or biofuel production (via anaerobic digestion), but some of this maize is likely to be eaten as a vegetable crop (sweetcorn) or as a cereal (cornmeal and flour). Also, any undercropping of solar panels that may occur has been excluded as it has been assumed that these will primarily be on grassland due to the difficulties in commercial harvesting of crops on such sites. We have also interpreted the category “other” to include primarily vegetables in the study areas. Areas of lowland peat that did not fall into any of the crop categories are largely under some form of conservation management, for example reed beds, fen woodlands or wet non-agricultural grasslands.

Table 2-1 LC+ Crops categories used in this analysis.

Broad category	LC+ Crops included
Vegetables	**be** Beet **fb** Field beans **pe** Peas **po** Potatoes **ot** Other
Cereals	**Ma** Maize **or** Oilseed rape **sb** Spring barley **so** Spring oats **sw** Spring wheat **wb** Winter barley **wo** Winter oats **ww** Winter wheat
Grasslands	**gr** Grass **sl** Solar panels

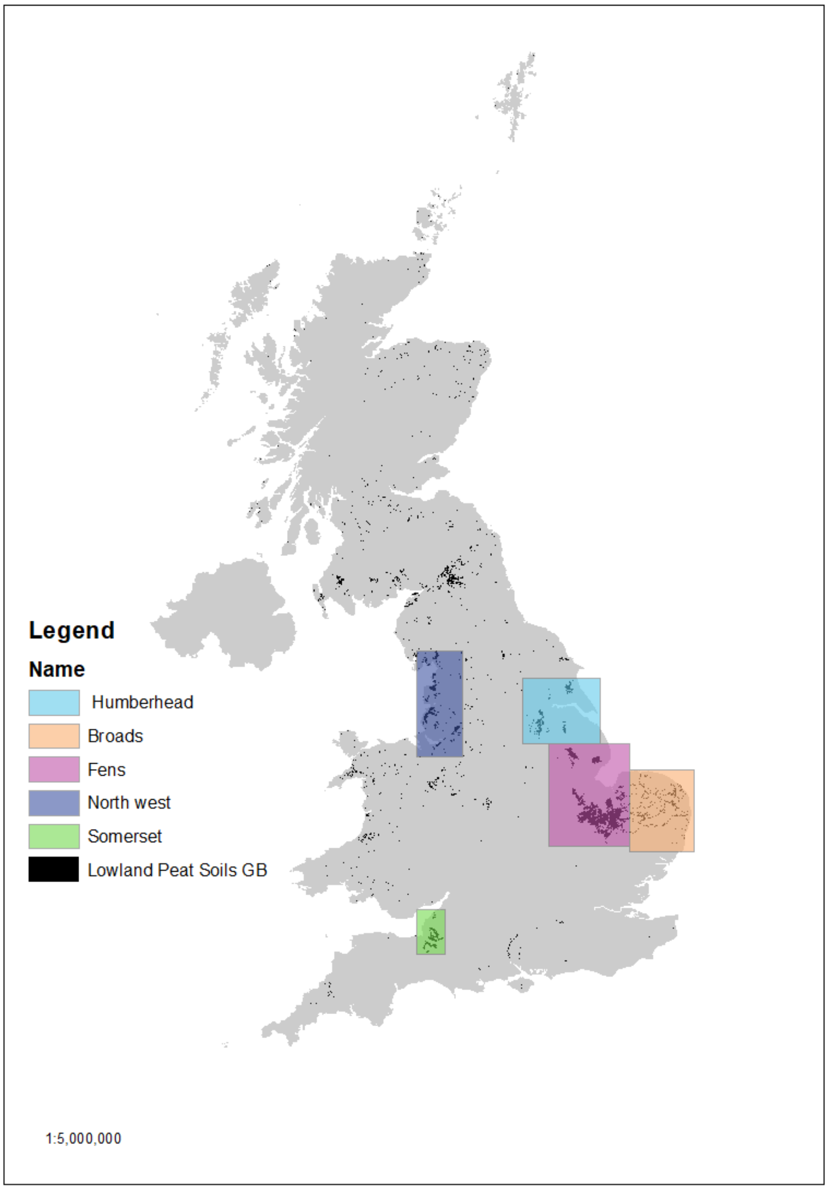


Figure 2-1UK regions used in the analysis. NE = North East, NW = North West, SC = South Central, SE = South East, SW = South West. Lowland peat soils are shown in black.

Crop types overlain on peat soils across GB are shown in Figures 2-4 – 2-11, with 250,000 ha mapped as agricultural land on peat according to the methods above. Of this, approximately 150,000 ha is on wasted (former) peat soils, while 100,000 ha remains as deep (> 40 cm) peat (Table 2-2). Within the peat areas mapped as cropland nearly 100,000 ha is in grass for livestock and/or silage production each year (Table 2-2). Mapping the end use of crops (for example differentiating between beet grown for sugar and beet grown for fodder crops) is not possible at a national scale so the figures in Table 2-2 refer to total areas. Although the total area of cropland on peat has remained relatively constant since

2015, there has been a change in the proportion of crops grown, with maize areas increasing from 6,000 ha in 2015 to 11,000 ha in 2021, and areas of oil seed rape grown on peat declining from 15,000 ha in 2015 to under 6,000 ha by 2021. However, it is important to note that this is not lowland peat specific as this is a national trend across all soil types (DEFRA 2022a). Over the same period the area used to grow cereal crops increased from 80,000 to 87,000 ha, and the area used to grow vegetable crops remained relatively constant. The proportion of agricultural lowland deep and wasted peat in GB are shown in Figure 2-2 (wasted peats were only mapped for England, peat in Wales, Scotland and Northern Ireland are assumed to be deep peat).

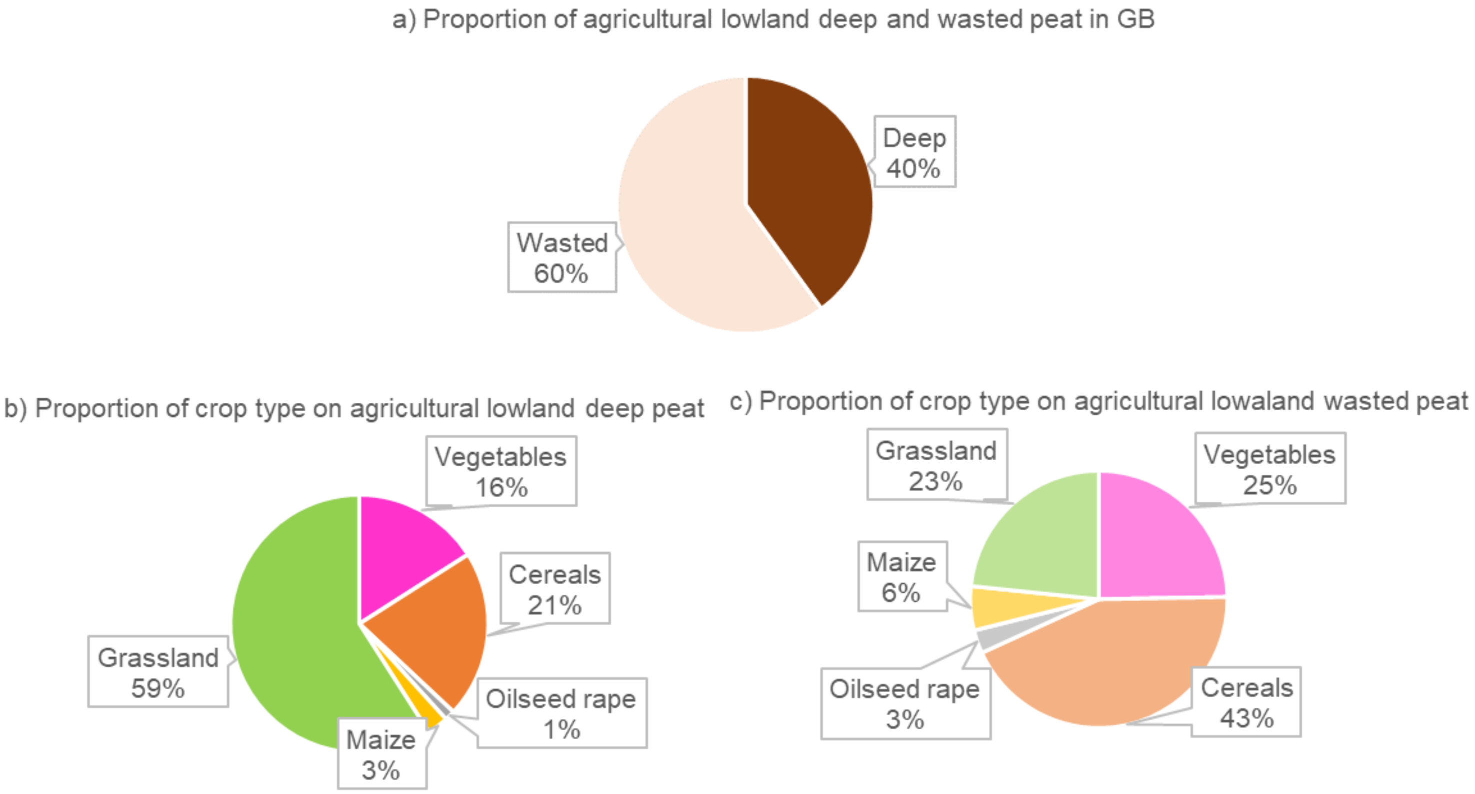


Figure 2-2 Proportion of agricultural lowland deep and wasted peat in GB (a), and the proportion of crop types on agricultural lowland deep (b) and wasted (c) peat. All data is based on 2021 data presented in Table 2-2.

Table 2-2 Areas of agricultural lowland peat (ha) separated by deep and wasted peat across the UK (note wasted peat mapping is only available for England). For more details on crops included in each category see Table 2-1.

	Peat Condition (ha)													
	2015		2016		2017		2018		2019		2020		2021	
	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted
	(ha)													
Vegetables	13,339	37,094	16,413	38,416	15,880	41,002	12,727	34,965	14,830	36,826	16,245	41,413	16,060	37,277
Cereals	18,163	61,140	16,301	60,656	17,686	58,037	19,224	64,153	19,739	63,007	19,621	58,812	21,106	65,537
Oilseed rape	3,063	12,376	2,409	10,751	2,198	9,122	2,171	10,114	1,868	8,352	1,674	5,938	1,290	4,416
Maize	1,701	4,356	1,815	5,306	3,049	7,627	3,631	5,040	3,304	7,338	2,679	9,029	2,678	8,363
Grassland	65,740	37,048	63,921	35,961	62,044	35,302	62,981	36,704	60,808	35,312	60,326	35,625	59,363	35,216
Total	102,006	152,014	100,858	151,089	100,858	151,089	100,735	150,977	100,550	150,836	100,547	150,818	100,498	150,809

2.1.1. Eastern Anglian Fens

*E*The Fens of Cambridgeshire and Lincolnshire sit within a region bounded by Cambridge and Newmarket in the south, Downham Market and Kings Lynn in the east, Peterborough in the west and Lincoln and Skegness in the north. These fenland areas have undergone large scale drainage since the 17th century, with systematic drainage carried out by Cornelius Vermuyden (Hutchinson 1980). This region holds approximately 75% of the total land in vegetable production on lowland peat across the whole of the GB (Figure 2-3; proportion based on 2021 data). Much of the agriculture in this region is on peat soils (in the region of 150,000 ha, see Figure 2-4 and Table 2-4), and the region is responsible for 33% of England's vegetable production and produces around £3.1 billion worth of food (NFU East Anglia 2019). It has been estimated that around 80,000 people are employed in the food chain in the fens, and over £3 billion is contributed to the regional economy per year. Of the 80,000 employees around 16,000 are directly employed in agriculture or agriculture supply (NFU East Anglia 2019). Over 20% of water intensive English crop output is grown in the fenland region (Table 2-3).

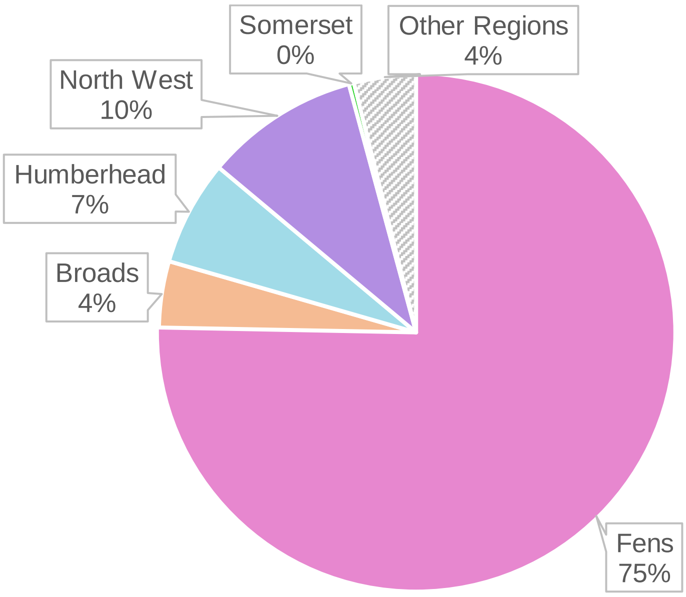


Figure 2-3 Proportion of lowland peat in vegetable production across GB for main agricultural lowland peat regions. Based on 2021 data.

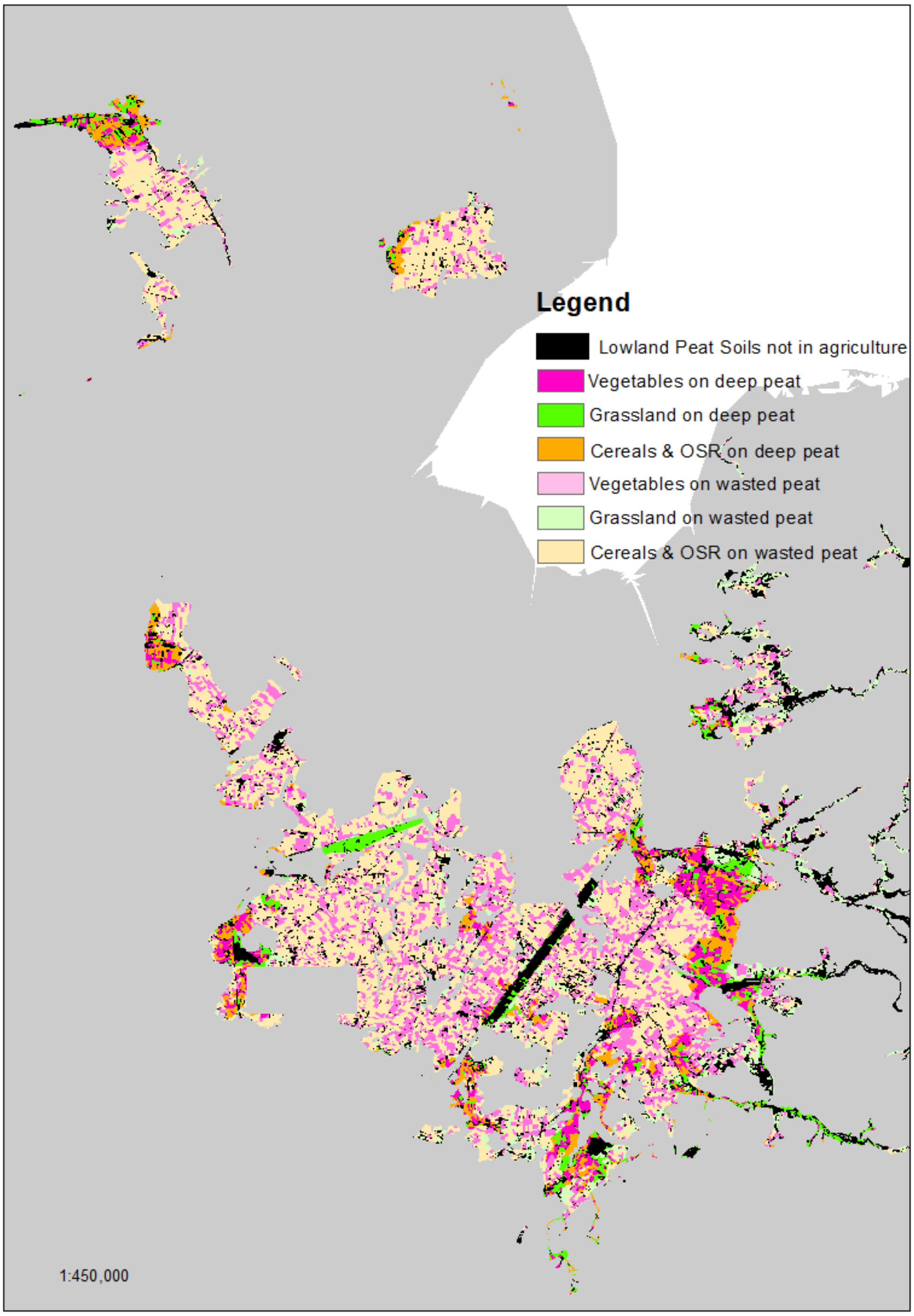


Figure 2-4 Lowland peat soils under cultivation for different crop types; grassland, cereal & oilseed rape (OSR) and vegetables in the East Anglian fens in 2021. Black areas are peat under non-agricultural land-uses such as conservation management

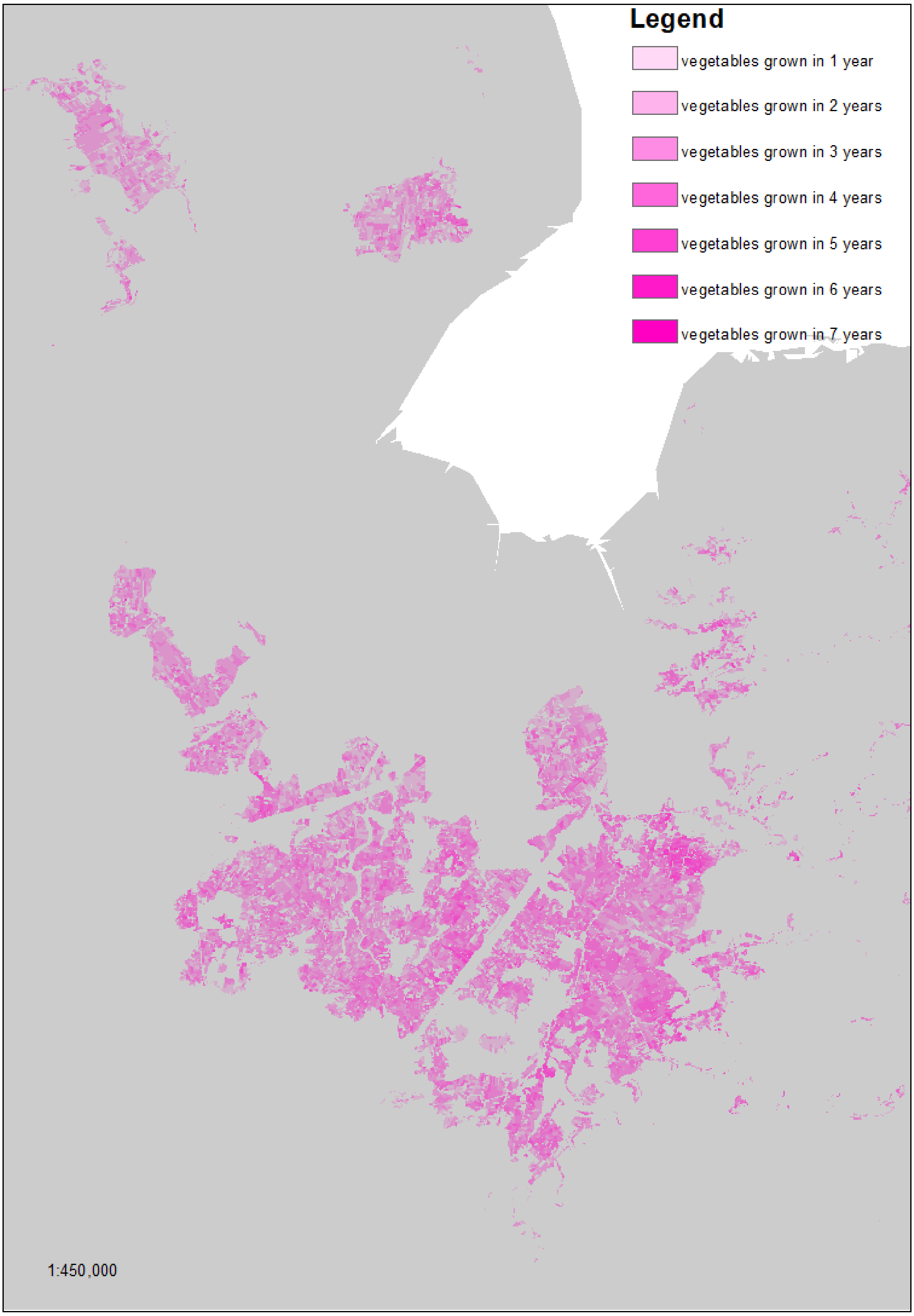


Figure 2-5 Vegetable production intensity in the East Anglian fens between 2015 and 2021. Pink shading denotes the number of years a given field was under vegetable cultivation between 2015 and 2021

Table 2-3 2016 water intensive crops in the fens. Data shown is the percentage of total produced across England, and the value to the economy in millions of £.(This includes crops grown on all soil types in this area). Extracted from NFU East Anglia report – Delivering for Britain - Food and Farming in the Fens (2019).

Crop	**% of England**	**2016 £million**
Potatoes	20%	112
Sugar beet	20%	30
Vegetables	32.8%	357
Plants and flowers	21.4%	232
Fruit	3.1%	19
Total crop output	21.5%	750

Across East Anglia 25,000 ha of deep peat are used for agriculture and over 100,000 ha on wasted peat. Similar to the national picture vegetable production areas have remained relatively constant, oilseed rape areas have reduced and maize areas have increased between 2015 and 2021. Grassland areas and cereal areas have both remained relatively constant, though proportionally less of the peatland area in East Anglia is used as productive grassland compared to the national picture (Table 2-4).

Table 2-4: Areas of agricultural lowland peat in the East Anglian Fens (ha).

East Anglian Fens	Deep peat				Wasted peat			
Year	Cereals & oilseed rape	Grassland	Vegetables	Total	Cereals & Oilseed rape	Grassland	Vegetables	Total
2015	11,043	6,947	7,195	25,185	64,108	11,032	31,769	106,908
2016	9,984	7,381	7,637	25,002	64,269	10,632	31,737	106,638
2017	10,043	6,733	8,226	25,002	60,954	10,104	35,580	106,638
2018	10,481	7,611	6,888	24,981	64,826	11,389	30,369	106,584
2019	10,306	6,579	8,041	24,926	64,631	10,263	31,652	106,545
2020	9,767	6,711	8,449	24,926	60,695	10,658	35,176	106,529
2021	10,016	6,440	8,471	24,926	64,310	10,525	31,693	106,529

2.1.1.1. Norfolk and Suffolk Broads

The Norfolk and Suffolk Broads are Britain's largest protected wetland area (Broads-authority.gov.uk) based around the main rivers of the region: the Waveney, Yare, Bure, Thurne, Ant, Chet and Wensum (Figure 4). The Broads themselves are shallow lakes, most of them manmade as they are flooded peat workings. In medieval times, peat was dug for fuel before being abandoned, in most cases by the end of the 14th century, when water levels rose (George 1992)

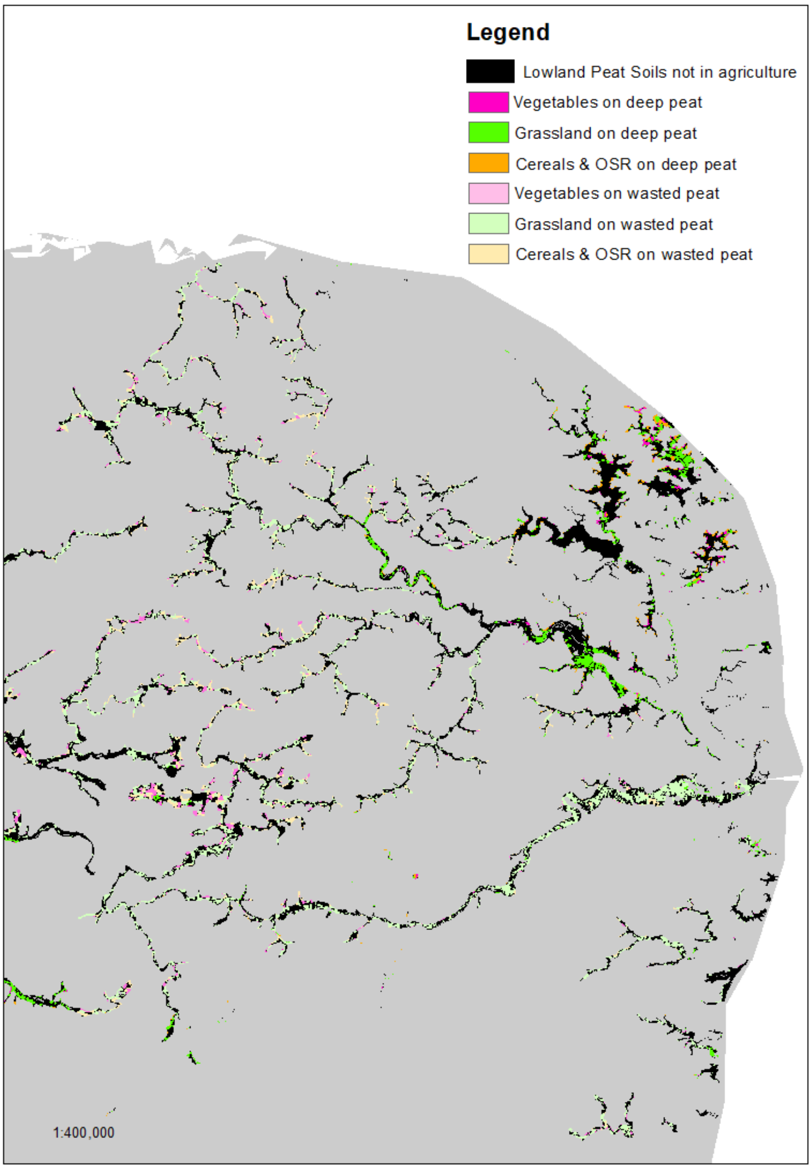


Figure 2-6 Lowland peat soils under cultivation for different crop types; grassland, cereal & oilseed rape (OSR) and vegetables in the Norfolk and Suffolk Broads in 2021. Note that due to map scales the eastern edge of the fens are shown. Black areas are peat under non-agricultural land-uses such as conservation management.

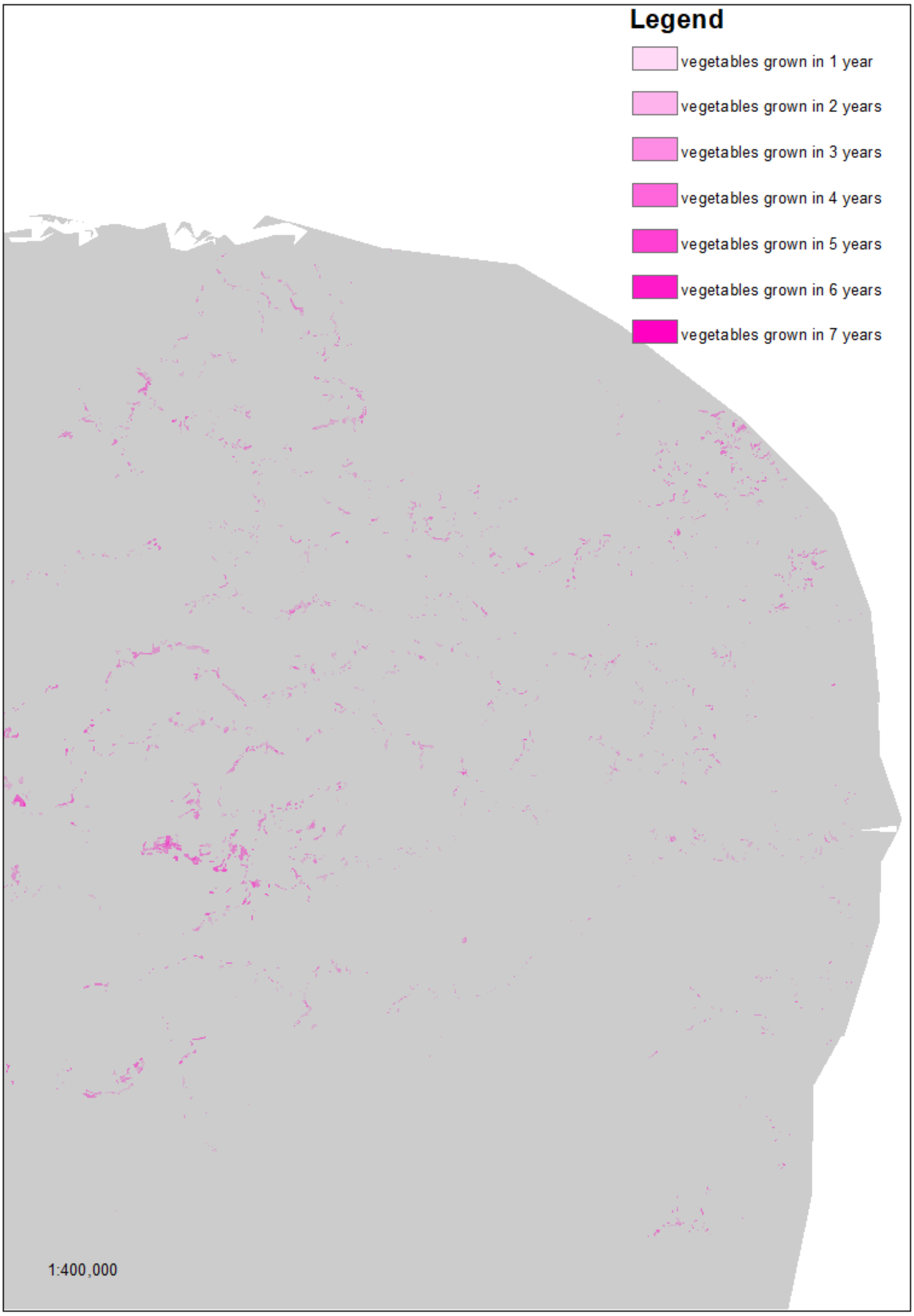


Figure 2-7 Vegetable production intensity in the Norfolk and Suffolk Broads between 2015 and 2021. Pink shading denotes the number of years a given field was under vegetable cultivation between 2015 and 2021

Although numbers are smaller than in the fens a significant proportion of England’s agricultural output comes from the Norfolk and Suffolk Broads, with the region producing 20% of the national sugar beet crop, most of which is destined for the local sugar factory at Cantley (NFU East Anglia 2010). Agriculture is a significant local employer, with approximately 8,500 people employed (NFU East Anglia 2010).

In the Norfolk and Suffolk Broads 3,750 ha of deep peatland over 15,000 ha of wasted peat is under agriculture. The majority (approximately two-thirds) of the peat soil is under grassland, with only small areas (< 2,500 ha) used for vegetable production (Table 2-5). Those areas used for vegetable production tended to be cropped in rotation with cereals, though some fields were used to grow vegetables for 5 or more of the 7 years used in this analysis (Figure 2-6).

Table 2-5 Lowland peat under agriculture in the Norfolk and Suffolk Broads (ha).

Norfolk and Suffolk Broads	Deep peat				Wasted peat			
Year	Cereals & oilseed rape	Grassland	Vegetables	Total	Cereals & oilseed rape	Grassland	Vegetables	Total
2015	768	2,576	545	3,889	3,644	10,002	2,017	15,663
2016	624	2,685	455	3,764	3,362	10,386	1,580	15,328
2017	671	2,709	384	3,764	3,493	10,106	1,729	15,328
2018	753	2,676	329	3,757	3,678	10,417	1,215	15,310
2019	745	2,660	348	3,753	3,654	10,148	1,507	15,309
2020	680	2,645	428	3,752	3,371	10,222	1,716	15,309
2021	721	2,610	421	3,752	3,354	10,156	1,798	15,309

2.1.1. Yorkshire and Humberside

The main Humberhead peatlands were originally lowland raised bogs surrounded by fen. The central bog areas comprise Thorne and Hatfield moors (humberheadpeatlands.org.uk), which have been worked for peat extraction throughout recorded history. Arable farming in the region largely occurs on fen peat and accounts for 48% of the farmed area, with the main crops including cereals, roots, oilseeds, and stock feed (Natural England 2012).

Across Yorkshire and Humberside 4,500 ha of deep peat supports agriculture, as well as 12,800 ha of wasted peat soils (Figure 2-7). Grassland and cereal crops are the main land cover types by area while, as seen in the national data, maize crops are increasing in area and oilseed rape is decreasing (Table 2-6). The majority of the peat soils under agriculture in this area are growing cereals and vegetables in rotation (Figure 2-8).

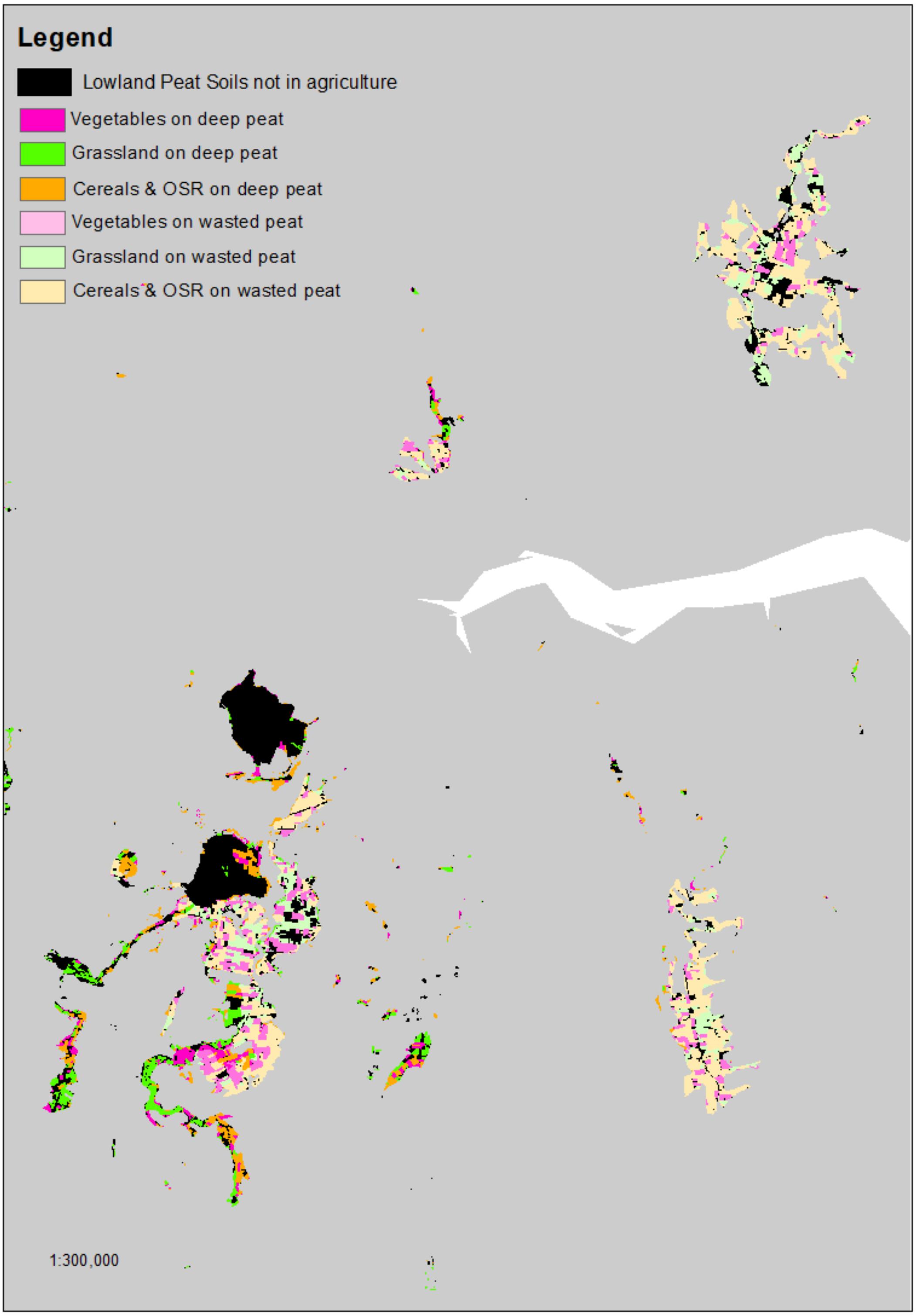


Figure 2-8 Lowland peat soils under cultivation for different crop types; grassland, cereal & oilseed rape (OSR) and vegetables in the Yorkshire / Humberside region in 2021. Black areas are peat under non-agricultural land-uses such as conservation management.

Figure 2-9 Vegetable production intensity in in the Yorkshire / Humberside region between 2015 and 2021. Pink shading denotes the number of years a given field was under vegetable cultivation between 2015 and 2021

Table 2-6 Agricultural lowland peat in the Yorkshire Humberside region, including the Humberhead levels (ha).

Humberhead levels	Deep peat				Wasted peat			
Year	Cereals & oilseed rape	Grassland	Vegetables	Total	Cereals & oilseed rape	Grassland	Vegetables	Total
2015	1,895	1,563	1,069	4,527	7,424	2,832	2,592	12,847
2016	1,541	1,022	1,958	4,521	6,524	2,193	4,132	12,848
2017	2,050	1,563	908	4,521	7,418	2,697	2,733	12,848
2018	1,943	1,514	1,057	4,514	7,672	2,553	2,616	12,841
2019	1,975	1,602	924	4,501	7,343	2,707	2,770	12,820
2020	1,573	1,641	1,287	4,501	6,709	2,755	3,356	12,820
2021	1,895	1,607	990	4,492	7,527	2,754	2,539	12,820

2.1.2. Northwest England

The Lancashire Mosslands were originally mostly areas of lowland raised bog, developed from shallow lakes across the landscape. During the 20th century techniques were developed to allow drainage of the bogs, resulting in the expansion of peat cutting and conversion to arable farming – with the addition of fertilisers to enhance the productivity of the low nutrient bog peat soils (Natural England 2013). There is also some fen peat in the vicinity of Southport, where vegetable production is extensive. Across the Mersey Valley National Character Area just under 50% of the farms were arable and horticulture in 2009.

Across NW England 18,000 ha of deep peat soils and nearly 8,000 ha of wasted peat soils support agriculture. Most of the wasted peat and a high proportion (approximately 2/3rds) of the deep peat is used for cereals and grassland. In contrast to the national picture the area of cropland on peat used for vegetable production in the North West is increasing, while only small areas of maize and oilseed rape were recorded (Table 2-7 and Figure 2-9). The areas of cropland in the north west of England used for vegetable production are cropped in rotation with cereal crops, so most of the land mapped as being under cereal production in 2021 (Figure 2-9) was used for vegetable production in one or more of the seven years covered in this analysis (Figure 2-10).

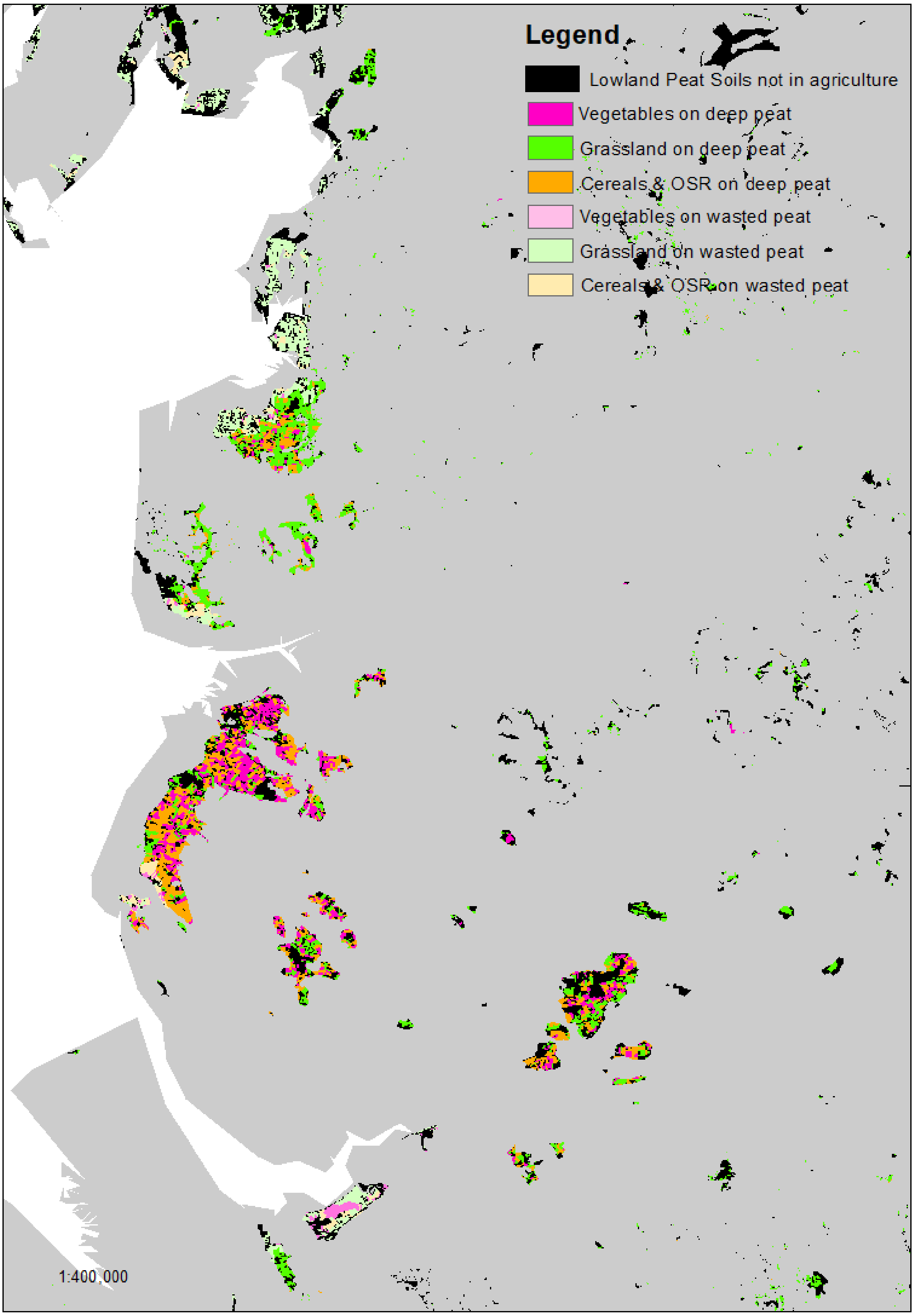


Figure 2-10 Lowland peat soils under cultivation for different crop types; grassland, cereal & oilseed rape (OSR) and vegetables in NW England in 2021. Black areas are peat under non-agricultural land-uses such as conservation management.

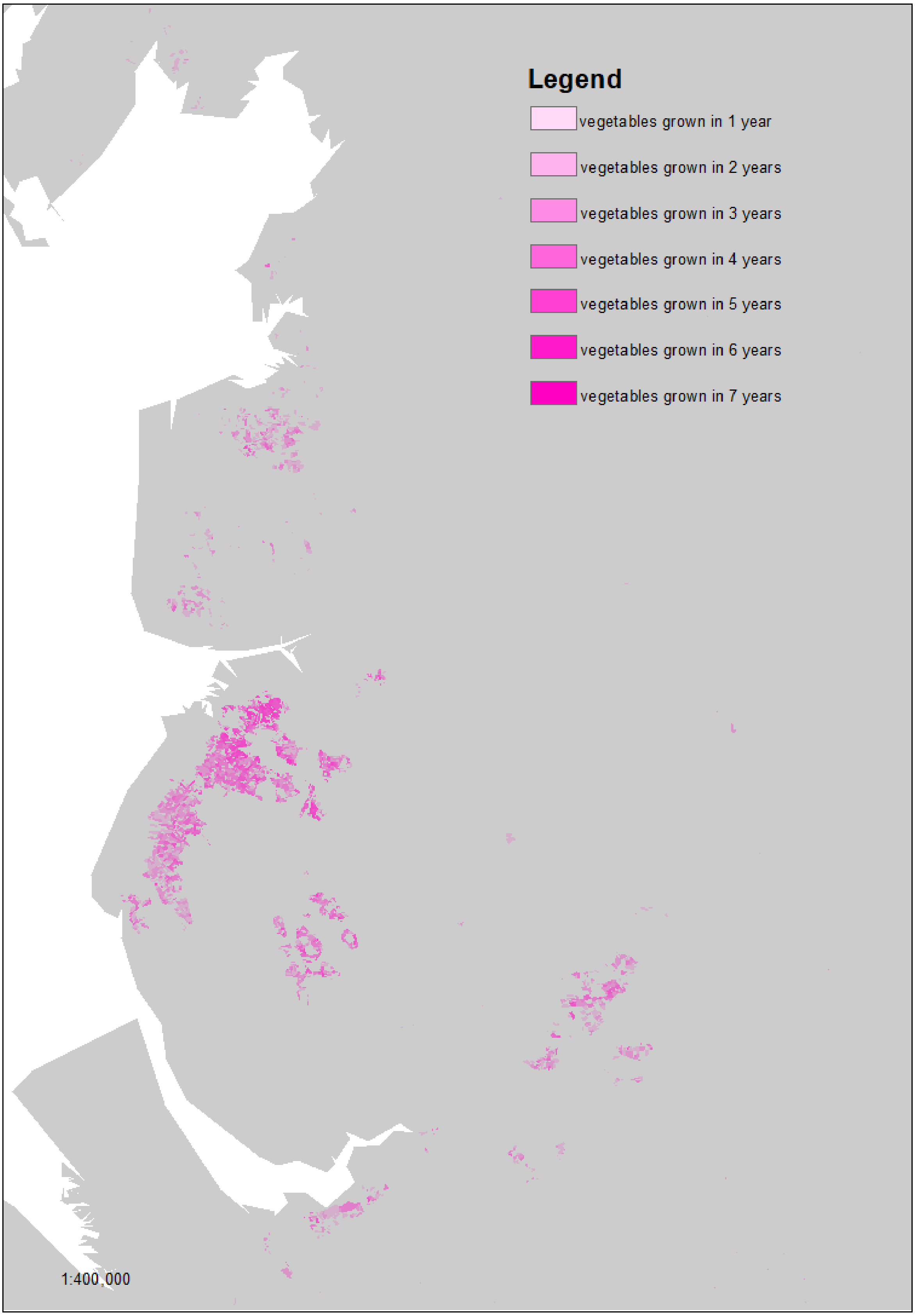


Figure 2-11 Vegetable production intensity in the NW England region between 2015 and 2021. Pink shading denotes the number of years a given field was under vegetable cultivation between 2015 and 202

Table 2-7 Agricultural lowland peat in the NW of England (ha).

North West	Deep peat				Wasted peat			
Year	Cereals & oilseed rape	Grassland	Vegetables	Total	Cereals & oilseed rape	Grassland	Vegetables	Total
2015	4,244	11,001	3,271	18,516	885	6,755	254	7,894
2016	3,791	9,695	4,986	18,472	812	6,428	470	7,710
2017	5,233	8,247	4,992	18,472	1,041	6,266	404	7,710
2018	6,682	8,291	3,471	18,444	1,119	6,308	269	7,696
2019	6,397	7,773	4,221	18,391	1,132	6,152	369	7,653
2020	6,531	7,643	4,214	18,388	1,182	5,992	479	7,653
2021	6,363	7,408	4,588	18,358	1,201	5,852	591	7,644

2.1.3. Somerset Levels

In the Somerset Levels there is over 12,000 ha of lowland peat in agriculture (Table 2-8, Figure 2-11). Almost all the agricultural land within this area is mapped as grassland, with only very small areas used to grow vegetables, cereals, maize, and oilseed rape (less than 10% of the total agricultural lowland peat in the Somerset Levels is part of an arable rotation with over 90% in grassland). As can be seen in Table 2-8, there is very little vegetable production on peat in any of the years 2015 – 2021 in the Somerset Levels.

Table 2-4 Agricultural lowland peat soils in the Somerset levels (ha).

Somerset Levels	Deep peat				Wasted peat			
Year	Cereals & oilseed rape	Grassland	Vegetables	Total	Cereals & oilseed rape	Grassland	Vegetables	Total
2015	253	7,618	77	7,947	334	3,959	59	4,351
2016	220	7,696	11	7,927	385	3,926	19	4,329
2017	264	7,599	64	7,927	332	3,890	107	4,329
2018	160	7,718	42	7,919	379	3,920	23	4,322
2019	228	7,672	16	7,916	325	3,932	59	4,315
2020	207	7,656	53	7,916	369	3,882	65	4,315
2021	301	7,515	100	7,916	394	3,852	70	4,315

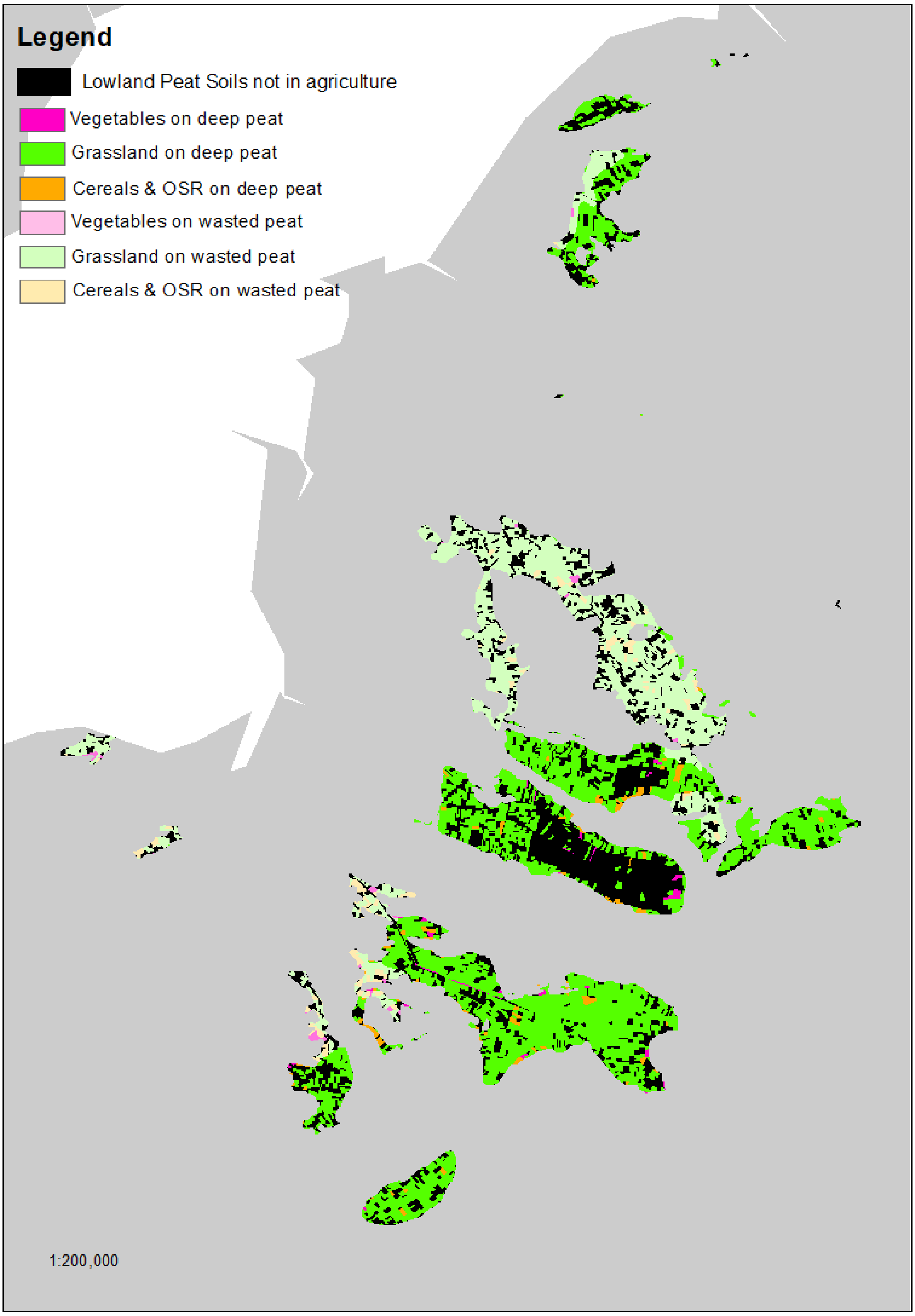


Figure 2-11 Lowland peat soils under cultivation for different crop types; grassland, cereal & oilseed rape, and vegetables in the Somerset Levels in 2021. Black areas are peat under non-agricultural land-uses such as conservation management. The large area in black in the centre of the map is the Avalon marshes, west of Glastonbury (previously a peat extraction site).

2.1.4. *Scotland*

Of the 18,000 ha mapped as agricultural lowland peat in Scotland almost all of it is grassland, with between 1,400 and 2,000 ha mapped as cereal production (depending on year) (Table 2-9). It is worth noting that crofting, a form of land tenure for small-scale food production, is likely to see some vegetables grown in the uplands where most peat soil in found in Scotland. Peat extraction is also extensive across Scotland with approximately 2,840 ha used for industrial extraction and 44,649 ha for domestic extraction in 2013 (Pike, 2021).

Table 2-9 Agricultural lowland peat soils under agriculture in Scotland (note that wasted peat soils are not mapped separately in Scotland).

Scotland	Peat (ha)						
	2015	2016	2017	2018	2019	2020	2021
Vegetables	201	419	430	286	584	600	633
Cereals& oilseed rape	1,743	1,457	1,532	1,519	1,701	2,144	2,141
Maize	5	11	55	103	55	40	50
Grassland	16,268	15,961	15,831	15,928	15,466	15,023	14,974
Total	18,216	17,847	17,847	17,837	17,806	17,806	17,798

2.1.5. Wales

Across Wales, there is approximately 4,000 ha of agricultural lowland peat, primarily in coastal areas, mainly on the Llŷn Peninsula, in Ceredigion and in Pembrokeshire (see Figure 2-1). Of this land almost all of it (over 90%) is grassland, with approximately 100 ha of lowland peat used to grow vegetables and cereals (Table 2-10). Evans et al. (2015), used Phase 1 habitat mapping from the 1980s and 1990s to determine cropland areas on peat and gave similar totals for arable crops on lowland peat in Wales (101 ha), suggesting that arable farming on lowland peat in Wales has been stable at this low level for 30 years.

Table 2-10 Lowland peat soils under agriculture in Wales (note that wasted peat soils are not mapped separately in Wales).

Wales	Peat (ha)													
	2015		2016		2017		2018		2019		2020		2021	
	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted
Vegetables	56	0	14	0	17	0	10	0	29	0	51	0	40	0
Cereals& oilseed rape	8	0	9	0	4	0	13	0	13	0	21	0	41	0
Maize	9	0	12	0	8	0	15	0	8	0	14	0	14	0
Grassland	4004	0	3968	0	3975	0	3956	0	3941	0	3906	0	3896	0
Total	4077	0	4004	0	4004	0	3994	0	3992	0	3992	0	3992	0

2.1.6. Northern Ireland

The Northern Irish land mass is 13,550 km^2, of which 75% is less than 150 m altitude. Although much of Northern Ireland is classified as agricultural land (76%), only 4% of the land is used for arable farming (Barry, 2016). Soil types in Northern Ireland are dominated by gleyed soils while peat soils cover approximately 14% of the landscape (Barry 2016). Most of these peat soils are blanket bog (approximately 50%), and other land uses include pasture (~20%), and plantation forestry (~10-15%). As of 2016, analysis showed that there was virtually no arable farming on peat in Northern Ireland (Barry, 2016), though this analysis did not discriminate between upland and lowland peats. Peat extraction in Northern Ireland is carried out at scale, in 2013 this included 503 ha used for industrial extraction and 87,539 ha affected by domestic extraction (Pike, 2021).

2.2. Summary

The region growing the most vegetable crops on lowland peat across the UK is East Anglia, primarily the Fenland region Figure 2-3Figure 2-3 Proportion of lowland peat in vegetable production across GB for main agricultural lowland peat regions. Based on 2021 data., with most of the arable land on peat growing vegetable crops, often in rotation with cereals. Vegetables are also grown in rotation on most agricultural lowland peat soils in North west England. In contrast the remaining regions in England, and Scotland and Wales have limited vegetable production on lowland peat, and the majority of agricultural peat soils in these areas are managed for grassland. In England the remaining deep peat soils in agricultural land use (apart from the Somerset Levels) tend to be used for vegetable crops in rotation, with only some use for cereal crops, while the wasted peat soils are more likely to be managed in a crop rotation that includes more years where cereals are grown.

3. Ecosystem- service trade-offs associated with current veg production on lowland peat in the UK

3.1. Food security

In the UK food security has been measured in terms of the proportion of the UK's total food requirements that are sourced from UK farms. In 2009 the UK was 59% self-sufficient across all food (Morris et al. 2010), a figure that seems to have remained similar when assessed again in 2020 (DEFRA 2021b), when the UK was 54% self-sufficient in fresh vegetables specifically (DEFRA, 2021b). At present UK food production is driven by market forces, rather than maximising calorie production from available land. As of 2010, it has been estimated that around 240,000 ha of drained lowland peat soils are farmed for food production (this across England (Morris et al. 2010). As covered in section 0 arable farming on peat soils produces a significant proportion of UK crops, with significant contributions towards UK food security.

3.2. Greenhouse gas emissions

A global assessment of emissions from croplands (excluding emissions from the livestock sector) found that crop cultivation on peatlands accounts for 32% of global crop emissions despite only providing 1.1% of the total crop calories. Rice production accounts for 48% of global crop emissions, caused by high methane emissions, whilst the remaining 20% is attributed to nitrous oxide emissions from fertiliser use (Carlson et al. 2017). Emissions from peatlands are particularly high due to drainage practices used to increase productivity, which exposes previously waterlogged anaerobic peat to oxygen and allows aerobic decomposition. In 2021 the total emissions from peatlands in the UK contributed 19 Mt CO_2 equivalent per year (approximately 4% of total UK emissions), with just over a third of these emissions from peatlands coming from cropland (Brown et al. 2023). Evans et al., (2021a) showed that the depth of aerated peat, which is a function of the water table depth and the peat depth, represents the dominant control on GHG emissions from managed peatlands, and estimated that halving the water table depth in drained agricultural peatlands could reduce both UK and global GHG emissions by ~1%. This analysis suggested that significant emissions reductions could be achieved through changes in agricultural water management and crops grown, even if land remains in crop production. Conversion of cropland to grassland could also reduce CO_2 emissions if accompanied by reduced drainage intensity, although some studies have highlighted risks of higher nitrous oxide emissions under some circumstances (e.g., Wen et al., 2021). It should also be noted that any lowland peatland that remains under some form of drainage-based management, even low intensity grazing, are still likely to be losing soil carbon and emitting GHGs (e.g., Peacock et al., 2019). As a result, no current form of drainage-based agricultural managed on peat can be considered truly sustainable.

3.3. Subsidence

Peat soils contain very little solid matter, and in their natural state are up to 90% water by volume (S Page et al. 2012). Once saturated peat soils are drained, the water is no longer present to provide support to the soil structure, and the process of subsidence begins. Subsidence is the overall outcome of several processes occurring within the soil: peat consolidation, compaction and shrinkage, and the decomposition of organic material now under aerobic conditions (e.g., Hooijer et al., 2012; Page et al., 2020).

Consolidation: the physical process of peat compression below the water table following water drainage and the resulting loss of buoyancy of the top peat layer. Most consolidation occurs rapidly following drainage.

Compaction and shrinkage: are physical processes that reduce the volume of the aerated peat layer following drainage. Compaction occurs due to pressure on the peat surface (e.g. by heavy machinery), while shrinkage occurs as the peat fibres dry out and become more tightly packed. These processes can continue for decades or centuries following peat drainage.

Decomposition: soil organic matter decomposes when the soil is exposed to air, removing the constraints on microbial activity that occur under anaerobic waterlogged conditions, and allowing more aerobic decomposition to occur. This process results in soil organic carbon being lost to the atmosphere as carbon dioxide, and will continue until all of the peat above the water table is gone.

Consolidation, compaction, and shrinkage all increase peat bulk density (more peat per unit volume) but do not directly in themselves lead to a loss of carbon from the peat soil. The decomposition of organic material (potentially along with wind or water erosion) is therefore responsible for loss of peat soil and resulting CO_2 emissions. The contribution of decomposition to the loss of peat volume varies widely, with estimates ranging from 35% to 100% (Couwenberg et al. 2010). For temperate peatlands, a figure of around 50% may be appropriate.

Studies in drained fenlands used for arable crops in England have found long term subsidence rates in the region of 0.5 to 2 cm per year (e.g. Dawson et al., 2010; Hutchinson, 1980; Richardson and Smith, 1977; for collated data see Table 3 of Evans et al., 2019). In addition to decomposition, wind erosion is also responsible for losses, up to 0.25 cm peat per year (Cumming 2018), particularly during wind blow events where the dry surface peat is blown off the fields. Some peat is also removed attached to root crops and harvested turf. Changes to the physical properties of soils include increased bulk density (Susan Page et al. 2020) and changed pore structure (Rezanezhad et al. 2016); changes to the hydrological regime including changes in water infiltration rates, hydraulic conductivity and runoff volumes and rates (J Holden et al. 2006; Liu and Lennartz 2019; Rezanezhad et al. 2016); and changes in the pore water chemistry (Joseph Holden et al. 2004). Eventually the peat is lost with the underlying mineral soils exposed (Susan Page et al. 2020). In addition to the direct impacts on farming, subsidence impacts many other aspects of living in peatland dominated areas including subsidence-induced damage to the transport network (road and rail) and damage to buildings. These aspects are extensively reviewed by Page et al., (2020).

3.4. Biodiversity

The historical drainage of lowland peat landscapes across Europe for the large-scale conversion of wetlands to intensive agricultural land has resulted in a wide range of documented biodiversity loss (Buisson 2008; van Eerden et al. 2010). As with agricultural intensification in other landscapes, the result is an increasingly fragmented set of habitats; in lowland peat, biodiversity is largely associated with ditches, shelterbelts, ponds/reservoirs, and washes. Ditches and other wet areas can act as refugia for rare species that were extensive within the pre-drainage wetland landscape. Mossman et al. (2012) note that for the Fens (and many other lowland peat landscapes), the biodiversity status of the wider landscape outside nature reserves/SSSIs is unclear since these areas are poorly recorded. We discuss restoration efforts and biodiversity benefits in section 7.

3.5. Local economy and livelihoods

The agricultural use of lowland peatlands is integrally linked to the economies of the local areas and the livelihoods of a relatively high proportion of the population living in the area (Freeman et al. 2022). In the East Anglian fenlands the ‘farm to fork’ food chain employs 80,000 people and generates £3 billion for the local economy, of which the direct agricultural production is worth £0.4 billion (NFU East Anglia 2019).

There are direct economic costs to the drainage of lowland peat for agriculture, including those occurring because of subsidence (Section 3.3). Soil movement in the UK was estimated to cost between £300 and £500 million per year in 2013 (Pritchard et al. 2013), of which a proportion is due to subsidence of drained peat soils. However, these costs are substantially low when compared to the net worth of agriculture on lowland peat to the UK economy, this is worth £1.23 billion in the fens alone (Countryside 2018). Nonetheless, this has caused problems for infrastructure, notably roads and railways, buildings, and utility infrastructure (Pritchard et al., 2013), and it is likely that many of the infrastructure costs of peatland subsidence are ‘hidden’, in that they are spread across the maintenance budgets of multiple organisations (e.g. local authorities, Highways Agency, utility and rail companies) and rarely considered specifically (Page et al., 2020). In the UK the economic costs of subsidence on housing and building stock are relatively low because inhabited areas tend to be on ‘islands’ of mineral soils within the peat landscape (Susan Page et al. 2020). However, subsidence can be an issue for buildings, for example Figure 3-1 shows two examples of buildings affected by subsidence: on the right two fenland cottages are shown leaning away from each other, while on the left a house that had foundations based on the underlying mineral substrate ended up 2 m above the surrounding landscape.

Figure 3-1 Examples of peat subsidence affecting buildings (taken from Susan Page et al. 2020; originally from Thompson 1957).

Roads and railways are also damaged by subsidence, particularly minor roads where the foundations were not designed to accommodate the weight of modern HGVs. The economic costs of repairing the damage has been estimated to be millions of pounds (Susan Page et al. 2020), without accounting for further costs associated with damage to the vehicles driving on them. Other infrastructure such as telephone and power lines are affected by surface movement and subsidence (Figure 3-2, taken from Page et al 2020).

Figure 3-2 Pylons affected by peat subsidence (Photo: Sue Page, taken from Page et al., 2020).

3.6. Flood risk

Peatland drainage and subsequent subsidence (see Section 3.3.5) lowers the land surface and leads to increased risk of flooding, particularly where, in extreme cases, the land surface is below sea level and at risk of coastal flooding,. In the UK large areas of farmed peat, particularly in the East Anglian fens, Norfolk and Suffolk Broads, and the Somerset levels, are lower than the surrounding river network (Susan Page et al. 2020) requiring pumped water management to prevent inundation. These low-lying peat areas have experienced severe flood events over the years, notably the Somerset Moors flooding in winter 2013-14. Flood risks to these areas are likely to be exacerbated further by climate change, given that extreme weather events are predicted to be more frequent and severe, and that subsidence of many peatland areas is continuing.

Under the Water Resources Act (1991) the Environment Agency and Natural Resources Wales have powers, in England and Wales respectively, to protect people, farmland and infrastructure from main river and tidal flooding, while local councils and Internal Drainage Boards (IDBs) have powers covering the flooding from surface water and non-main rivers. The EA and NRW powers allow them to enact works to minimise the risk of flooding. IDBs are independent public bodies who provide specialist local management of watercourses and land to provide drainage and irrigation as required. They operate across over 1 million hectares of land, including most of the main lowland peatland areas under agriculture in England – the East Anglian Fens, the Humberhead peatlands, the Somerset Levels and Moors and the Norfolk and Suffolk Broads (Susan Page et al. 2020). However, there are no IDBs covering the cultivated lowland peat areas of Northwest England.

One management option that has the potential to reduce flood risk, that is being trialled in areas of the Somerset Levels, is the reconnection of rivers with their flood plains, slowing flows in water courses, restoring, and creating wetland areas to absorb and store water and improving soil management (Page et al., 2020). Past work has shown that there is potential for lowland wetlands to improve natural flood management with 23 out of 28 studies finding that floodplain wetlands delayed or reduced flooding (Bullock and Acreman 2003), along with modelling work suggesting that reconnecting rivers with their floodplains can reduce peak flows by 50 – 150% (Acreman et al. 2003).

3.7. Knowledge gaps

A main knowledge gap impacting our ability to understand the impact of farming on lowland peat soils across the UK is the lack of national scale peat maps that are also accurate at a local scale. Natural England are leading a project to develop a new England Peat Map by 2024 but at present the peat maps for all four UK countries continue to be largely reliant on soil surveys undertaken decades ago. There is also a limited national-scale knowledge of peat depth, and subsequently total carbon stocks, which are needed to effectively target peat conservations, restoration, and mitigation measures.

As concluded by a recent review of the societal impacts of lowland peatland agriculture (Susan Page et al. 2020) there are still key uncertainties relating to the financial costs resulting from damage to infrastructure on peatlands, both from subsidence and flooding, and the societal costs of providing and maintaining drainage and flood defences. Page et al., (2020) recommend that a more detailed assessment quantifying the costs, in order to demonstrate an accurate cost-benefit analysis of management options. Further research into the impacts of alternative water and land management options for lowland peatlands (for example paludiculture, conversion to grazing, management of water tables) on measures such as subsidence and GHG emissions, as well as other ecosystem services and disservices such as water resource, flood, and water quality regulation, are also needed to feed into this analysis. As noted almost ten years ago by Reed et al (2014) these evidence gaps, and the challenges of ‘stacking’ multiple benefits of land-management interventions in public of private payment for ecosystem service schemes, represent important barriers to change in agricultural peatland landscapes.

4. Defining regenerative agriculture and challenges for vegetable production on peat

There is currently no legislative framework that defines the use of the term ‘regenerative agriculture’, in terms of either permitted or prohibited farming practices. In general, regenerative farming used as an umbrella term to describe farming systems that seek to building and maintain soil health. Regenerative agriculture also focuses on increasing biodiversity, enhancing ecosystem services, building resilience to climate change, and improving the water cycle, among other things. The main pioneer organisation for regenerative farming in the UK is Groundswell; this farm and agricultural conference/show has identified 5 principles that are considered to underpin regenerative agriculture (Figure 4-1):

1) Minimise soil disturbance
2) Keep the soil surface covered
3) Maintain living roots
4) Grow a diverse range of crops
5) Integrate livestock

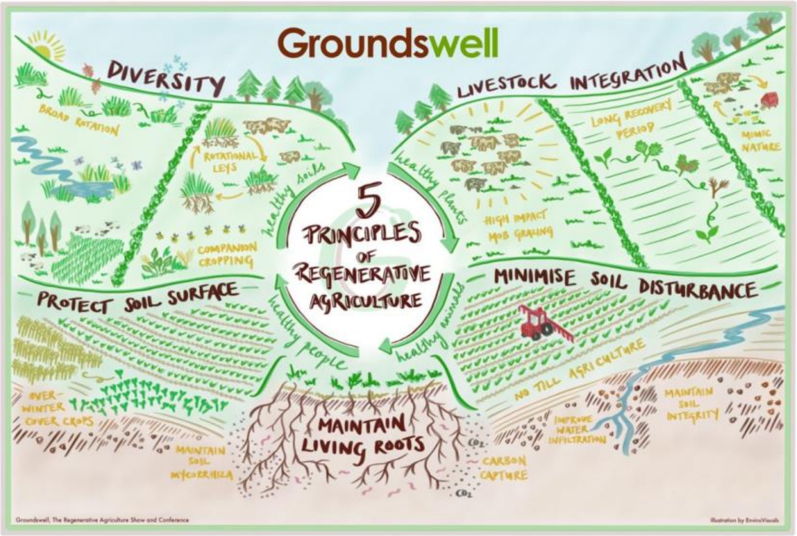


Figure 4-1 Infographic that highlights the 5 principles of regenerative agriculture, extracted from Groundswell (2021)*.*

These regenerative agriculture foundations are largely recognised across the wider agricultural community but have until now been predominantly developed for mineral soils, with little to no focus on peat. Because GHG emissions from agricultural peatlands are inherently high from drainage practices, there is a risk that regenerative concepts that aim to deliver emission reductions may provide only marginal reductions without implementing wetter management, albeit while still delivering other environmental benefits (e.g. biodiversity). For example, growing a diverse range of crops can achieve higher biodiversity by accommodating more butterfly and insect populations. Nevertheless, regenerative vegetable farming on peat requires wetter soil management practices in combination with conventional regenerative concepts (e.g., reduce soil disturbance). Wetter farming measurements are discussed in section 4.1, whilst conventional regenerative concepts and the ecosystem services they can deliver (e.g., biodiversity), which are largely developed and reported for mineral soils, are discussed in Appendix 2.

4.1. Why peat soils require additional/different regenerative measures

The proportional reduction in emissions that regenerative practices can deliver on drained peat soils are much smaller compared to mineral soils, because drainage practices alone are responsible for >80% of emissions from agricultural lowland peat (Freeman et al. 2022). This means that where regenerative practices are implemented without the concomitant implementation of wetter farming practices, emission reductions are likely to be small or negligible.

In the UK, lowland peat soils under vegetable production are typically drained to at least 50 cm below the surface throughout the year and often much lower (>90 cm) during the summer (although vegetable production areas on deep peat with subsurface drains may raise water levels when crops are on the field in order to irrigate the crop). Evans et al. (2021a) estimated that raising water tables within the peat layer by 10 cm could reduce carbon emissions by as much as 5 tonnes of CO_2 per hectare per year, based on UK measurement data. Net reductions in GHG emissions are likely until the water table is within 10-20 cm of the surface, which is above the level at which most crops can be grown; in other words, any management interventions that permit vegetable crops to be grown with higher water tables are likely to result in GHG emissions reductions. These measures could include continuously raising water levels, limiting the extent of summer water table drawdown (especially for deeper peats) and ‘dynamic’ water level management, in which fields are maintained as wet as possible during periods when no crop is present. Combining these measures with some regenerative farming practices could lead to additional emissions reductions. However, it is doubtful whether any form of drainage-based vegetable production could halt GHG emissions entirely, because some peat oxidation is likely to occur even with relatively high water levels. There is also a risk of emissions of N_2O associated from drained peat used for vegetable production, even where water levels are relatively high, as a result of high rates of nitrogen fertiliser application.

4.2. Dynamic water table management

Dynamic water table management refers to practices that effectively raise water table depths as high as possible, both spatially and temporally, taking account of the presence or absence of crops on each field, the crop soil moisture requirements and water table tolerance of individual crops when present, and the requirements of farm operations into account (e.g. harvesting with heavy machinery). The shallowest possible water table depth within a crop rotation will largely be dictated by a particular crop's plant rooting zone, as excessive water can negatively affect root growth and subsequently crop yields (Wang et al. 2004). It is therefore likely that shallow rooting crops (e.g., lettuces) within a rotation will be able to tolerate higher water table conditions and therefore deliver higher emission reductions compared with deeper rooting crops (e.g., potatoes). However, a key challenge for this is our limited understanding as to which crops can tolerate wetter conditions and the impact this might have on yield; we summarise wetter soil thresholds for some crops in Table 6-1. Understanding crop specific soil moisture thresholds is a key knowledge gap and is required to manipulate water table depth appropriately to deliver maximum emission reductions without significantly affecting crop productivity and/or causing the crop to fail.

Of the few studies that do explore water table impacts on yields, they show that shallow rooting and tuber crop yields can increase with raised water tables (Berglund and Berglund 2011; Lambers and Oliveira 2019; Musarika et al. 2017; Stanley and Harbaugh 2002), as a result of improved water supply, whilst deeper rooting crops have reduced yields (Kahlown and Ashraf 2005; Renger et al. 2002). For example, reducing the water table depth from -50 to -30cm reduced deeper rooting celery yields by 19% (Matysek et al. 2019) yet increased shallower rooting radish yields by 33% (Musarika et al. 2017). It must be noted that some of these studies explored large reductions in water table depths (from waterlogged conditions through to shallow water table depth <=-30 cm), we therefore highlight that reductions in yield are all relative to baseline water table depths. For example, a 10 cm reduction in water table depth from a very deep water table depth (>-70 cm) is unlikely to affect yield regardless of crop type. We strongly recommend that future research focuses on the development of crop specific dynamic water table management guidelines.

Other opportunities to reduce emissions include the manipulation of water table depths through the season, where drainage intensity is reduced during the winter when there is a reduced need to travel on the fields for crop management activity. During periods when standard farm machinery for sowing and harvesting is needed farmers would drop the water table to allow for this. The reductions in emissions from manipulating high water tables in the winter are potentially significant, as approximately 23-42% of net CO_2 emissions occur during the winter (Christopher Evans et al. 2016) and evidence from a mesocosm study showed that maintaining a -30 cm water table depth in the winter delivered 33% emission reductions compared with -50 cm. However, there are some plant fungal diseases associated with wetter soil conditions, which may reduce crop yields (Katan 2000). Manipulating water table depths in practice both spatially and temporally has several major challenges, which are discussed in section 7.3.

4.3. Irrigation

Irrigation is commonly practiced in horticulture and is regularly used in the UK, typically in the summer, to supplement rainfall. In potatoes c. 54% of the crop area is irrigated and in outdoor field vegetables such as carrots, onions, parsnips, and salad crops c. 31% of the crop area is irrigated, (J. W. Knox et al. 2020b). Irrigation increases soil moisture content which could lead to reduced carbon emissions if moisture levels become high enough to impede microbial activity (Rochette et al., 2010), but also has the potential to increase emissions if soil moisture is raised from very low levels to levels more suitable for microbial decomposition (Evans et al., unpublished report to Defra) . Increasing irrigation frequency and/or intensity may therefore have the potential to reduce emissions, but would need to be implemented appropriately. At present, irrigation is used in areas where summer rainfall is low and unable to support crop water demand, so there is some risk that irrigation could enhance rather than suppress peat decomposition rates. Furthermore, limited data (UKCEH, unpublished data for DESNZ) suggest that irrigation combined with high rates of fertiliser application to vegetable crops could result in high rates of N_2O emission. Furthermore, most catchments in which horticultural production takes place have been defined as already being either over-licenced and/or over-abstracted by the Environment Agency (J. W. Knox et al. 2020a). Water resources are also expected to become more limited in the UK due to climate change.

Therefore the increased water demand that would be required to reduce emissions significantly through the use of irrigation alone are unlikely to be achievable. In practice, optimisation of irrigation is likely to have the largest impact where it is implemented together with dynamic water table management to mitigate further emissions during dry periods where water table depths may drop naturally.

4.4. Water availability

There is a widespread perception that re-wetting agricultural peatlands could intensify regional water demand and resulting water scarcity. This concern is most acute in the drier, eastern parts of the UK, notably in the East Anglian Fenland and Broadland areas, where lower rainfall levels, intensive agriculture and rising populations mean that water availability is already a major concern. In the Fenland area there are plans being developed to increase water storage capacity via new reservoir construction, and to improve capacity to transfer water within and between different areas (Anglian Water and Cambridge Water 2022) (Future Fenlands report). However, relative to the overall area of agricultural peatlands, and bearing in mind the other demands on water resources, these plans are unlikely to substantively increase water availability for peatland management at larger scales.

On the other hand, the evidence to show that wetter management of peatlands will increase overall water demand is not strong. An initial analysis of flux tower evapotranspiration data for the Defra LAPTF by UKCEH suggests that annual water loss from areas of natural reedbed (where water losses might best expected to be highest) was similar to that from irrigated vegetable production land; further analysis of this issue is ongoing. Raising water levels during winter, when excess water is available, would not place additional demand on supplies at other times. The challenge, as noted earlier is that most of the abstraction for irrigation occurs during summer, when water is scarce, with only around a third of abstraction occurring in winter.

It is also worth noting that *all* the UK's lowland peatlands formed naturally, as wetlands, under broadly similar climatic conditions to those occurring today. In other words, there would be sufficient water to support peat formation in the absence of human modification of the hydrological system and competing water demands. Indeed, the Fens and other lowland peat areas would rapidly revert to wetlands in the absence of continued pumped drainage; the Future Fens report suggests that most of the lower Ouse catchment would be flooded within a few years if the pumps were switched off. While this is clearly not a desirable outcome, it does illustrate that sufficient water would be available if, instead of pumping excess water out to sea during the winter, it could be stored within the landscape and released when required in summer. The challenge therefore is one of water storage and distribution, not one of overall water availability.

Freeman et al. (2022) reviewed the water management requirements for higher water level management of agricultural peatlands. These include greater storage capacity to retain excess winter water, either by constructing more farm reservoirs or by allowing some areas of land to flood over winter and releasing this water to other areas in summer. These areas could include land managed for paludiculture, or expanded areas of 'washland' (areas adjacent to rivers used to hold floodwaters, which have formed part of the drainage systems of the Fenland and Humberhead peatlands since the 17th century). More sophisticated pumping systems are being developed in some areas, allowing more controlled water management than existing pumps, which can typically only be switched on or off.

Existing ditch networks can be used to move water within the landscape, but may require adaptation to make them suitable for more precise water level control, for example through the creation of smaller water management zones. At the field scale, subsurface drains (which are typically present in fields used for vegetable production) can be used to transfer water from the ditch network into the field, as well as to remove it. Work in the Netherlands and Germany is testing this approach for water level management, including using pressurised drains to 'push' water into the field, but results are currently inconclusive. In general, it will be easier to manage water levels in smaller, flatter fields, as noted above. Areas that can be hydrologically isolated (individual fields, whole farms, or multiple farms) and managed uniformly will be easier to manipulate than multiple hydrologically interconnected areas with different target water levels in different fields. This may be challenging to achieve, particularly where it requires coordination between multiple farms

5. Alternative regenerative land-uses on lowland peat

Manipulating water table depths to near surface levels (0 to 10 cm below the surface) offers the optimal carbon derived greenhouse gas mitigation for lowland peat (C. D. Evans et al. 2021a). Within this range it is likely that CO_2 emissions will be reduced to zero or that (if peat-forming vegetation is present) the system will become a CO_2 sink. Emissions of N_2O are also likely to be close to zero from saturated soils. Although CH_4 emissions can increase as the water table approaches the surface, raising water levels generally has a beneficial overall impact in terms of climate mitigation provided the field does not become continuously flooded (Couwenberg et al. 2011; C. D. Evans et al. 2021a; Tiemeyer et al. 2020). Under optimal water level conditions, peatlands have a long-term cooling impact on the climate, although this will vary to some extent depending on the land use. There is a common perception that re-wetted lowland peatlands can only be managed for conservation, however a growing number of options to managed re-wetted land commercially (e.g. paludiculture and carbon farming) are emerging, which we discuss in section 5.1.

Dynamic water table management practices are key in facilitating these opportunities to maintain higher water levels in the peat. Too wet and CH_4 emissions may outweigh the CO_2 emission reductions associated with wetter soils, too dry and CO_2 emissions may remain high. To support productive use of the land it is also likely that water levels will need to be dropped during periods when travelling on site is required (e.g. harvesting a biomass crop, maintenance work on solar panels). Alternatively, highly specialised machinery has been developed to allow for operational activities on waterlogged soils (mainly in the Netherlands), but farmers are unlikely to invest in these expensive tools due to the high financial risk associated with a complete shift in business model. Nonetheless, implementing paludicluture with these highly specialised machines could further reduce the overall emissions by removing the need to lower the water table and subsequently eliminating the emissions derived from temporarily draining soils.

5.1. High water table farming (‘paludiculture’)

This section draws on the detailed review that assesses the potential for paludiculture in England and Wales (Mulholland et al. 2020b). Paludiculture is loosely defined as the profitable production of wetland crops under waterlogged conditions. Crops that can be cultivated for paludiculture are therefore limited to species that thrive under wetland conditions, which can include crops for bioenergy, food production, and/or construction material.

5.1.1. Biomass crops

The cultivation of biomass crops is widely practiced across the UK, predominantly for the bioenergy market through (1) combustion of dried biomass and/or (2) anaerobic digestion of green material. Despite the long history of reed production for thatch, and other traditional economic uses of wetland biomass, , the concept of cultivating biomass crops for bioenergy under wetland conditions is in its infancy, yet offers substantial emission reductions from peat comparative to conventional cropping on peat. Prospective species identified for paludiculture in the UK include a variety of trees, grasses, sedges, and cattails. Of these the native species *Phragmites australis* (common reed) and *Typha latifolia* (bulrush) have been identified as crops that show the greatest potential for bioenergy use under wetland conditions. An alternative crop with evidence to suggest it can thrive under wetter conditions is the non-native *Miscanthus* (elephant grass) (Silvestri et al. 2017)This has not yet been formally recognised as a potential paludiculture crop on the 'Paludiculture live list', although given that the vast majority of food crop species grown on peat are not native to the UK, there is no intrinsic reason why all commercial paludiculture crops should need to be native, provided that they are non-invasive. Potential biomass offtake and biomass quality is highly variable between crops (Table 5-1) which can largely depend on several factors, such as genotype.

Table 5-1 Ranges of potential biomass production and higher heating value, and some key issues for the potential paludiculture crops. Extracted and adapted from (Mulholland et al. 2020b)

	Phragmites australis	*Typha latifolia*	*Miscanthus*
Potential biomass production (t ha^{-1} yr^{-1})	3.72-12.60	3.58-22.10	12.0-12.47
Energy value (MJ kg^{-1})	16.9-17.7	17.0	18.0-18.8

Although paludiculture offers opportunities to reduce emissions from lowland peat, the cultivation of biomass crops for bioenergy cannot on its own deliver carbon sequestration, because any sequestered carbon is re-mitted when used for energy. This results in a neutral carbon balance (if all the crop biomass is removed from site). If the bioenergy produced is used as a direct substitute for fossil fuel use then the overall impact will be a net reduction in CO_2 emissions, although as the UK energy mix transitions from fossil fuels to renewables this net reduction is becoming smaller. Combining bioenergy production with carbon capture and storage (BECCS) represents a major element of the UK's Net Zero strategy, and could in principle be implemented for biomass crops grown on peat. However, BECCS has yet to be implemented at scale, and if biomass crops for BECCS are to be grown on peat then it is vital that any remaining CO_2 emissions from the cultivated peat are included in the overall carbon calculations. This is not currently the case for anaerobic digestion plants which receive feedstocks such as maize and sugar beet that are grown on drained peat. In this case, the CO_2 emissions from peat oxidation may reduce, negate, or even exceed any putative CO_2 emission savings resulting from the production of biogas. In a biomass production system based on re-wetted peat, however, these offsetting emissions should be greatly reduced, or even reversed if the field becomes a net carbon sink, making paludiculture-based biomass production on peat a much more appealing option from a climate mitigation perspective.

Although bioenergy is the dominant market for biomass crops, there are other traditional and growing markets, including building materials (from traditional thatch to novel products), agricultural conditioners, animal bedding/fodder, medicines/supplements, and raw materials. Using crops for long-lived construction materials has the potential to contribute towards long-term CO_2 storage, such as garden fencing, panelling, and insulation.

5.1.2. Food crops

Opportunities to cultivate food under wetland conditions are highly desirable because they could offer carbon emission reductions without compromising on food production, which is the biggest trade-off associated with other paludiculture opportunities (e.g. biomass crops). Due to the UK's temperate climate, food crops that can be cultivated viably under wetland conditions are limited. Crops with an existing market include celery, water cress and berries (e.g. cranberries) whilst some other crops such as floating sweet grass, nettles, water pepper and meadowsweet have also been suggested but would require development of new supply chains and markets. Rice is one of the most important food crops in the world, and is grown under wetland conditions, but cannot currently be grown successfully in the UK's climate. However paludiculture trials using rice are now being undertaken in other areas of Northern continental Europe, and it is conceivable that some varieties of rice could be grown on peat in the UK under a future climate.

5.1.3. Solar farming

Solar farms are areas of land installed with interconnected photovoltaic panels which harvest solar energy to supply power. At present, solar farms on peat tend to be on drained land, offering little or no mitigation of CO_2 emissions from peat oxidation, but in principle there is no reason why land under solar panels needs to remain drained. The establishment of solar farms on wet peat could offer emission reductions from both supressed peat oxidation and the substitution of non-renewable energy with renewables. In turn, this offers potential income streams from the carbon financing market and energy market where energy is sold, or overall on-farm energy cost savings where energy produced is used on-farm. Finally, solar farms on re-wetted peat could provide the energy requirements to transition UK vegetable production towards sustainable indoor farming systems. If ‘wet solar’ and indoor farming systems were co-located on peat, this would help to address some of the socio-economic barriers to transitioning to new methods of vegetable production, for example by minimising disruption to existing supply chains.

While current renewable incentives are leading to the construction of ‘dry’ solar farms on drained lowland peat, the adoption of solar farming on rewetted peat would require some changes in public incentive schemes, as well as improved water management infrastructure. Implementation of ‘wet solar’ could be encouraged and supported with private carbon finance.

5.1.4. Tree planting

There are a variety of national and regional tree planting schemes with funding opportunities for farmers and land owners (NFU 2022). However, planting on wet peat is limited to species that can tolerate flooding (e.g. willow and alder), and current regulations prevent any trees from being planted on deep peat (despite wet ‘carr’ woodland on fen peat being a rare natural habitat in the UK). A recent decision support framework by DEFRA (2022b) provides guidance for tree planting on lowland peat:

> *“On lowland deep (or shallow/wasted) peat that is currently drained and subject to arable or intensive grazing as a land use, the establishment of wet woodland as native*

> *woodland habitat, or productive woodland under wetland conditions (most likely short rotation coppice as a paludicultural crop) may be appropriate where the water table is raised to protect the peat. Agreement would be required from FC and Natural England."*

Short rotation coppice (SRC) is a bioenergy crop with a growing UK market. SRC uses high-yielding varieties of poplar, alder and/or willow which are harvested on a 2-5 year cycle. In principle SRC production on wet peat is possible, and although yields may be lower than those obtainable on dry soils, this should be balanced against the potential for reduced CO_2 emissions from re-wetted peat. Withy production on peat is a traditional practice, undertaken for centuries, to cultivate willow for thatching, basketmaking, gardening and construction. The Somerset Levels are the only area in the UK that still practices withy production.

5.1.5. Carbon farming

Carbon farming refers to the active management of land to capture and store carbon and/or reduce greenhouse gas emissions at the field/farm level. Similar to some forms of paludiculture, carbon farming involves the cultivation of fast-growing biomass crops, but instead of harvesting the crops for sale they would either be left *in situ* to form new peat, or converted to decomposition-resistant forms of carbon such as biochar to enable long-term carbon storage. From a business model perspective, farmers would be paid to implement land use and/or land management practices that support carbon farming. Funding can come from public funds such as the Common Agricultural Policy, or private sources via supply chains (e.g. price premiums for carbon neutral produce) or the voluntary carbon market (McDonald et al. 2021). The production of biochar from biomass produced on re-wetted peat has the potential to generate energy as a co-product and could, if the biochar is returned to the peat, provide a novel form of bioenergy with carbon capture and storage (BECCS). This concept is being explored currently via the linked UKRI Peatland Greenhouse Gas Removal Demonstrator and DESNZ Reverse Coal projects.

Opportunities for carbon farming on lowland peat are not yet well established. For example, the Peatland Code, a voluntary certification standard to market the climate benefits of carbon farming on peat (IUCN 2022a) only supports peatland restoration projects. The revised version Peatland Code 2.0 was released in 2023, and now includes a procedure for supporting restoration projects on lowland fen peat. In principle this procedure could also be used to support paludiculture or carbon farming (emissions reductions or sequestration) on lowland peat, although use of the Code to support projects that stop short of full restoration remains under discussion. . With emerging funding opportunities like the Peatland Code on lowland peat, there are opportunities for farmers to bring income in from both the commodities being grown (e.g. biomass crops) and carbon credits sold. This will largely depend on funding criteria, but stacking incentives like this (and potentially other benefits of re-wetted land such as flood water storage or nutrient removal by biomass crops) are likely to be more palatable amongst farmers as it offers opportunities to replace lost income associated with stopping or reducing high value cropping on drained peat.

5.2. Integrated farming systems

Integrated farming comprises cropping methods and other agricultural production techniques which fulfil both ecological and economic demands. Given the different opportunities for alternative land uses on peat, as discussed earlier in Section 5.1, there are several farm system combinations that could be classified into an integrated system. For example, combining solar farming with wetter soil management could be classed as solar farming integrated with carbon farming, bringing in revenue from both solar energy and carbon financing markets. Vertical farming, which we discuss below, has also been suggested to potentially improve the economic viability of alternative regenerative land uses when integrated together.

5.2.1. Vertical farms

Vertical farming technologies have been developed to reduce the environmental impacts of agriculture whilst maximising productivity. These systems use multi-layer growing platforms to extend growing seasons and increase yields per unit area of land footprint compared to conventional farming. In the context of lowland peat, powering these systems with on- farm renewables including wetland-based solar, wind or bioenergy production, could see revenue from both carbon financing and the marketable crops grown in the vertical farming facility whilst significantly reducing carbon emissions. It is important to note that because of their high energy requirements it is essential to run these systems on renewable energy sources, as without this their carbon footprint would be much higher than conventional production (Van Gerrewey et al. 2022) . Achieving this will require innovative approaches to reduce their energy requirements, for example maximising on natural light without reliance on artificial lighting, or very little reliance to lengthen light periods when natural light becomes limiting (e.g., through autumn). Currently these technologies are limited to certain crops, typically herbs and leafy greens, where vertical farms have been reported to achieve 80 times the yield per square meter of open-field agriculture (Van Gerrewey et al. 2022). The production of lower-value, higher-volume crops such as root vegetables remains uneconomic at present.

6. Relocating vegetable production off lowland peat

Whilst horticultural crops are grown throughout the UK, commercial production for major supply chains of each vegetable crop type is often heavily concentrated in regional pockets based on soil types and/or grouped due to logistics/production capabilities. The main vegetable crops associated with lowland peat soils are celery, lettuce, brassicas, leeks, and potatoes. Fenland celery is a short-season (winter) crop grown on peaty soils in the East Anglian Fens that has EU geographically protected status. Other crops are also grown as part of vegetable cropping systems on lowland peat soils, e.g., onions, beetroot, but for these crops, production on lowland peat soils accounts for less than a third of the total UK production. Vegetable production systems linked to conventional supply chains are also driven by quality specifications, so that it is not overall crop productivity but rather the production of vegetables within marketable specifications for each supply chain that is critical (Zurek et al. 2020). Hence, for retailers and processors/ manufacturers maintaining sufficient crop production of the right quality (with the specification varying by market) is more important than maintaining overall productivity.

85% of all farmland in the UK is used for grazing, or to produce feed that supports livestock production for meat and dairy (The National Food Strategy 2021). While some areas are unsuitable for crop production, other areas could support cereal or vegetable production. With meat and dairy consumption expected to fall in the coming years as part of a shift to plant-based diets, this raises the possibility of converting some areas of grassland on mineral soil into arable or vegetable production. Moving cereals currently grown on organic soils to mineral soils could also free up some of this land for re-wetting (helping to offset continued emissions from vegetable production on organic soils), permit movement of vegetable production from high-emitting deep peats to lower-emitting wasted peats, or permit vegetable production to occur over larger areas but at a lower intensity (e.g. with dynamic water level management or with vegetables being grown in rotation with crops that require less drainage). . In this section, we will briefly consider the opportunities and constraints associated with the relocation of vegetable production away from lowland peat, with a focus on celery, lettuce, brassicas, leeks, celeriac, and potatoes.

6.1. Key factors determining location suitability for relocation of vegetable production from lowland peat

Land suitability is a function of both crop requirements and land characteristics. 'Suitability is a measure of how well the qualities of land unit match the requirements of a particular form of land use' (FAO 1976; Van Diepen et al. 1991). In brief, which crops can be grown requires the land/soil characteristics, socio-economics, markets, and infrastructure characteristics to be considered and all influence land evaluation. Therefore, land suitability analysis is an interdisciplinary approach that integrates information from different sources like soil science, crop science, meteorology, social science, economics, and management.

6.1.1. Crop requirements

A summary of the requirements for the most common vegetable crops grown on lowland peats, together with some indications of the characteristics of typical cultivation systems, are summarised in Table 6-1. As discussed earlier some crops perform better than others under higher water table conditions (Wang et al. 2004); these differences are also highlighted where known.

Table 6-1The most common vegetable crops grown on lowland peats with an indicative summary of crop requirements together with indications of the characteristics of typical cultivation systems. Where crops are highlighted in green suggests there is some positive evidence to suggest crops can be part of a wetter cropping rotation, amber for negative evidence and blue requires further research.

Crop	**Nutrient requirement**	**Water requirement**	**Tillage intensity**	**Tolerance of water table at <40 cm**	**Other system characteristics**
Celery	Moderate	Moderate/ high	Moderate	Good	Transplanted Modified tillage for self-blanching varieties
Lettuce	Low/ moderate	High	Low/ moderate	Good	Transplanted Extended season cropping currently used Variety choice has big impact on management and market value. Some salad leaf production has moved to vertical farming systems
Summer brassicas e.g. broccoli, kale, cabbage, cauliflower	High	Low/ moderate	Moderate / high	Moderate but increased disease risk	Transplanted
Winter brassicas e.g. cabbage, cauliflower, sprouts	Very high	Low/ moderate	High	Moderate but increased disease risk	Transplanted
Leeks	Moderate	Low/ moderate	Low to high	Moderate	Transplanted Big difference between short-season

					summer production and winter leeks
Celeriac	Moderate/ high	Moderate/ high	High	Not known	Transplanted
Potatoes and other root crops	Moderate/ high	Moderate/ high	High/ very high	Poor	Tuber crops (potatoes), or transplants. Ridging/bed forming needed. Destoning on some soils.

Nutrients. The Nutrient Management Guide (RB209) Section 6 provides advice based on UK trials for vegetable and bulb crops (AHDB 2021) shows a range of nutrient uptake requirements for vegetable crops (summarised in Table 6-1). The high nitrogen mineralisation potential on soils of >10% organic matter (organic soils) and peaty soils (> 20% organic matter) is also highlighted in the Nutrient Management Guide (2021) which then reduces the required N fertiliser application to 30-50% of the rate recommended on mineral soils. Note that this ‘free’ nitrogen is a result of peat oxidation, and therefore intrinsically linked to CO_2 emissions and to the depletion of soil organic matter stocks. A range of factors including crop, soil type and previous rotational history affect the actual differential in the recommendations.

Water. Irrigation is used to supplement rainfall for many vegetable crops, especially in the South and East of England. An adequate water supply is essential to support both quality and productivity; water requirements differ between crops (summarised in Table 6-1). Most irrigation water is abstracted from surface water (52%) and ground water (41%) sources with the remainder from public water supply, ponds, and harvested rainwater (7%; (J. W. Knox et al. 2020a)). Abstraction is seasonal, with two thirds typically occurring in the summer. The remaining a third is abstracted during the winter months when river flows are high, then stored in farm reservoirs for use in the summer. Irrigation is often targeted to establish transplants, but crops such as celery, lettuce, leeks, courgettes, onions, and radish respond to irrigation throughout the season where significant soil moisture deficits occur (DEFRA/ADAS 2003). Peat and peaty loam (i.e. wasted peat) soils are considered to have a high soil water availability compared with most mineral soils; fine sandy/ silt loam soils may also have high water availability (DEFRA/ADAS 2003). This means that irrigation requirements (water and associated energy for pumping etc) are often lower on lowland peat soils compared with the same crop grown on mineral soils.

Climate change projections identify that the south and east of England will become increasingly arid (J. Knox et al. 2010) which will further stretch irrigation capacity. However, these changes will also mean that some crops will be able to be grown further north, west and at higher altitudes where water availability will also be higher. Research suggests that the response to increased temperatures is likely to be positive for many field vegetable crops, though salad and calabrese crops may suffer (Collier et al. 2008). Changes in climate will also affect a range of other factors including the range and severity of pest and disease attacks.

Tillage. As discussed earlier, tillage for vegetable crops is often intensive and repeated in-season and may include de-stoning, bed-forming etc. alongside primary tillage operations. However, there are differences in the number of tillage operations and their required depth and intensity for different crops (Table x). Good soil structure is essential to optimise both nutrient and water use efficiency, hence any reductions in tillage intensity in vegetable systems need to be implemented carefully to reduce the risk of yield loss.

6.1.2. Fit with arable (combinable crop) rotations

Field vegetable crops are agronomically distinctive both from combinable crops (cereals, oilseeds, pulses) and often also from each other. Consequently, grower specialisation with a single grower renting land for production from other farm businesses has often replaced small-scale production across diverse farms. This has allowed for the development of, and investment in, specialist planting and harvesting machinery, together with consolidation of processing and marketing capacity (see section 6.1.3). These changes have increased both overall production and labour productivity. Labour constraints are driving further intensification through mechanisation e.g. robotic harvesting (e.g. (Birrell et al. 2020)). These farming models (not peat specific) can lead to large-scale monoculture farming practices which can cause increased risks to pests and disease. Therefore, relocation of vegetable crops from lowland peat soils (or to new locations on mineral soils) is most likely to be met by expansion of the rented land base used by specialist growers who would then drop into arable rotations managed by others. Whilst it is accepted that there is a finite availability of quality land with the infrastructure required for growing vegetables, this land base cannot be identified and quantified easily.

Vegetable crops can provide a spring break crop opportunity for arable crop rotations. However the number of economically viable arable break crops has been reducing, in part due to the loss of active ingredients for pest, disease and weed control. Rotational fit is often complex, with the timing of sowing and harvesting disrupting production of several adjacent crops or affecting the amount / type of cover cropping options. Weed control is a key issue in many crop rotations, and the use of herbicides with long residual effects in the crop rotation can impair growth and development of many vegetable crops (e.g. (O'Sullivan et al. 1999)). Therefore, integration of vegetable crops in arable rotations may also limit the weed control options within the remainder of the rotation. The higher tillage intensity associated with vegetable crops compared with most arable crops means that vegetables are often considered to be a 'poor fit' within regenerative cropping systems, except at small-scale for local markets, and hence land availability in the right rotational context is likely to be constrained. More work is needed both to develop soil-improving practices for vegetables (as discussed above) and also to limit soil-damaging practices which are often associated with late harvests of vegetable crops in cold wet conditions (see https://www.cfeonline.org.uk/environmental-management/soil-health-initiative-managing-soils-for-a-sustainable-future-in-field-vegetables/).

6.1.3. Market / economic factors

Global competition in the fruit and vegetable market for access to the shelves of major retailers is fierce. There are three main determinants of competitiveness in this sector, which are similar to those operating in the supply chains of major processors/ food manufacturers. Only one of these relates to matching production with the physical and climatic conditions of the area to maintain low production costs. The other determinants are efficient and centralised marketing, together with optimisation of logistics to reduce losses during handling and transport. In UK commercial vegetable production, marketing and logistics are now highly centralised, as this enables production to meet the requirements of the centralised purchase platforms of large-scale retailers (De Roest et al. 2018). However, connection to local markets and marketing channels can also support smaller and more diversified farming systems, as discussed for the non-commercial sector above.

6.2. Evaluating the trade-offs for relocating vegetable production

There are limited data available to assess the impacts of relocating vegetable production from lowland peat soils. However, it is very likely that production of the same vegetable crops on mineral soils will markedly increase requirements for nitrogen fertiliser (or organic amendments, see Table 6-2 -Nitrogen application requirements for different crops. Extracted from RB209 Nutrient Management Guide *(AHDB 2020) assuming mineral soils have a soil N supply indices of 1 and 2 and peat soils 5 and 6 for areas cultivating with an excess winter rainfall <150mm (generally located in the east of England)*.) and water (including energy for irrigation) compared with the equivalent cropping systems on lowland peat. As noted above, however, lower N fertiliser requirements in peat soils are the result of organic matter oxidation due to drainage, and are therefore associated with high CO_2 emissions and inherently unsustainable.

Table 6-2 -Nitrogen application requirements for different crops. Extracted from RB209 Nutrient Management Guide (AHDB 2020) assuming mineral soils have a soil N supply indices of 1 and 2 and peat soils 5 and 6 for areas cultivating with an excess winter rainfall <150mm (generally located in the east of England). Application rates may vary depending on specific crop variations and sowing/planting times.

Crop type	N recommendation kg N ha^{-1}	
	Mineral soil	Peat soil
Lettuce	160-180	30-75
Bulb onions	110-120	0
Radish	80-90	0-20
Sugar beet	80-100	0-40
Oilseed rape	160-190	0-40
Wheat	120-240	0-80

Some other environmental impacts of vegetable production systems on mineral soils is also expected to be higher than the cereals /grassland production displaced. However, as long as direct CO_2 emissions from drained peat are reduced or due to higher water tables as a result of relocation, then there is still likely to be a significant net benefit of relocating production for GHG emissions. These benefits accrue whenever drained peat under any land use (including cereal or grassland production) is rewetted (as discussed above). Therefore, alongside consideration of relocation of vegetable cropping systems, a full consideration of the opportunities for higher water table cropping systems (e.g., for celery, summer lettuce, summer leeks and summer brassicas, potentially grown in rotation with paludiculture crops) should be carried out.

Vegetable crop production often has larger workforce number requirements than the alternative crops that might substitute them on peat soils. Although the veg production workforce relies on migrant labour there may still be significant socio-economic impacts which will be context dependent. Similarly, if the crops are grown in different areas then food processing plants may need to be moved or replaced with new smaller facilities. Alternatively, food may need to be transported further to and from existing facilities. All these will likely have a negative impact that will off-set some of the benefits of moving vegetable crop production from being grown on peat.

Despite this, there are opportunities to decentralise and diversify the vegetable supply system without any major threat to the supermarket supply chain. This includes urban and peri-urban production models where perishable high value crops (e.g., lettuce) are grown in urban areas whilst rural areas continue to cultivate the bulkier crops (e.g., broccoli on peat, The Landworkers Alliance and Growing Communities, 2022). This can be achieved at different scales from community gardens through to vertical farming, we discuss how green spaces in urban areas offer opportunities for horticultural production in section 6.3.

6.3. Role of non-commercial growers

Allotments and community gardens across the UK already support a network of committed and knowledgeable gardeners and provide a significant fruit and vegetable production outside the commercial market. Because of the scale of production in these systems, fresh fruit and vegetables tend to be sold or consumed locally, outside conventional supply chains, and these activities are also recognised to have added health and social benefits for individuals and the community. DEFRA (2017) estimated that 7% of the nation's fruits and vegetables by value were produced during the Dig for Victory campaign in World War II through non-commercial production e.g. production in allotments, parks, gardens. Edmondson et al. (2020) showed that allotment growing is as productive as commercial vegetable systems and that 1.5% of the land area within a city (Leicester, UK) could provide sufficient fresh fruit and vegetables to meet the needs of 2.6% of the city's population. Walsh et al. (2022) also assessed the potential availability of urban green spaces across Great Britain, largely private residential gardens, and amenity spaces, and then modelled their potential horticultural productivity. This study showed that urban green spaces, at their upper limit, have the capacity to support production that is 8× greater than current domestic production of fruit and vegetables. However, Walsh et al. (2022) also recognised that these estimates do not account for significant challenges relating to production inefficiencies, availability of labour and potential public health issues relating to historic soil contamination. Increasing vegetable production in allotments, private gardens and in small-scale market gardens may help to offset any reduction in vegetable production that results from relocation of vegetable production away from lowland peat, especially for direct consumption, local restaurants, and retail. However, to meet the demands of existing commercial supply chains, major (and costly) changes would be required to address the logistical challenges of bringing together products from many small suppliers to meet market demands for volume and quality.

7. Lowland peat restoration – challenges and opportunities

7.1. Where to restore peat and where to keep farming? A peat condition metric approach.

The Land Use Policies for a Net Zero UK report (Committee on Climate Change UK 2020a) developed a scenario involving restoration of at least 50% of upland and 25% of lowland peat by 2050 in order to achieve net zero. Subsequently, the ‘Balanced Net Zero’ scenario for the Agriculture and land use, land use change and forestry in the UK’s Sixth Carbon Budget (Committee on Climate Change UK 2020b) set out more stringent targets. These include the full restoration or stabilisation of upland peat by 2045, together with rewetting or implementing sustainable management on 75% of lowland cropland and rewetting 50% of lowland peat grassland by 2050. Defra’s Lowland Agricultural Peat Task Force has sought to identify the policies, incentives, infrastructure investments and evidence requirements to deliver change at the required scale, whilst maintaining viable farm businesses and food production. As part of the proposed incentives, it is envisaged that the new Environmental Land Management Scheme for England (where most cultivated lowland peat is located) will compensate farmers for implementing sustainable management measures on peat, ranging from raised water tables or irrigation in cropland to paludiculture and re-wetting (DEFRA 2023). As outlined by ‘The opportunities of agri-carbon markets’ report by Green Alliance Financing mechanisms such as the UK Peatland Code (IUCN 2022b), as well as a number of independent schemes, are seeking to facilitate private investment in peatland management for climate change mitigation via the sale of carbon credits, or via the 'insetting' of emissions reductions or CO_2 removals within business operations and supply chains. These approaches are not necessarily exclusive, and indeed a combination of public and private finance may be needed to deliver large-scale change within these highly profitable, intensively managed, and important food-producing landscapes.

Despite the high level of ambition set out in the Sixth Carbon Budget, rewetting or implementing sustainable management on 75% of lowland cropland could have major implications for rural economies and the UK's food supply, with a risk that the environmental costs of food production, including greenhouse gas emissions, are simply transferred overseas. On the other hand, a strategic combination of restoration, technological innovation, and the reconfiguring of production systems, building on the land sparing and sharing concepts, could achieve a combination of food security, biodiversity, and climate change mitigation benefits. A decision making tool is likely to be required to optimise decision-making within this complex landscape, and to help identify those areas where restoration may be appropriate. The tool will need to have a strong empirical evidence base to ensure that land-management decisions are appropriate for local environmental and societal conditions, and that anticipated outcomes can be delivered. Rigorous monitoring, reporting and verification (MRV) systems will also be needed. These tools should be co-developed and refined with all the major lowland peat stakeholders, including vegetable farmers. Below we identify the key conditions that would need to be explored; we note that they are not limited to the conditions discussed below.

7.2. Peat depth

Peat depth determines the remaining amount of carbon that could potentially be lost under continued drained conditions; the deeper the remaining peat, the more carbon is available and therefore susceptible to peat oxidation, which is likely to result in larger and more sustained overall carbon losses. Conversely, the remaining peat depth also determines the amount of carbon available for preservation (and therefore the amount of emissions reduction that could be achieved) if water tables were to be raised. Note that the present-day peat depth will, for most if not all cultivated peatlands, be lower than the original peat depth, as a result of historic drainage and soil loss. As a result, it should not be treated as an upper limit on the potential carbon stock of the system, which could potentially be increased through restoration or active ‘carbon farming’ – although at natural rates of peat formation it would take centuries or even millennia to return the peat to its original depth.

While opportunities for new carbon capture exist, from the perspective of climate change mitigation within cropped peatlands, the first priority is to reduce or (if possible) halt ongoing emissions. In this context, it would therefore be most effective to target deeper peats (where the amount of carbon still at risk of loss is highest) for protection by raising water levels, for example via restoration or paludiculture. However, lowland areas with drained deep peat are also among the highest-value cropping systems, and are disproportionately used for horticulture, meaning that the vegetable supply chain would be compromised unless it were relocated. On this account there are ongoing debates between stakeholders as to whether it is appropriate to prioritise deeper peats for restoration, considering that cultivated deep peat soils generally have the smallest energy requirement for crop nutrition and cultivation (e.g. fertiliser and irrigation requirements) compared to most other agricultural soils (Tzilivakis et al. 2005). However, in the long term continued farming on deep peat is not sustainable from a food security perspective, since the peat will deplete gradually until it loses its fertility and capacity to deliver high-yielding vegetable crops without increased inputs. In addition, deep peat production areas tend to comprise smaller (and flatter, or laser-levelled) fields, with a high level of water level control such as subsurface drains, making these areas relatively conducive to higher water level management

While deep peat clearly represents a high priority for restoration or mitigation measures, this does not mean that areas of shallower peat and areas of ‘wasted’ peat (i.e. peat which has been reduced in depth to less than 40 cm, sometimes termed skirt soils) should be ignored. Recent measurements indicate that these areas remain important sources of CO_2 emissions and can retain a large soil carbon stock which remains vulnerable to oxidation. These areas typically have lower (although still high) agricultural value and are more often used for cereal production. They nevertheless remain important for vegetable production as part of mixed rotations, as is evident from the maps presented earlier. Shallower peatlands are often more heterogeneous than deeper peats, with larger fields containing more variable soils and topography, making optimised water level management difficult. With remaining peat depths often shallower than the plough depth, raising water levels to the point at which they would meaningfully reduce the amount of peat exposed to oxidation may not be possible to combine with ongoing crop production.

In these areas irrigation or other forms of soil moisture protection such as mulching may offer alternative mitigation options.

Alternatively, these shallower peatlands may offer opportunities for restoration, protecting the remaining carbon stock and potentially supporting new peat formation and CO_2 sequestration (along with biodiversity gains and other benefits such as water storage and flood regulation). In principle, peat formation can be initiated in any hydrologically and topographically appropriate location (including bare ground, such as former sand and gravel extraction sites) so peat restoration is not necessarily restricted to areas of deep peat, and the potential for net carbon gain may even be higher in site which have historically seen the greatest carbon loss. Given their typically lower agricultural value compared to deep peats, skirt soils may even offer larger net benefits in terms of carbon and other gains, once the lower opportunity costs of halting or reducing production have been taken into account. Nevertheless, restoring such areas (and indeed all agriculturally utilised lowland peat) represents a major challenge, and best practices for restoring their carbon and greenhouse gas function through restoration have not yet been fully developed or tested.

Finally, there is some risk that the impact of future climate change could limit the capacity of restored lowland peatlands to support peat formation (Gallego-Sala et al. 2010). However, there is strong evidence that a wet peatland (regardless of location) is less vulnerable to climate change than a drained one, and therefore any measures which raised water tables in peatlands should be expected to increase climate change resilience. At worst, the restoration of both shallow peat and deep peat should help to prevent remaining carbon stocks being lost (thereby reducing emissions form current very high values), even if they do not promote active peat growth and carbon accumulation.

7.3. Water availability

Water availability is essential for lowland peat restoration, the challenges associated with water availability across lowland peat landscapes is discussed in 4.4.

7.4. What can restoration achieve?

A study that quantified restoration success on 320 rewetted fen peatlands across temperate Europe found that 40% of the vegetation and 80% of the hydrology at rewetted sites resembled the same composition or functioning of a typical near-natural peatland (Kreyling et al. 2021). However, the rewetting of previously drained fen peatlands generally induces the establishment of tall, graminoid wetland species such as *Typha latifolia* or *Phalaris arundinacea* which has negative implications on overall biodiversity (vegetation) and ecosystem functioning (hydrology, geochemistry; Kreyling et al., 2021). While rewetting reduces carbon emissions by inhibiting peat decomposition the total carbon balance achieved will largely depend on a number of factors such as, the former land use prior to restoration and plant communities established, similarly this applies to the biodiversity benefits. The carbon balance on peat is extremely sensitive to extreme weather events, which are predicted to occur more often, which could hinder successful restoration where climate change mitigation is the main objective. There are however some studies showing that rewetted peatlands can act as a carbon sink despite extended dry and hot periods (Beyer et al. 2021; Schwieger et al. 2021).

8. Stakeholder perspectives – workshop report

A workshop led by Jennifer Rhymes aimed to identify the barriers to and opportunities for regenerative vegetable production on lowland peat. A wide range of conventional and regenerative farming practices/procedures that aim to improve on-farm sustainability were discussed amongst stakeholders, with a particular focus on soil carbon (e.g. minimising soil carbon losses and reducing greenhouse gas emissions). This included discussions on reduced tillage practices all the way through to high water table and vertical farming. The purpose of the workshop was to facilitate discussions, identify which practices should be considered regenerative and how effective and practical they are (soil health, yields, etc.). The workshop was held at Baston Village Hall, Peterborough PE6 9PA on the 13th of June. The workshop was opened with a 10 minute presentation from Jennifer Rhymes on the background to the triple challenge context on lowland peat, to deliver food security, maintain/restore biodiversity and mitigate climate change, which was followed up with various discussions and activities. We report the findings below.

8.1. What is grown on lowland peat and associated soils?

Farmers and growers at the workshop (and subsequently at the Fenland SOIL farmers' dialogue event) mapped the crops grown to the soils they have on farm (Table 1). All the growers present were large-scale vegetable growers where a large proportion of the vegetables produced entered the supermarket or food service supply chain. Hence small-scale production (e.g. veg. boxes, market gardens) are not specifically covered by these notes. All farmers identified that more than one soil type was present on their farm or across their rented land-base.

Table 8-1 Farmer glossary for soils in lowland peat (developed in the East Anglian Fens as part of a Cambridgeshire and Peterborough Combined Authority – funded project, 2021) with mapping of crops grown on the different soils. Where no crops are listed, this indicates that this soil type was not found within the land base of the growers consulted here.

	Clay	**Sand**	**Silt**	**Chalk**	**Gravel**
Deep (partly) fibrous peat over 50% OM (handles a bit like a traditional growbag) >1m (water table still in peat), may be Bear's Muck present, over …	**Deep black fibrous over clay (1)**	**Deep black fibrous over sand (2)**	**Deep black fibrous over silt (3)**	**Deep black fibrous over chalk (4)**	**Deep black fibrous over gravel (5)**
	Carrots, celery, green beans, lettuce, maize, radish, onions, potatoes, turf, wheat.	Turf.			
Deep humified (sooty) peat may be over more fibrous layers > 1m (water table in peat), over 50% OM, surface blows easily when dry, over…	**Deep sooty black over clay (6)**	**Deep sooty black over sand (7)**	**Deep sooty black over silt (8)**	**Deep sooty black over chalk (9)**	**Deep sooty black over gravel (10)**
	Celery, leek, lettuce, radish, onions, potatoes, wheat.				
Humified (light/sooty peat) 0.4 - 1m over … (some mineral material mixed into peat, peat below plough depth, but drains, if present, are in mineral material)	**Light black over clay (11); also mix with roddens.**	**Light black over sand or gravel (12)**	**Light black over silt (13)**	**Light black over chalk (14)**	**As 12**
	Green beans, maize, millet, onions, oilseed rape, peas, potatoes, sugar beet, wheat, barley.	Celery, leek, lettuce, radish, onions, potatoes, wheat.			
With clay, when mixed in, giving structure to the peat (in contrast to 11)	**Medium black over clay (15)**				
	Beans (combinable), oilseed rape, potatoes, wheat.				
Mixed black (mineral and peat mixed) or very shallow peat layer (organo-mineral soil); drains in mineral material	**Heavy peat (16); also mix with roddens**	**Black sand (17)**	**Black silt (18)**	**Chalky black (19)**	**Gravelly black (20)**
	Salad (summer cropping only), beans (combinable),	Lettuce, turf.			Onions, potatoes, sugar beet, wheat.

	maize, oilseed rape, wheat, barley.				
Rodden (also rodhams)	**Clay roddens (21)**		**Roddens - mainly silt (22)**		
			Onions		
Mineral soils	**Heavy clay soils (23)**	**Sandy loam (24)**	**Silty soils (25)**	**Mineral over chalk (26)**	**Gravelly soils (27)**
	Beans (combinable), oilseed rape, peas, sunflowers, wheat, barley.	Onions, maize, potatoes, wheat.		Onions.	
	Disturbed soils - post-copralite mining (28)	**Pure sand (29)**		**White over black (30) - chalk and shells over peat**	
		Onions.		Lettuce, maize, brassicas, wheat.	
Mineral soils associated with watercourses	**Old river bed - clay (31)**	**Old river deposits - fine black sand (32)**			
		Old river bank - sandy loam over clay (33)			
		Grassland – Countryside stewardship.			
	Drain cleanings - commonly strips, deposition over many years (34)	**Old shorelines; stone lines - narrow strips at zero a.o.d (35)**			

8.2. What does regenerative farming mean for vegetable production systems?

Break out groups discussed what regenerative farming meant to them, the following general points were highlighted;

- Soil-focussed – protecting, not depleting any of the chemical, physical, biological aspects
- Using cover crops and overwintered stubbles
- Crop rotation
- System not single crop focus
- Improves biodiversity
- ‘Superhero approach’ – improving, not depleting.

Groups then discussed each of the main regenerative principles in the context of vegetable production and identified examples from practice, where possible.

Reducing tillage intensity

- All growers should be seeking to reduce compaction.
- Reducing tillage intensity will reduce soil disturbance and reduce diesel costs as well as reducing carbon loss.
- Min. till and no-till approaches are well developed for combinable crops
- But in cracking soils, the direct drill didn’t work well. Need some light tillage so seeds were held in finer topsoil later to germinate.
- Soil impacts are not just in tillage but in harvest too, especially for root crops.
- Machinery costs are very high –purchasing a single machine that can work well for all crops/ soils is impossible.
- There are zero-till potato trials being carried out at 1-2 hectare scales. This might be possible
- We are a long way from zero-till for bulb crops
- Grower experience is that no plough radish does not grow happily

- Where seeds are very small, then a fine seedbed has been important – but seed tape may provide an approach that can work in a wider range of seedbed conditions
- More options for transplanted crops
- Strip tillage reduces overall intensity
- Peas before potatoes has proved to be effective in improving soil condition (tilth created naturally through roots) so that tillage intensity can be reduced.
- Spring crops are often established in single pass system following an overwinter cover crop; but the cover crop may have needed a tillage operation to support its establishment.
- Tillage impacts are soil and season dependent
- Tillage is an important cultural control tool for weeds – so reduced tillage intensity might mean more herbicide use.

Creating continuous cover (mulching, cover crops)

- This is a central regen. principle – hard core.
- Cover is important in soils at risk of erosion through wind or rain – this is a big problem in peat soils.
- Range of cover crops available but limited information on what species to use / nor use in certain situations
- Mustard grown as a preceding cover crop has been shown to have a negative impact on radish crops
- Impacts of cover as a food for soil borne pests e.g. wireworm is important; sometimes periods of bare ground are important as part of a non-chemical pest control strategy.
- Some species have negative impacts on grazing animals – but not always easy to find the information.
- The most difficult thing is often how to destroy the cover crop to create a good seed bed.
- In Canada, growing willow on unproductive land and cut and spread as a mulch on cropped land. Can also grow willow as hedges /windbreaks – then cut after three years and spread.

Integrated pest and weed management strategies

- Starts with careful crop rotation design
- Risk management approach – for fungicides and insecticides
- Integrating cultural controls with targeted chemical use
- Physical barriers e.g. mesh (cabbage root fly)
- Mechanical weeding
- Spot weeding
- Band spraying
- Less well developed for weeds
- Residual herbicides often don't work well on peat soils, so more contact herbicides are needed.
- Wet areas of the field often show less effective herbicide use.
- Timing of herbicide use is therefore more crucial on peaty soils.
- Crop density can be used to try and out compete weeds
- Tillage is an important part of weed control

Optimising nutrient supply (feeding soil and crop)

- Focussed data collection e.g. soil sampling, tissue testing, to support crop nutrition
- Vegetable production systems have high outputs hence need relatively high inputs to balance nutrient export
- These are high value crops so an approach that focusses on minimising financial risk is likely to over-fertilise (unless this has been shown to have negative impacts on quality) to avoid losing a marketable crop at present.
- Organic sources may be limited by supply chain rules
- Green manures are an option but practically difficult and limited effective guidance for practice
- Inorganic fertilisers (especially N) acidify the soil and might reduce microbial activity
- Where cover crops are used they can help to mop up nutrients and keep them within the system

- Where transition to drip irrigation has occurred, this is most often coupled with fertigation to gain best value from investment. This allows targeted crop nutrition – bacterial additions also made via drip.
- Fertigation gives high crop nutrient use efficiency compared to soil application
- For peat (and associated) soils) RB209 is of limited value. Mn and Mg seem to lock up quickly on peat soils, P and K are locked up on black soils over clay. Farmers knowledge of nutrient interactions is key – but more information could be targeted by soil types.
- Feeding the plant directly through foliar applications can give a quick solution. But not all nutrients can be supplied effectively in this way.

Optimising water use (irrigation management)

- For all soils, irrigation should be based on measurements of soil moisture and careful scheduling
- Increasing use of soil moisture probes, but need to make sure information is robust.
- Some soils will not need irrigation for some crops e.g. potatoes on deep silts
- A small number of sites/soils can be irrigated sub-surface – a significant part of fen land will be at least partly irrigated in this way. This is very efficient as direct evaporation losses are zero.
- Boom and sprinkler systems are both more efficient than rain guns, drip systems are even more efficient.
- Drip systems are a higher investment (£15000 per ha versus £700 per ha for boom)
- Drip systems are more vulnerable to wildlife (pecking etc)
- Irrigation may be used to reduce wind erosion in susceptible soils e.g. peats especially where ground cover is low e.g. early season leeks
- Flooding can be used as part of an IPM strategy e.g. flooding as part of PCN control
- On peat soil, bearing capacity for machines is reduced very quickly as they wet up.

8.2.1. Constraints to adoption of regenerative practices in vegetable production on lowland peatland

- Crops not in ground for long with fast turn-around times; multiple-cropping in season can lead to more soil disturbance compared with combinable cropping systems even if reduced disturbance practices are used.
- Need to find homes for crops with short-term impacts within long-term restoring rotations to support consumer demand without blacklisting crops or soils.
- Supply chain and customer quality demands lead to high waste; if we reduced this waste then cropping intensity could be lowered.
- Timing of demands – every one asks for the crop today (or on a specific date) whatever the weather
- Supply chain penalties for failure to supply mean practices need to be risk minimising – unfortunately most regenerative approaches increase variability
- Winter cover crops can over-dry soil for the following vegetables meaning more irrigation (seasonal water balance in the east of the UK is a constraint)
- Wet ground in winter when harvests are required can lead to more soil damage (this is a problem everywhere but more so in the west and north of the UK and on medium/heavy soils)
- Different crops can need different water table levels at the same time.
- Control of water table levels is usually at IDB not field scale. IDBs are focussed on managing flood risk – would be good if they had a wider remit with regard to water levels but legally constrained.
- Landowner / tenant interactions keys – often specialist vegetable production is part of a larger rotation and the two are not well integrated
- Climate – weather patterns are irregular and not easily predicted, so the best plans can be disrupted leading to short-term degenerative practices
- Machinery we need is not available or too costly

- Communications within supply chain, but also landlord/tenant – need to be able o discuss not just now but consequences of actions and factor those in better.

8.2.2. Opportunities that might make transition to regenerative practices easier

- Trials/research to show whether conventional crops can be grown at high water levels
- Payments for delivering a healthier environment
- Biodiversity net gain
- Support to change towards more efficient irrigation methods
- Support for greater collaboration
- Some practices will reduce input costs e.g. fuel
- Development of equipment /technology
- Work to support development of practical approaches on farm to better target pesticides/ herbicides
- Supply chain and consumer education – allowing more 'blemishes', occasional gaps in supply to protect soils
- More storage so harvest timings can be better matched with best weather not demand
- Work to allow all parties to weigh up the risks for both the short and longer-term to inform decision-making.

8.3. What does not work if we have higher water tables on peat soils?

We were reminded of the challenge and the 'sweet spot' in terms of the minimisation of GHG emissions on peat soils i.e. maintaining the water table at a depth of 10cm.

It was noted by the groups that achieving this high water table in practice would be very difficult with current systems. Drainage systems would need to be updated across the landscape to allow for water table manipulation, which would be very high cost. Land would also need to be level and/or the trade-offs within a high water table area of having some areas with flooding and some with much lower water tables would need to be considered.

Setting, this practical challenge aside, groups then considered what the impacts would be for current vegetable production systems if this high water table were to be implemented.

Travelling – a tractor would make a huge mess

- Drones
- Designated drive ways – floating / concrete
- Manipulation of water table in season so dropping water table for establishment and harvest as a minimum
- Lighter tractors
- Robotics might allow more lighter machines to deliver operations
- Permanent structures e.g. gantry systems
- New harvesting techniques/machinery

Crop limitations

- No vegetable crops identified as well suited to high water tables – but research should be done to see if there are crops / varieties that might work better than others
    - Identify crops that need to be moved off peat
- Breeding might generate new crops / varieties if this was a target
    - Change root architecture and moisture tolerance
- Could learning from hydroponics be applied at field scale?
- Issues establishing crops
    - Use of plant tape systems
    - Raised beds (but this moves soils)
    - May need to raise plants and transplant e.g. onion sets instead of seeds
        - Adds cost
        - Growing media issues
    - Temporary lowering of water table / controlling water table
- Some crops may be unsuitable e.g. with tap roots and tubers
- Challenges for managing crop nutrition
- Issues to be addressed in terms of water quality – risk of pollution but also release of toxic elements under anaerobic conditions

- Need to look for new / adapted crops perhaps for the bioeconomy
    - Rice
    - Reeds
    - Grasses
    - Hemp
    - Bull rushes
    - Shallow rooted crops
    - Substitutions (i.e. similar crops but better adapted)

Water management

- More water storage needed – farm reservoirs?
- Increased pumping requirements
- Where will energy come from – solar, wind, hydro needs to be considered alongside.
- Needs improved drainage infrastructure
- Water leaving the farm would need to be treated before return to the main surface water system

The groups then discussed what was needed in both the short- and longer-term (e.g. research, new technology) to address these blocks to vegetable production on lowland peat soils.

- Trials in lowland peat environments to see what is possible and practical
- Machinery development
- Crop breeding
- Processing capability and market development for new crops
- Conversations and collaborative working between IDBs and water companies to take an integrated approach to water management
- Better understanding of the costs at farm, IDB and wider landscape-scale
- New water management infrastructure

8.4. What about alternative regenerative land-uses on lowland peat?

We recognised that if there were areas where it were no longer possible to grow vegetable crops due to raising of water tables then this could have a variety of implications in terms of new land uses for the lowland peat soils and also to maintain vegetable production elsewhere. Attendees looked at the range of alternatives proposed and then annotated the sheets to identify opportunities/ strengths as well as barriers/weaknesses (Table 2).

Table 8-2 Comments on alternative land-uses for lowland peat soils and alternative to maintain vegetable production if it were no longer possible to grow veg on higher WT peat soils

	Opportunities /strengths	Barriers / weaknesses
For lowland peat soils		
Paludiculture (new wetland-adapted crops)	• Grown correctly will reduce GHG emissions • Can tap into existing markets – thatching, clothing	• May not be a market for easiest crops to implement • Machinery issues may be same as for veg • Limited agronomic and practical growing knowledge • Unknown economics – high risk, unknown reward
Biomass / bioenergy crops	• Carbon sequestration • Displacement of fossil fuels • Energy security	• Machinery issues may be same as for veg • Inefficient energy production
Renewable energy e.g. solar	• Could we combine crops and solar • Clean energy	• Potential drainage issues • Soil structure damage during construction
Tree planting	• Increased biodiversity • New habitat creation • Restoration of carr woodland	• Not sure this is best in terms of biodiversity gain and/or overall ecosystem services • Can dry peat • Trees unstable in peat – wind blow • Cost • Lack of knowledge for lowland peats
High water table, high nature value	• Carbon sequestration • Increased biodiversity • Habitat restoration • Carbon finance or biodiversity net gain funding • Ecotourism	• Major social change • What duration? • Who pays?
To maintain vegetable production		

Expand production on mineral soils	We have experience/ knowledge Range of crops could be grown	Lower yields so more land required Displaces other food production Is there enough suitable land in the UK? More imports needed – so impacts on land, water overseas May reduce diversity of crops that can be grown Water availability – crops will need irrigation N fertiliser use likely to be higher – impact on GHG emissions.
Vertical and other non-soil production	Flexible High yield per m^2 Controlled environment Well suited to biocontrol High resource use efficiency Year round Easier automation Can include wide diversity including aquaculture	Energy efficiency? Photon energy efficiency? Not suitable for large crops – e.g. cabbages? Not suitable for commodity crops e.g. potatoes High set up cost Public perception not yet tested

8.5. What might this look like across the landscape?

We used a snapshot of a small IDB showing maps of a realistic but imaginary bit of lowland peat landscape with background information on drainage (difficult to drain, average, well-drained), peat depth (deep peat, shallow peat, skirt fen, silt) and land productivity (high, average, poor). The maps were developed by Megan Hudson for Fenland SOIL and were used with permission, consequently these are not reproduced here. The break out groups were asked to consider how they might deliver the triple challenge within this landscape.

Separately the groups identified the same areas

1. To create wetland and block drains - deep peat, low productivity, water table change has low impact on surrounding areas.
2. To develop a conservation focussed / rewilding area e.g. carr woodland – shallow peat with silt roddens, low productivity, water table change has low impact on surrounding areas.
3. To improve biodiversity e.g. through high diversity grassland mixes (bees and seeds) – other low productivity areas with average to well-drained skirt soils

This would have reduced food production on 20-25% of the area, but given the targeting to low productivity areas it is likely to have reduced overall productivity by 10-15%. The groups recognised that before any actions were taken more information would be needed about:

- Historic environment
- Land ownership
- Any pollution risk from the disused industrial site

Both groups began by looking at low productivity areas. Although this is a relative term and overall productivity may be higher here than in other landscapes, the groups recognised the additional value of delivery on objectives beyond food production, especially reducing net GHG emissions. Further modelling would be needed to determine the % reduction compared to the current land use baseline.

The next focus would be the average productivity areas on deep peat which may be able to support wetter cropping (whether veg, bioenergy or bioeconomy crops).

It may be necessary to include development of a reservoir within the IDB to support the active water table management proposed.

Both groups considered hat vertical farming approaches should be located close to the markets for products – within cities and/or industrial areas.

9. Land sparing and land sharing model pathways to address restoration targets across lowland peat landscapes

There is often a polarised debate as to whether land sparing (high-yield, conventionally intensified agriculture on a smaller footprint of land) or land-sharing (low-yield, environmentally friendly agriculture on a larger footprint of land) are the best approaches to deliver sustainable food security across the agricultural sector (Bennett 2017; Grass et al. 2021). However, these approaches do not have to be mutually exclusive as both promote the multifunctionality of agricultural landscapes. It has been argued that a combined approach is more effective as land-sharing promotes ecosystem services in agricultural settings, subsequently delivering sustainable agriculture, whilst setting land aside through land-sparing approaches is crucial for the conservation of species that are not compatible with agriculture (Grass et al. 2021).

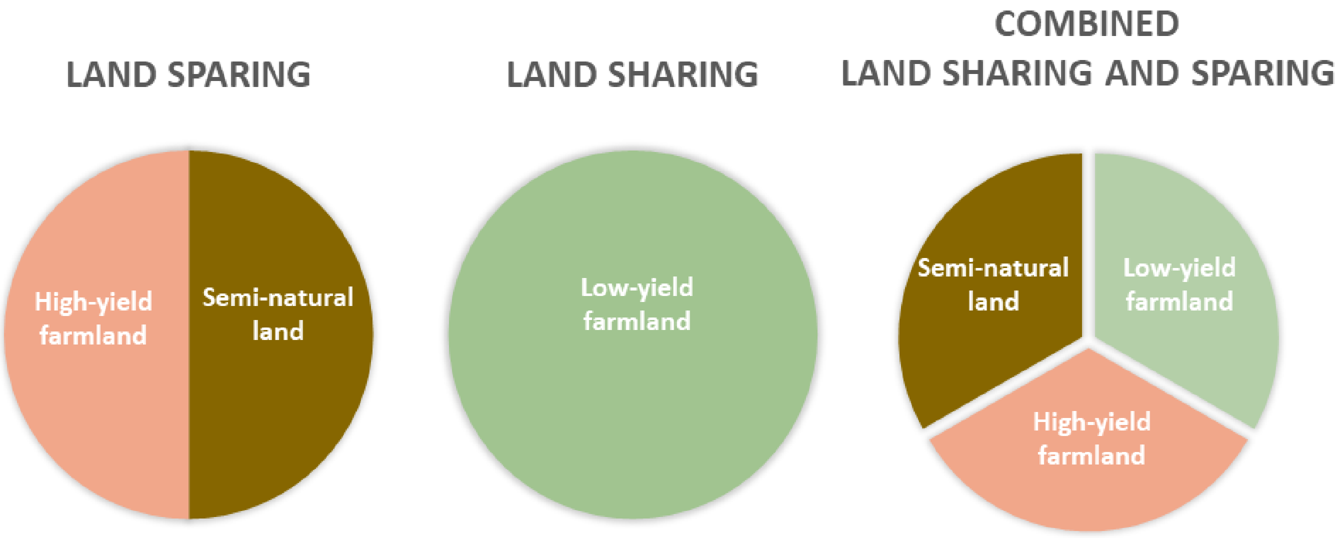


Figure 9-1 What land sparing, land sharing and a combined approach looks like. Extracted and modified from from the 2021 Natural Food Strategy – The Plan report.

This combined approach would create a mosaic of different landscapes: land under conservation, low intensity farmland and higher intensity farmland. Across peatland landscapes, this could include options discussed in sections 5 to 7, such as regenerative vegetable farming combined with water management, wetland restoration and other land-uses. We illustrate a hypothetical landscape that combines the land sharing and sparing concept in Figure 9-2, which would include the relocation of some vegetable production away from peaty soils (relocation is not depicted in Figure 9-2). Note that areas with the potential for land use change will be constrained by peat depth and water availability as discussed in section 7.

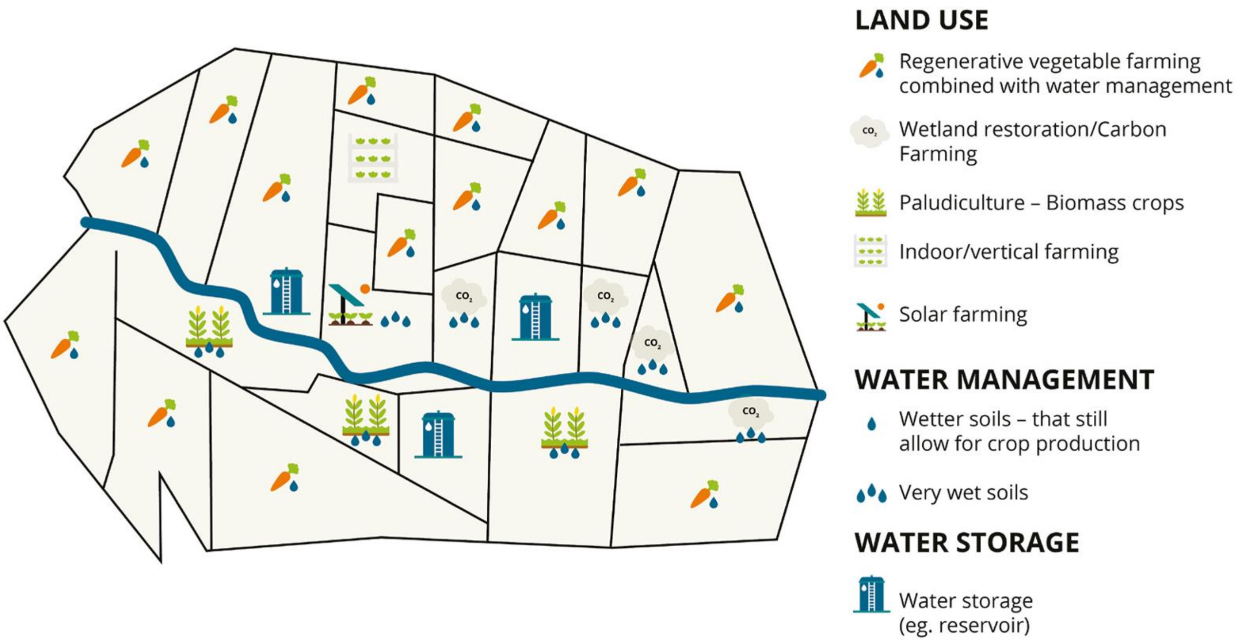


Figure 9-2 What land sparing, land sharing and a combined approach might look like across a lowland peat landscape. Extracted from from the 2022 Vegetable Production on Lowland peat booklet (Rhymes et al. 2022)*.*

The Land Use Policies for a Net Zero UK report (Committee on Climate Change UK 2020a) suggested a need to restore at least 25% of lowland peat by 2050 and apply some form of mitigation to a further 50%, in order to achieve net zero. We draw on the land sparing and land sharing concepts to explore three potential pathways to meet the CCC’s restoration and mitigation targets. Here we will assess how effective each pathway might be at reducing carbon emissions and maintaining vegetable production. These pathways include;

Pathway 1. Continued vegetable production on peat – Intensifying production on a smaller land area footprint, implementing wetter farming practices on all deep peat and restoring 25% of the land area.

Pathway 2. Relocating vegetable production away from lowland peat to free up 25% of land for restoration, whilst also implementing wetter farming practices on all deep peat.

Pathway 3. A combined approach

The effectiveness of each pathway for reducing GHG emissions was modelled relative to a current emissions baseline. We also evaluated the extent to which vegetable production would need to increase through higher yields on remaining peat areas if it were not to be displaced (Pathway 1 and 3 only).

9.1. Pathway modelling methods

Areas for vegetables, cereals and grass grown on wasted and deep lowland peat soils in England were taken from UKCEH crop maps, using the average land area from 2015-2021 (methods described in section 2-1). Baseline emissions for these areas were calculated using 'business as usual' emissions factors for cropland (vegetables and cereals) and grassland on both deep and wasted peat (Table 9-1; Evans et al., 2021b). Livestock emissions were calculated and included for total emissions on grass by calculating the average GHG emission rates per animal type in 2016 based on work by Rothamsted Research for the CCC Net Zero analysis in 2018 (Thomson et al. 2018). These total emissions were then converted into rates per livestock unit, averaged for dairy, beef and sheep, and multiplied by the average livestock unit (0.58) for grazing on lowlands (Natural England 2009). Emissions from fertiliser applications were not included.

Table 9-1 Emission factors (combined CO_2, CH_4 and N_2O expressed as tonnes CO_2 equivalent per hectare per year) used to calculate emissions for each pathway scenario. Emission factors are based on Evans et al. (2021b).

	Land use	Water table depth (cm)	Peat type	Emission Factor $t\ CO_2e\ ha^{-1}\ yr^{-1}$
Business as usual	Cropland	90	Wasted	20.9
			Deep	45.5
	Grassland	50	Wasted	16.8
			Deep	21.7
Wetter Farming	Cropland	45	Wasted	21.0
			Deep	23.5
	Grassland	25	Wasted	10.0
			Deep	10.0
Rewetted fen		0	Wasted	3.19
			Deep	3.19

Emissions for each pathway scenario were then calculated based on projected changes to land use. All scenarios assumed that 25% of the total lowland peat area were to be rewetted to meet the 25% lowland peat restoration target outlined by the Land Use Policies for Net Zero (Committee on Climate Change UK 2020a); here the rewetted fen emission factors were used (Table 9-1). Emissions from land in vegetable, cereal and grass production were calculated similarly to the baseline calculations except it was assumed that wetter farming was practiced for all land uses on deep peat, where water table depths halved for each land use (see wetter farming – Table 9-1). Each of the pathways and their assumptions are described below in Table 9-2.

Table 9-2 Pathway descriptions to meet the 25% rewetting CCC's restoration targets.

Pathway	**Meeting rewetting targets**	**Delivering productivity shortfall**
1 A	A proportional 25% of each land use (grass, cereal and veg) on each soil type (deep v wasted) is restored to rewetted fen. Wetter farming* is implemented on remaining areas of deep peat in veg, cereal and grass.	Productivity shortfall made up by increasing yields on the remaining land.
1 B	Deep peat is prioritised for rewetting, where grass, cereal and veg on deep peat are proportionally taken out of production to meet the 25% rewetting target. Wetter farming* is implemented on remaining areas of deep peat in veg, cereal and grass.	Productivity shortfall is made up by increasing yields on the remaining land.
2 A	A proportional 25% of each land use (grass, cereal and veg) on each soil type (deep v wasted) is restored to rewetted fen.	Productivity shortfall made up by moving production onto mineral soil.

	Wetter farming* is implemented on remaining areas of deep peat in veg, cereal and grass.	
2 B	Deep peat is prioritised for rewetting, where grass, cereal and veg on deep peat are proportionally taken out of production to meet the 25% rewetting target. Wetter farming* is implemented on remaining areas of deep peat in veg, cereal and grass.	Productivity shortfall is made up by moving production onto mineral soil.
2 C	All cereal production on deep peat is displaced onto mineral soil and freed for rewetting. The shortfall in land required to meet the 25% rewetting target is proportionally displaced across veg and grass on deep peat. Wetter farming* is implemented on remaining areas of deep peat in veg, cereal and grass.	The shortfall in veg production on deep peat is met by relocating this veg production onto land in cereal on wasted peat, where the cereal shortfall on wasted peat is displaced onto mineral soils. The remaining veg, grass and cereal shortfall is made up by moving production onto mineral soil.
3	All cereal production on deep peat is displaced onto mineral soil and freed for rewetting. The shortfall in land required to meet the 25% rewetting target is proportionally displaced across veg and grass on deep peat. Wetter farming* is implemented on remaining areas of deep peat in veg, cereal and grass.	The shortfall in veg production on deep peat is met by relocating this veg production onto land in cereal on wasted peat, where the cereal shortfall on wasted peat is displaced onto mineral soils. Any remaining veg, grass and cereal shortfall is made up by moving production onto mineral soil and increasing yield on peat by 10%.

*Wetter farming – Water table depth management changes from -90 cm to -45 cm for cropland and -50 cm to -25cm for grassland.

9.1.1. Additional emission calculations

Here we describe the methods used to calculate emissions from yield increases on peat and any cultivation displacement made onto mineral soils for veg, cereal and/or grass.

Where pathways involve increasing yields on peat (pathway 1 and 3 only) emissions associated with additional fertiliser required to meet these yields were accounted for, however emissions for standard fertiliser applications were not. We describe this in detail below;

Additional Fertiliser: Emissions associated with increasing yields on lowland peat were calculated as the additional fertiliser requirements needed to meet yield increases. For example, to support a 10% yield increase it was assumed that 10% of standard fertiliser applications rates were required, where we only accounted for the additional fertiliser requirements. Fertiliser application values were based on the "Fertiliser use on farm crops for crop year 2020" report from The British survey of fertiliser practice (DEFRA 2021c). An average value for vegetable crops was calculated from the values for Potatoes (main crop) and Vegetables (other) from Table GB4.2. An average value for cereal crops was calculated from the values for Spring Wheat, Winter Wheat, Spring Barley, Winter Barley, Oats and Rye/Triticale/Durum wheat from Table GB4.1. The equation and emission factor for calculating emissions were taken from the Tier 1 approach in the 2006 IPCC Guidelines (Eggleston et al., 2006; Equation 11.1, Table 11.1). Emissions from fertiliser use occur on an annual basis.

Where pathways involve displacing production onto mineral soil and changing land uses on existing mineral soil (pathway 2 and 3), these emissions were calculated as differences between the original and new land use. These emission differences were subsequently applied to the vegetable and cereal production total. Land use changes off peat assume that mineral soil in grass is converted into arable to meet vegetable and/or cereal production shortfalls. This was not possible for grass, this is therefore defined as a shortfall in grass production. Emission estimations included;

Land Use Change (LUC) Soil Carbon: The value for the average change in soil carbon stock between grassland and cropland for England was taken from the "UK Greenhouse Gas Inventory, 1990 to 2020" report Annexes ('UK Greenhouse Gas Inventory 1990-2020: Annexes' 2022), Table A 3.4.5. Here, it was assumed that this change occurs over 20 years, with the difference in stocks divided by 20 to give the average value per year over the 20 years.

Land Use Change Direct N_2O: Direct N_2O emissions associated with land use change were calculated using IPCC Tier 1 method (Eggleston et al., 2006; Equation 11.1)). Results are given as the average value per year over first 20 years since land use change.

Non-Forest biomass: Emissions due to the change in carbon in biomass (above- and below-ground) were calculated using biomass stock factors from the *UK Greenhouse Gas Inventory 1990-2020: Annexes* report, Table A 3.4.12 for the value for cropland and Table A 3.4.14 for the value for non-shrubby grassland (based on values for improved pasture). Note that there was a higher biomass carbon content in cropland (5 tC/ha) compared to grassland (2.8 tC/ha), as the value corresponds to the equilibrium biomass carbon stock during the year. This emission/sequestration occurs in the first year of the land use change only.

Indirect N_2O: Leaching of nitrate associated with land use change, and subsequent 'indirect' N_2O emissions via its denitrification in watercourses, was calculated using the IPCC Tier 1 method (Equation 11.10 in the IPCC 2006 Guidelines). Result are given as the average value per year over first 20 years since land use change.

Cropland management soils: Changes in carbon stocks in soils due to the management of cropland are calculated using Equation 2.25 in the IPCC 2006 Guidelines, with stock change factors used in the 1990-2020 LULUCF inventory. We assume that the cropland is managed under Full till and High inputs, and that the changes occur over a 20-year period (the result are therefore the average value per year over the first 20 years).

Grassland management: In cases where grass on peat is displaced onto mineral soil, it is assumed that there are no resulting carbon stock changes as there is no change in grassland management.

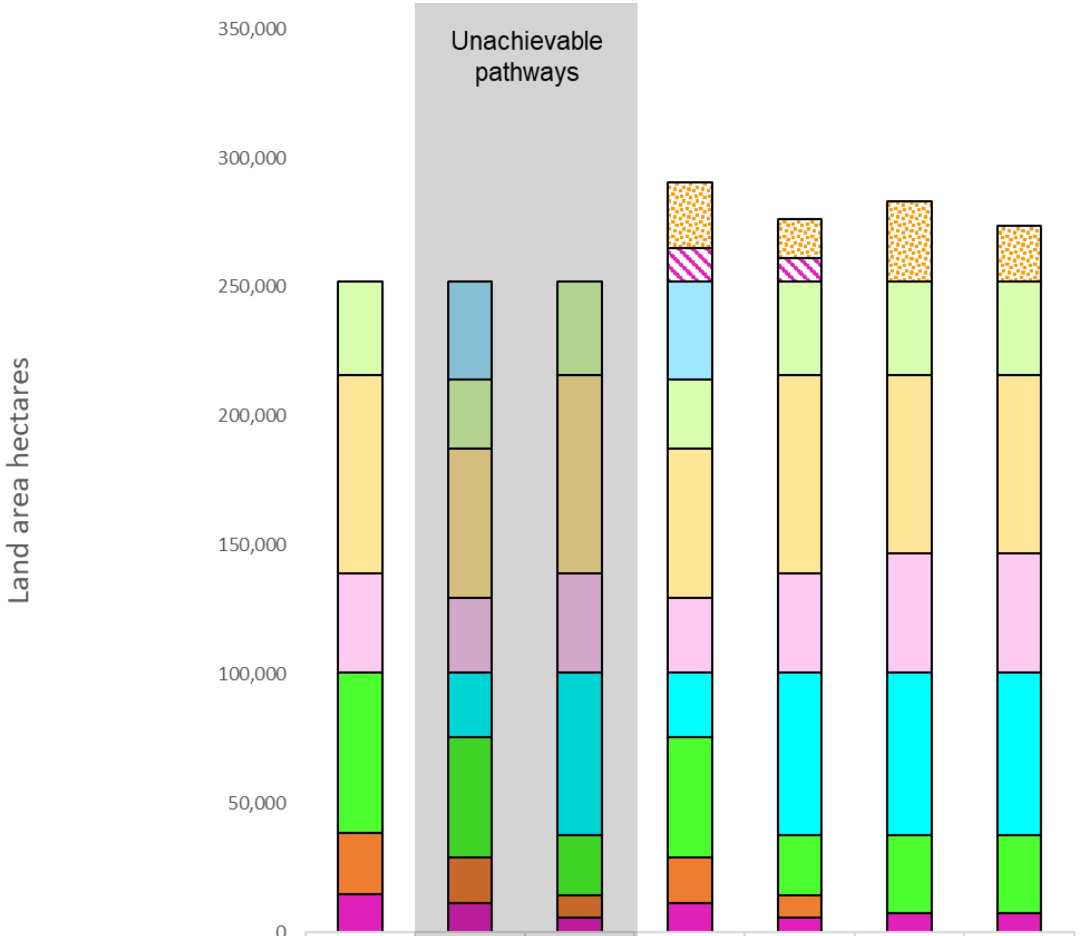
Fertiliser: Emissions associated with fertiliser use are calculated for crops moved to mineral soil, using values of N fertiliser application from the report "Fertiliser use on farm crops for crop year 2020" from The British survey of fertiliser practice (DEFRA 2021c). An average value for vegetable crops was calculated from the values for Potatoes (main crop) and Vegetables (other) from Table GB4.2. An average value for cereal crops was calculated from the values for Spring Wheat, Winter Wheat, Spring Barley, Winter Barley, Oats and Rye/Triticale/Durum wheat from Table GB4.1. The equation and emission factor for calculating emissions were taken from the Tier 1 approach in the 2006 IPCC Guidelines

(Eggleston et al., 2006; Equation 11.1, Table 11.1). Emissions from fertiliser use occur on an annual basis.

IPCC guidelines can be found at https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html. The emissions factors used for mineral soils reflect those used in the 1990-2020 LULUCF inventory. The results shown give the emissions in the first year following the land use change, in the same way as organic soil emissions.

9.2. Pathway analysis results

Land use change pathways on agricultural lowland peat that meet the 25% lowland peat restoration target (Committee on Climate Change UK 2020a) are illustrated in Figure 9-3. In order to free land up for rewetting, it is necessary to take some areas of lowland peat out of cultivation. The resulting shortfall in crop production then needs to be replaced by yield increases on the remaining peat land in cultivation, by displacing production onto mineral soils, or by a combination of the two. Our results show that pathways which attempt to meet this shortfall solely through yield increases on peat (pathway 1A and 1B) are unrealistic, because of the unachievable yield increases that would be required for veg, cereal and grass (Table 9-3; up to 66% for grass production for pathway 1B). This implies that realistic pathways to restore 25% of lowland peat while maintaining food production will need to combine achievable yield increases with the displacement of some production onto mineral soils, such as pathway 3. However, given that 26% of fruit and veg and 14% of cereal go to waste at the farm-gate globally (WWF, 2021), opportunities to reduce this waste could contribute towards improving yield requirements without displacing production. This could include reducing waste through improved crop disease management, reduced harvesting damage and greater on-farm processing. Retailers could also play a role here, in cases where crops are wasted simply because they do not meet cosmetic or other expectations.



	Baseline	1A	1B	2A	2B	2C	3
Mineral New Cereal	0	0	0	25,173	14,753	31,305	21,913
Mineral New Veg	0	0	0	13,303	9,411	0	0
Wasted Peat Rewetted	0	37,773	0	37,773	0	0	0
Wasted Peat Grass	35,881	26,911	35,881	26,911	35,881	35,881	35,881
Wasted Peat Cereal	77,067	57,800	77,067	57,800	77,067	69,387	69,387
Wasted Peat Veg	38,142	28,606	38,142	28,606	38,142	45,822	45,822
Deep Peat Rewetted	0	25,216	62,989	25,216	62,989	62,989	62,989
Deep Peat Grass	62,169	46,627	23,345	46,627	23,345	30,485	30,485
Deep Peat Cereal	23,624	17,718	8,871	17,718	8,871	0	0
Deep Peat Veg	15,071	11,303	5,659	11,303	5,659	7,390	7,390

Figure 9-3 Areas of lowland peat and (where relevant) mineral soils, in hectares, that are rewetted or are in vegetable, cereal or grass cultivation, for different land use change pathway scenarios. Peat areas are classified as either 'deep' (> 40 cm, i.e. 'peat according to the English soil classification) or 'wasted (< 40 cm of peat remaining as a result of long-term peat wastage)

Table 9-3 Percentage yield increase requirements to meet current supply for each land use pathway, partitioned by vegetables, cereals, and grass cultivation on peat. Percentages in red denote unobtainable yield increases.

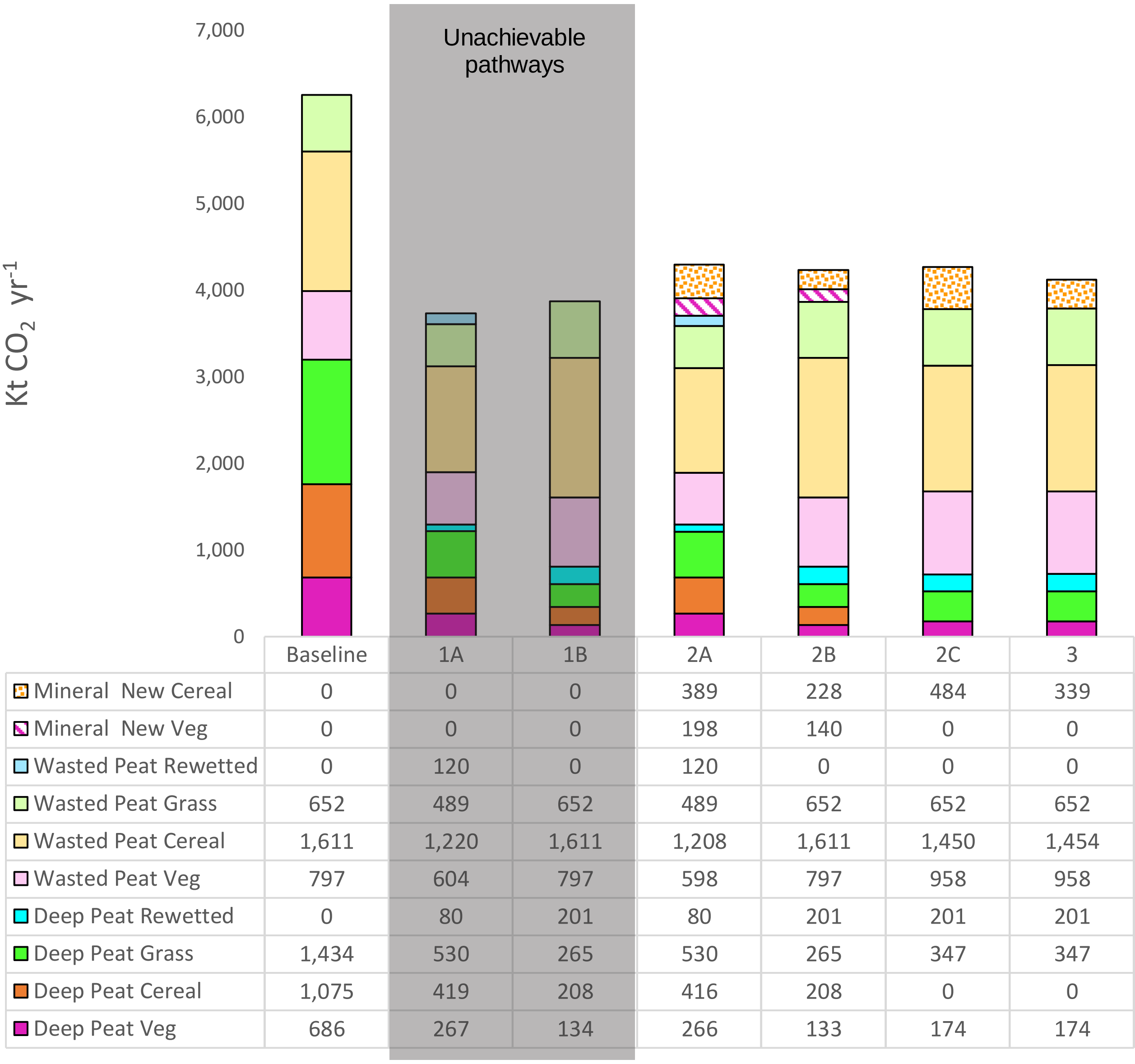
Yield increase requirements	Baseline	1A	1B	2A	2B	2C	3
Veg	0%	33%	21%	0%	0%	0%	0%
Cereal	0%	33%	17%	0%	0%	0%	10%
Grass	0%	33%	66%	0%	0%	0%	10%

Calculated GHG emissions from each land use pathway scenario and potential emission reductions are illustrated in Figure 9-4. As described above, all of the pathways meet the CCC's target of 25% re-wetting of lowland peat, and on average they would deliver an emissions reduction of 2,168 Kt CO_2 yr^{-1} relative to the current baseline. The largest difference in emissions between pathways is 565 Kt CO_2 yr^{-1}, between Pathways 1A (lowest) and 2A (highest). The largest overall emissions reductions were delivered by rewetting 25% of deep lowland peat and implementing wetter farming practices on deep peat areas in agriculture, including veg, cereal and grass cultivation.

Although wetter management practices (restoration and wetter farming) offer the highest emission reductions, further emission reductions can be achieved through land use change. These reductions vary depending on the original land-use (e.g., from grass to rewetted versus cereal to rewetted); the type of soil allocated to land-use change (deep versus wasted peat) and the proportion of crops that are displaced from peat to mineral soils. Because pathways 1A and 1B require unachievable yield increase requirements we exclude them from our final pathway comparisons, particularly as the proportional increase in fertiliser application rates modelled (based on yield increase requirements, Table 9-3) would never be implemented due to fertiliser application regulations, cost, and losses to leaching. Of the 'plausible' pathways (2A, 2B, 2C and 3), pathway 3 offers the highest emission reductions. This pathway takes a combined 'land sparing' and 'land sharing' approach (Figure 9-3) to meet the 25% rewetting target; deep peat is prioritised for rewetting, vegetable supply is maintained by replacing some cereal production on peat, and the resulting cereal and grass production shortfall is made up by a combination of relatively achievable 10% yield increases on remaining areas on peat, and some displacement of cereal production onto mineral soils.

Pathway 3 offers higher emission reductions than all variations of pathway 2 9Figure 9-4) because emissions associated with 10% yield increases are small compared to emissions linked to displacement according to the methodology applied. However, it should be noted that complete displacement of vegetable production to mineral soils would offer much higher emissions reductions potential, because veg grown on mineral soils is only associated with 0.01 t CO_2e ha^{-1} yr^{-1}, compared to 45.5 t CO_2e ha^{-1} yr^{-1} when grown on deeply drained deep peat. Barriers to such a large-scale displacement of vegetable production to mineral soils are associated with other factors such as higher input and operating costs, as discussed in section 6.

It is also important to note that this analysis does not explore the longer-term implications of land-use change. Wetter farming practices on peat would reduce rates of soil carbon loss but are unlikely to halt it entirely (and hence most of the peat carbon stock will be lost eventually) whereas effective re-wetting has the potential to stabilise or even enhance the peat carbon stock. The longer-term benefits of re-wetting would be greatest for deeper peats because they have more soil carbon left to lose than wasted peat.



	Baseline	1A	1B	2A	2B	2C	3
▨ Mineral New Cereal	0	0	0	389	228	484	339
▨ Mineral New Veg	0	0	0	198	140	0	0
☐ Wasted Peat Rewetted	0	120	0	120	0	0	0
☐ Wasted Peat Grass	652	489	652	489	652	652	652
☐ Wasted Peat Cereal	1,611	1,220	1,611	1,208	1,611	1,450	1,454
☐ Wasted Peat Veg	797	604	797	598	797	958	958
■ Deep Peat Rewetted	0	80	201	80	201	201	201
🟩 Deep Peat Grass	1,434	530	265	530	265	347	347
■ Deep Peat Cereal	1,075	419	208	416	208	0	0
■ Deep Peat Veg	686	267	134	266	133	174	174

Figure 9-4 GHG emissions from a combination of lowland peat under vegetable, cereal or grass cultivation, rewetted former agricultural peatland, and (where relevant) areas of mineral soil converted to arable production to address shortfalls in crop production as a result of lowland peat re-wetting. Pathways and soil classifications as above..

10. Shifting towards plant-based diets

There is increasing evidence to show that plant-based diets can deliver co-benefits for health, climate, and the environment (WWF 2020a) with significant opportunities to reduce GHG emissions. Emission reductions from plant-based diets are achieved by reducing the overall emissions that are sourced from livestock/dairy production, which are generally higher than plant-based commodities (Poore and Nemecek 2018), even when the increase in vegetable production needed for plant-based diets is accounted for. In light of this, there have been various recommendations to reduce the quantity of meat and dairy consumed by the IPCC report on climate change with a set target to reduce the consumption of the most carbon-intensive foods (e.g. beef, lamb and dairy) by at least 35% by 2050 (2019).

It has been reported that the land area used to supply fruit, vegetables, legumes, nuts, seeds, and roots would need to increase by 150% to support an entire UK vegan population (WWF 2020a). Although there will be opportunities to meet the increased vegetable demand by farming vegetables on mineral soils (see Section Relocating vegetable production off lowland peat) there are risks for vegetable production to expand further on lowland peat, particularly as peat offers the potential to supply increased demand without substantial infrastructure investment to support vegetable production. This could potentially jeopardise lowland peat restoration targets and more importantly the overall emission reduction potential associated with plant-based diets, given that vegetable production on lowland peat has higher emissions per ha than any other land use in the UK. Considering this, we explored the implications of different diet scenarios on UK lowland peat land use by assuming that the change in land area requirements to support diet scenarios would be implemented without any consideration for meeting the 25% lowland peat rewetting target (Committee on Climate Change UK 2020a). This exercise will demonstrate whether the 25% rewetting target can be met under these scenarios and highlight the implications this might have on emissions from lowland peat areas.

10.1. Diet scenario modelling methodology

Diet scenarios were taken from the WWF (2020a) report - Bending the Curve: The Restorative Power of Planet-Based Diets”, which included the UK’s current, NDG (National Dietary Guideline), EAT-Lancet, Pescatarian, Vegetarian and Vegan diets. The report provides the area of land in the UK that is currently used to meet crop demands for the UK’s current diet and land use area requirements for different diet scenarios. Based on this data we calculated the percentage difference in land areas for vegetable, cereal and grass production under different diet scenarios compared to the current diet land area requirements Table 10-1. Here percentage change in area requirements for vegetables were based on the sum of the fruits and vegetables, legumes, nuts and seeds, and roots. The percentage change in area requirement for cereals is the sum of grains and for grass is the sum of dairy and red meat. These areas include areas required for imports (vegetables grown outside of the UK) and areas grown domestically (including areas needed for exports). It was not possible to separate this data into areas needed for domestic produce, imports, and exports, as such, it was assumed that the percentage increase would be equal for domestic produce, imports, and exports. It is also important to note that some vegetables and cereals are likely to be cultivated as feedstock for domestic livestock production, we were unable to differentiate between areas of land used to cultivate crops for human consumption versus feedstock for livestock.

Table 10-1 Proportional percentage of land area requirements compared to the current diet to meet UK vegetable, cereal and grass demands under different diet scenarios, where 100% represents no change in land areas, below 100% represents a reduction and above 100% represents an increase. Percentages were calculated from data published in Bending the Curve: The Restorative Power of Planet-Based Diets WWF (2020a). *This includes land needed to supply crops for imports, exports, and UK consumption.*

	Current Diet	NDG	Eat-Lancet	Pescetarian	Vegetarian	Vegan
Vegetables	100%	113%	193%	199%	222%	250%
Cereals	100%	90%	104%	108%	100%	109%
Grass	100%	83%	23%	14%	14%	0%

We apply this percentage change to the average areas for vegetables, cereals and grass grown on wasted and deep lowland peat soils in England from 2015-2021 (methods described in section 2) to calculate land use change requirements needed for each diet scenario. Land use change allocation took a cascading approach to prioritise any land freed for rewetting onto areas of deep peat. The cascading approach used is as follows:

- In order of priority (until full allocation was met) land increase requirements for vegetable production were allocated to freed land on freed wasted peat in cereal, wasted peat in grass, deep peat in cereal and deep peat in grass.
- In order of priority (until full allocation was met) land increase requirements for cereal production were allocated to freed wasted peat in vegetables, wasted peat in grass, deep peat in vegetables and deep peat in grass.
- All diet scenarios saw a decrease in land area requirements for grass production as such any freed land that was not allocated to vegetable or cereal production was allocated for rewetting.

Baseline emissions for these areas were calculated using the business-as-usual emissions factors for (Evans et al., 2021b) cropland (vegetables and cereals) and grassland on both deep and wasted peat (Table9-1). Livestock emissions were calculated and included for total emissions on grass by calculating the average GHG emission rates per animal type in 2016 based on work by Rothamsted Research for the CCC Net Zero analysis (Thomson et al. 2018), which were then converted into rates per livestock unit, averaged for dairy, beef and sheep and multiplied by the average livestock unit (0.58) for grazing on lowlands (Natural England 2009). Emissions from fertiliser applications were not included in this analysis. It is also important to note that this analysis only accounts for emissions attributed to vegetable, cereal and/or grass production on lowland peat and does not account for any emissions on mineral soils.

10.2. Diet scenarios on lowland peat

Land use changes under different diet scenarios are illustrated in (Figure 10-1) and partitioned by peat depth (deep and wasted) in (Table 10-2). The 25% lowland peat rewetting targets outlined by The Land Use Policies for a Net Zero UK report (Committee on Climate Change UK 2020a) would not be met under any of the land use changes for diet scenarios explored (Table 10-3). The Eat-Lancet and Pescatarian diet freed the highest proportion of lowland peat, 9%, which was closely followed by the national dietary guidelines and vegetarian diet at 8%. The vegan diet only supported 4% of the total lowland peat area for rewetting because of the of the inherently higher area of land required for vegetable production compared to any of the other diet scenarios (Table 10-3).

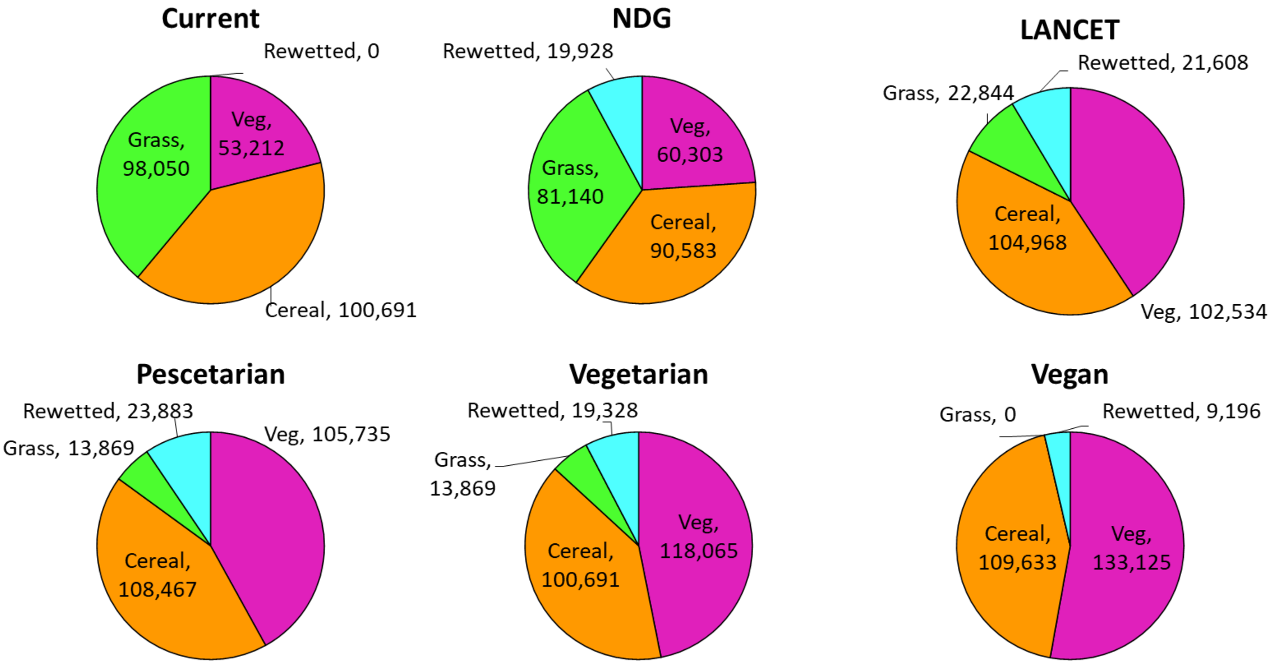


Figure 10-1 Proportion of land area in vegetable, cereal, and grass production under different diet scenarios. Land area annotations are in ha.

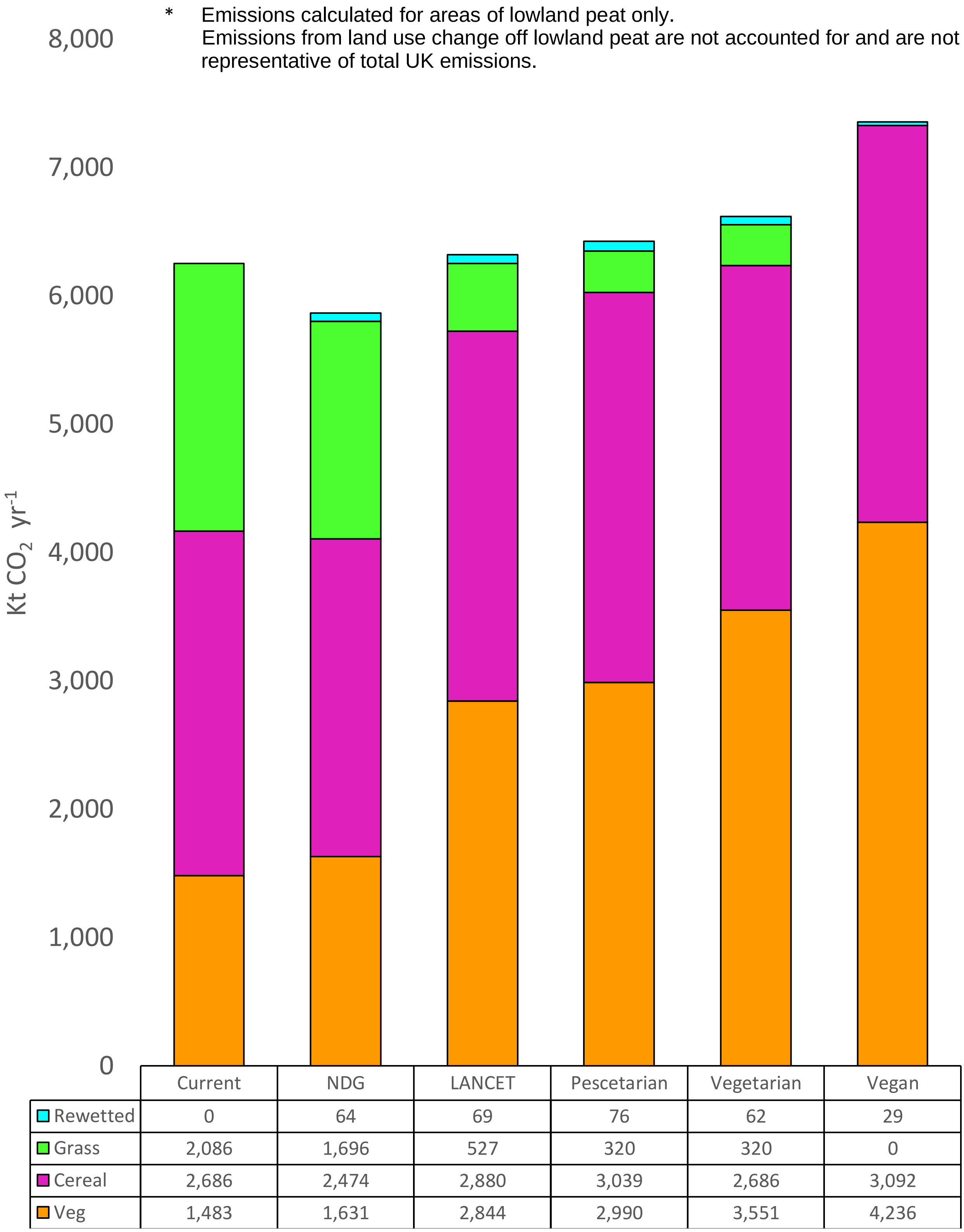
Table 10-2 Land area (ha) for each land use partitioned by deep and wasted peat soils.

		Current	**NDG**	**LANCET**	**Pescetarian**	**Vegetarian**	**Vegan**
Deep peat	Veg	15,071	15,071	28,511	31,712	44,042	59,102
	Cereal	23,624	23,624	27,901	31,400	23,624	32,566
	Grass	62,169	45,259	22,844	13,869	13,869	0
	Rewetted	0	16,910	21,608	23,883	19,328	9,196
Wasted peat	Veg	38,142	45,233	74,023	74,023	74,023	74,023
	Cereal	77,067	66,959	77,067	77,067	77,067	77,067
	Grass	35,881	35,881	0	0	0	0
	Rewetted	0	3,017	0	0	0	0

Table 10-3 Proportion of lowland peat land area rewetted.

	Current Diet	**NDG**	**LANCET**	**Pescetarian**	**Vegetarian**	**Vegan**
Proportion of lowland peat rewetted	0%	8%	9%	9%	8%	4%

With regards to the implications these land use changes have on emissions from lowland peat areas only, the national dietary guidelines was the only diet to support any emission reductions compared to emissions from the current diet scenario. This is because of the higher proportion of land freed for rewetting and higher proportion of land in grass compared to the other diet scenarios, where emissions from cropland on lowland peat are characteristically higher than grasslands (Table 9-1). However, because this analysis does not include changes in emissions from land use changes that occur off peat to support these diet scenarios it is important to note that these results are not representative of the implications each diet would have on the total UK emissions. When considering total UK emissions, the eat-lancet, pescatarian, vegetarian and vegan diet scenarios offer significant emission savings compared to the current and national dietary guideline scenarios (WWF 2020b). Nonetheless, we show the potential negative implications that increased cereal and vegetable production demands could have if production proportionally increased across lowland peat landscapes and highlights how rewetting targets would not be met without appropriate allocation.



* Emissions calculated for areas of lowland peat only.
Emissions from land use change off lowland peat are not accounted for and are not representative of total UK emissions.

	Current	NDG	LANCET	Pescetarian	Vegetarian	Vegan
🟦 Rewetted	0	64	69	76	62	29
🟩 Grass	2,086	1,696	527	320	320	0
🟪 Cereal	2,686	2,474	2,880	3,039	2,686	3,092
🟧 Veg	1,483	1,631	2,844	2,990	3,551	4,236

Figure 10-2 Lowland peat emissions from vegetable, cereal, or grass cultivation under different population diet scenarios.

11. Conclusions and recommendations

Other notes on relocation to consider for conclusions

- *Some vegetable crops are potentially suited to higher water table cropping (@30-40 cm depth) – celery, summer lettuce, summer leeks, summer brassicas.*
- *Higher water table cropping systems will require changes to the cropping system (integration of covers, herbicide management, machinery adaptation); these may increase production cost and may not be economically viable without support for transition.*
- *New crop rotations, including paludiculture crops, will be needed for sustainable vegetable production on lowland peat.*
- *Given that focus is higher water tables on lowland peat (not reducing tillage intensity, cover cropping etc), then relocating potatoes, cereals, sugar beet, winter vegetables from lowland peat should be a priority, as these crops are not tolerant of higher water tables and/or are equally well suited to cultivation on mineral soils.*
- *Expansion of market garden and allotment scale production through new producers and expansion of existing provision to meet local market need (retail and restaurant) is possible, but viability of such systems within commercial vegetable supply chains is unlikely to be achievable.*
- *Displacement of potatoes, winter leeks, brassicas and extended season lettuce production is likely to be met by expansion of provision by existing growers on mineral soils (or by imports). However, the perceived 'poor fit' of such crops within regenerative cropping systems means that land availability in the right rotational context is likely to be constrained. More work is needed both to develop soil-improving practices and to limit soil-damaging practices associated with vegetable production on mineral soils.*
- *Relocating vegetable systems and the integration of vegetable crops into a wider range of arable cropping systems is very significantly constrained by the logistics for specialist planting and harvesting skills and machinery, as well as packhouse locations and availability.*
- *Increased fertiliser and water requirements of vegetable production on mineral soils (including energy for irrigation) compared with cropping systems*

on lowland peat are expected. Impacts of vegetable production compared with cereals /grassland production displaced higher. However, as long as direct emissions from drained peat cease due to relocation then there is a significant net benefit for GHG.

- *Without specifically identifying where vegetable production might be moved to it is not possible to quantify changes in where labour forces and other food production infrastructure and logistics might be located. Vegetable crop production often has larger workforce number requirements than the alternative crops that might substitute them on peat soils. There may well be a significant socio-economic impact if existing workers need to commute or move to a new area. This could lead to deprivation/decline of an existing area, if it remains as farmland, but also put a strain on the area the workforce need to move, including building of new homes and public infrastructure. Similarly, if the crops are grown in a different and potentially less concentrated area then food processing plants may need to be moved or replaced with new smaller facilities. Alternatively, food may need to be transported further to and from existing facilities. All these will likely have a negative impact that will off-set some of the benefits of moving vegetable crop production from being grown on peat.*

11.1. Supermarket recommendations

1) **Collating information on product sourcing and supply chain emissions**. Our assessment confirms that a significant proportion of the overall UK supply of some vegetables comes from drained lowland peat soils. However, beyond the identity of the supplier, there does not appear to be consistent recording of whether vegetables were grown on peat, on mineral soils, or indoors, or of the specific management practices employed. This makes it difficult for supermarkets to determine the embodied emissions of the produce they sell (whether these are associated with peat oxidation or other activities such as fertiliser use, energy use and transportation), or therefore their overall ‘Scope 3’ supply chain emissions. Requiring suppliers to record the location and soil type on which crops were grown would enable a baseline assessment to be made, while providing specific management data might enable more accurate estimates to be

made. In the latter case, this would enable the GHG benefit of mitigation measures such as higher water level management to be quantified.

2) **Explore the benefits and trade-offs of sourcing crops off peat in your supply chains:** As this report has discussed, there may be opportunities to increase arable production elsewhere in the UK on mineral soils or indoors, but considerable care is required to ensure that emissions from peat oxidation are not simply replaced by emissions from fertiliser or energy use, and that this does not lead to major disruption of current supply chains. In general, sourcing more produce from beyond the UK risks simply displacing emissions, as well as increasing transport emissions and reducing UK food security. Some crops identified for sourcing off peat include maize, potatoes, and sugar beet.
3) **Sourcing produce from wetter peat management:** this could form part of the supermarket's overall purchasing strategy to support the type of integrated farm management approaches discussed in the report. For example, a business might internally offset ('inset') emissions from areas of peatland used for vegetable production by releasing other lower-value areas for restoration, paludiculture or 'carbon farming'. Mitigation measures within areas used for vegetable production, such as the implementation of seasonally or annually higher water levels, should also be supported.
4) **Placing a consumer premium on low-carbon produce**: If improved information can be obtained on embodied emissions as described above, this could form the basis for pricing schemes that reward suppliers for reducing their emissions by paying a premium. This could follow a similar approach to organic produce (i.e. consumers can choose to select a lower-carbon product at a higher price) . Such an approach would require an agreed methodology for emissions accounting across the sector, and the implementation of effective monitoring, reporting and verification (MRV) schemes. This will be challenging given the lack of granular data available for peat sourced produce. Efforts to build this capacity with eco-labelling producers should be initiated.
5) **Providing more information on individual products**: In general, public awareness of the emissions associated with food production is low. A scheme which provided simple information on the 'carbon footprint' of products (that does not incorporate emission savings from offsetting),

alongside other information such as locality, seasonality, and nutritional and calorific content, would enable consumers to make more informed purchasing choices. This could involve paying a premium for lower-carbon products, as described above, or choosing completely different products that have lower climate impacts. This scheme would clearly need to extend far beyond vegetables grown on peat, but given the magnitude of emissions from some fresh produce grown on peat this should clearly form part of the overall calculation. This should also reflect temporal variations in emissions to encourage behavioural shifts towards eating produce more seasonally.

6) **Reducing wastage in supply chains**: At present, supermarket contracts typically require suppliers to guarantee a certain level of supply. This can lead to overproduction; for example lettuce producers have to be able to meet weather-dependent peaks in consumer demand (‘barbecue weekends’) that are impossible to predict in advance requiring them to plant up a larger area and discard crops that reach harvestable age when demand is lower. This effectively means that large areas of lowland peat are being drained and cultivated, and generating high GHG emissions, without producing any food that is consumed. Reducing this level of overproduction would require the supermarket sector to accept that demand may outstrip supply at some peak times, which may be unpalatable to consumers. However, recent experiences during Covid-19 and subsequent challenges in global supply chains may have led to greater public acceptance that retailers may not be able to able to provide everything all the time. If the supermarket sector as a whole were to demand less stringent guarantees from suppliers this could have the effect of substantially reducing overall food waste, land demand and resulting emissions, and could also free up some existing cropland on peat for the implementation of emissions reduction or carbon sequestration measures.

7) **Whole chain production costs need to be covered**: Further understanding of the buying and selling prices of produce by incorporating whole business costs across the whole sector is required, this includes the cost of emissions of production, waste and the environmental cost passed onto the consumer and the wider community. This should also include the environmental cost of importing and transporting foods.

8) **Undertake research to further assess the impacts of sourcing from lowland peat and potential consequences of reduction**: looking specifically at how a reduction in sourcing from lowland peat might intersect with retailer ambitions on sustainable diets (i.e. eating more veg), the potential trade implications and flow on effects for human rights and other sustainability issues.

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Appendix 1. Nature and distribution of agriculture on peaty soils split by county boundaries.

Areas identified as agricultural lowland peat (methods described in section 2.1 of the report) were split into regions (Figure A1) by the UK regional boundary map (Office for National Statistics 2020).

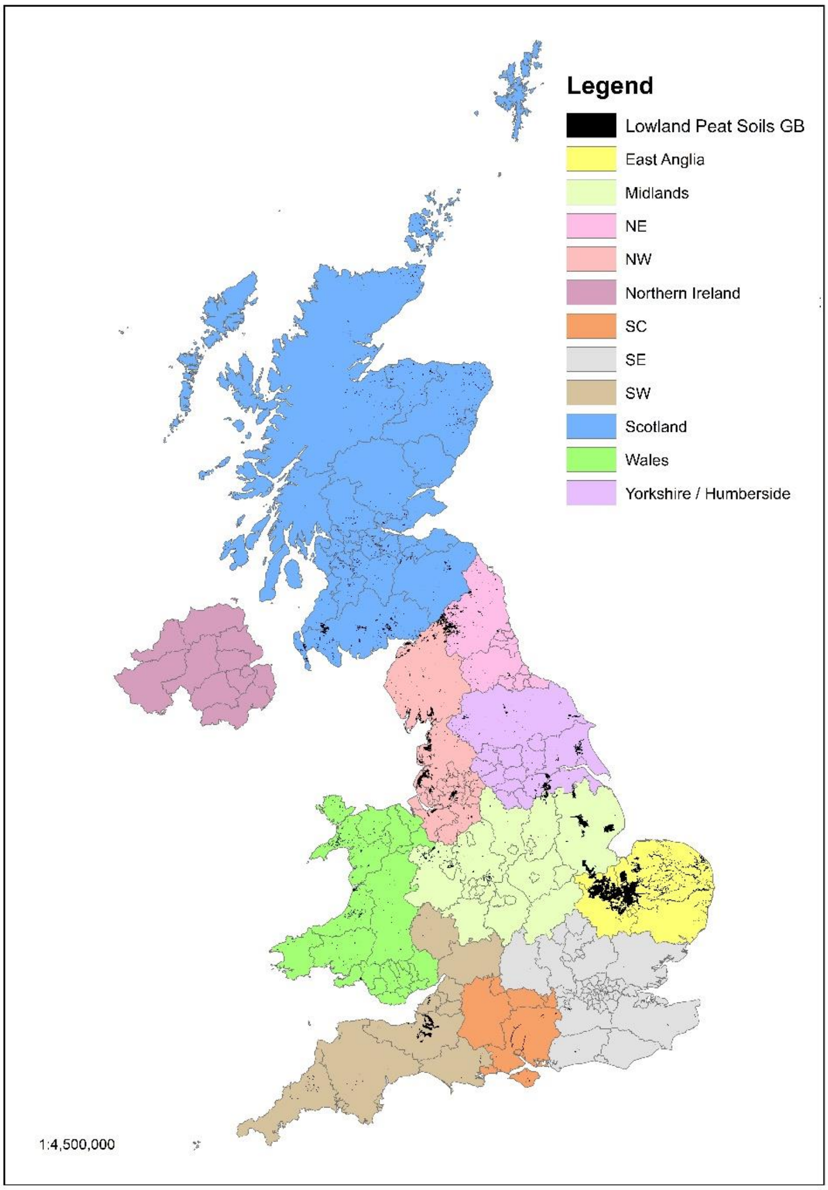

Figure A1 UK regions used in the analysis. NE = North East, NW = North West, SC = South Central, SE = South East, SW = South West. Lowland peat soils are shown in black.

Appendix 1.1 Eastern England

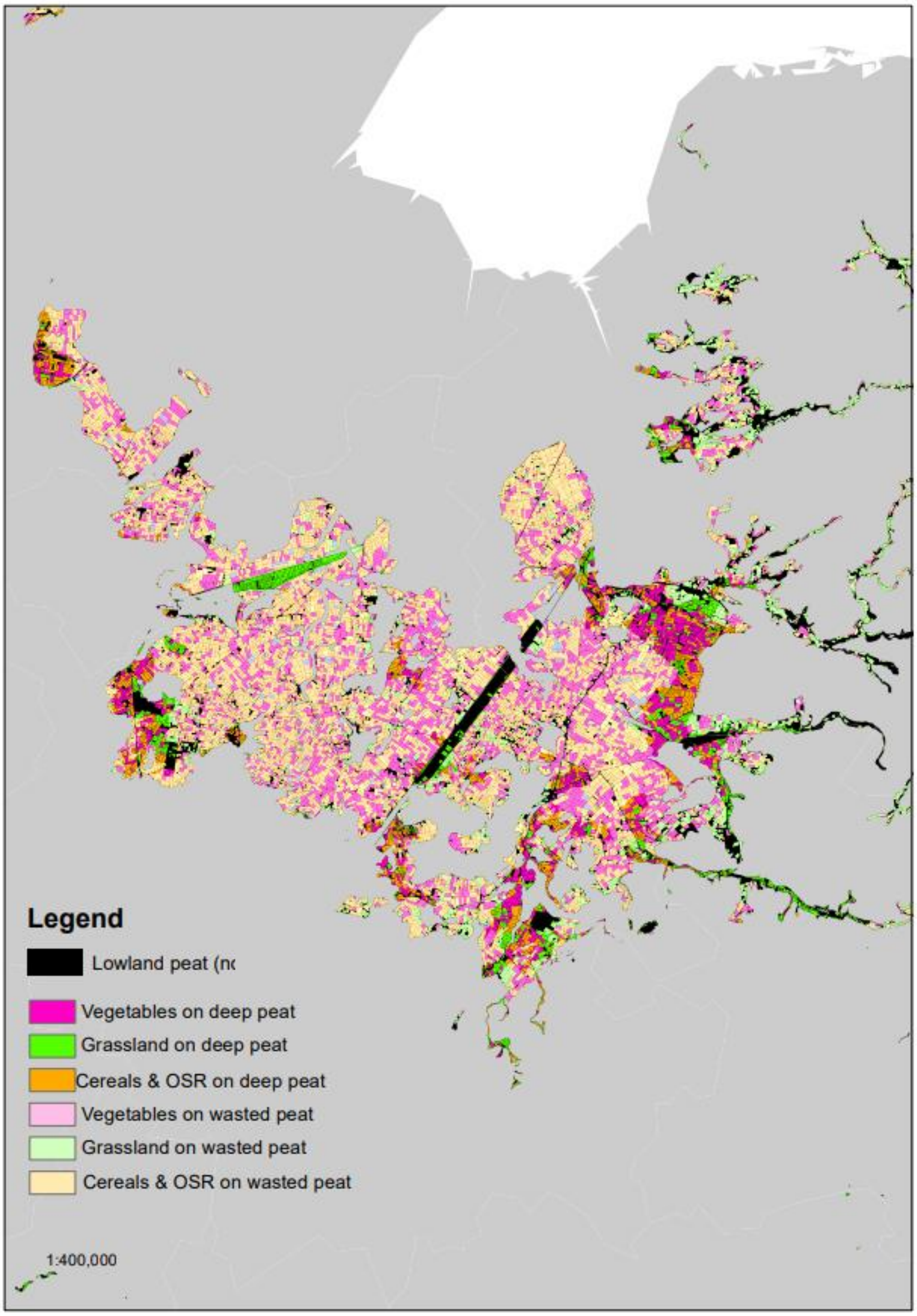

Figure A2 Lowland peat soils under cultivation for different crop types; grassland, cereal & oilseed rape (OSR) and vegetables in Eastern Englandin 2021. Black areas are peat under non-agricultural land-uses such as conservation management

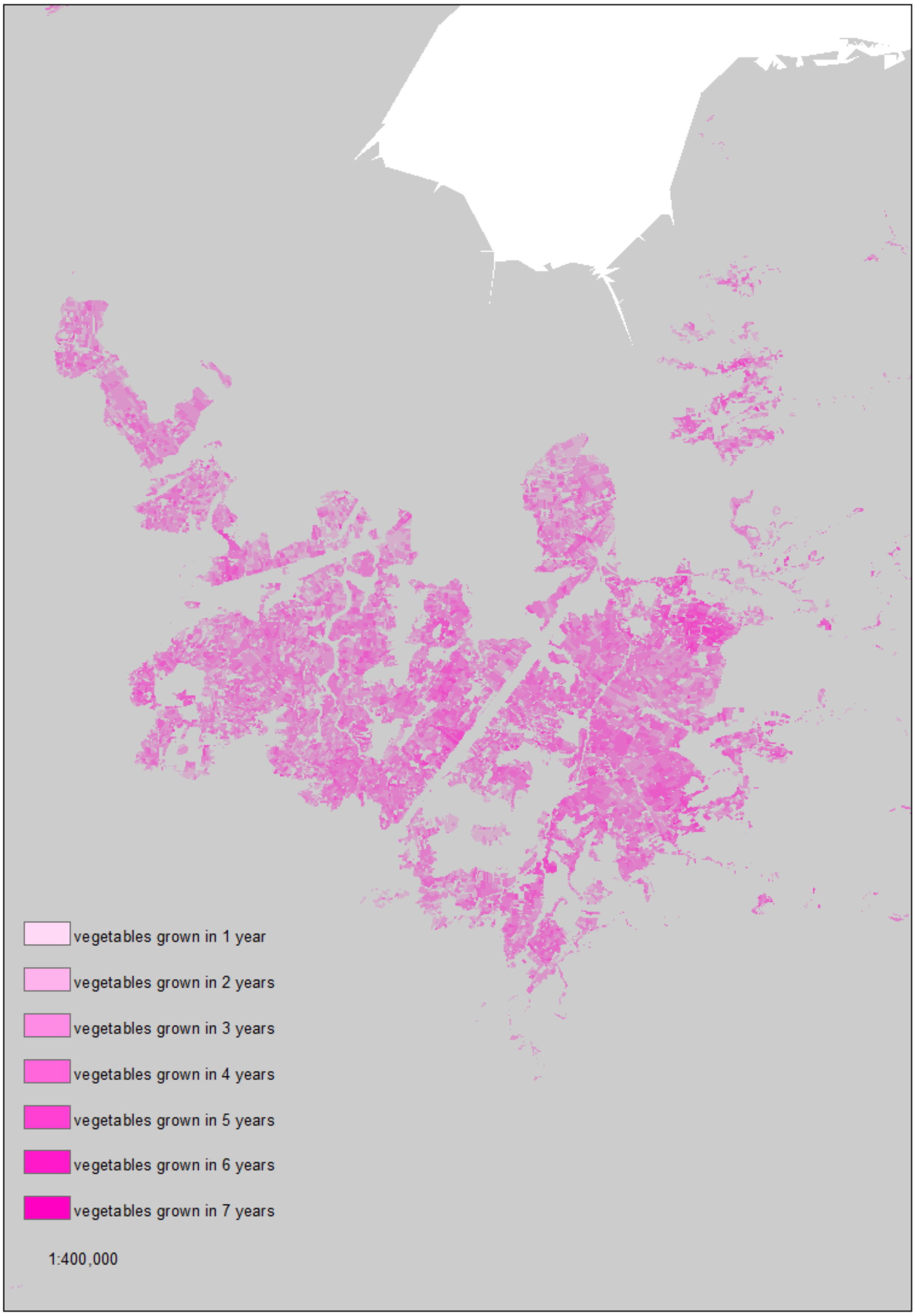

Figure A3 Vegetable production intensity in the East Anglian fens between 2015 and 2021. Pink shading denotes the number of years a given field was under vegetable cultivation between 2015 and 2021

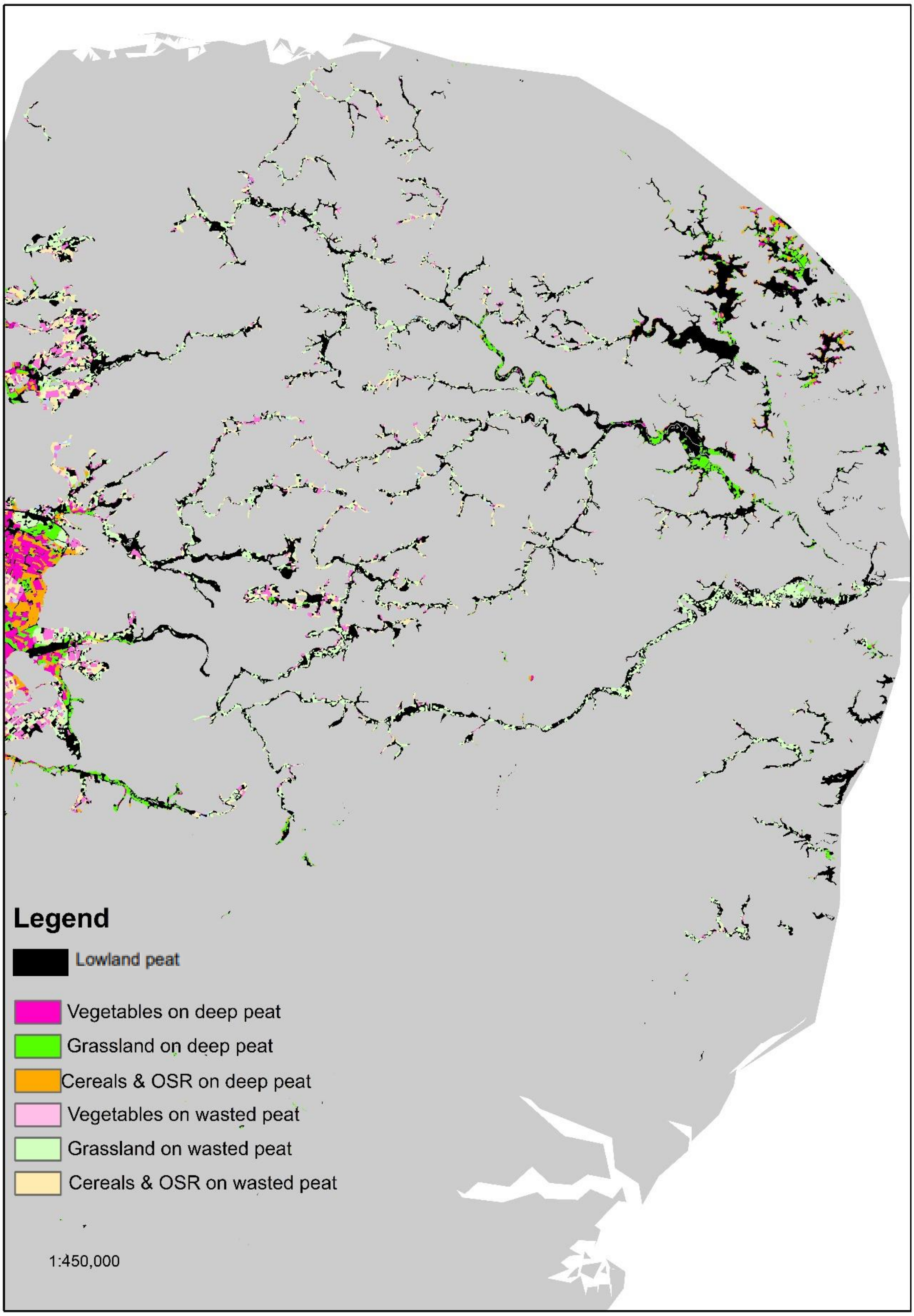

Figure A4 Lowland peat soils under cultivation for different crop types; grassland, cereal & oilseed rape (OSR) and vegetables in the Norfolk and Suffolk Broads in 2021. Note that due to map scales the eastern edge of the fens are shown. Black areas are peat under non-agricultural land-uses such as conservation management.

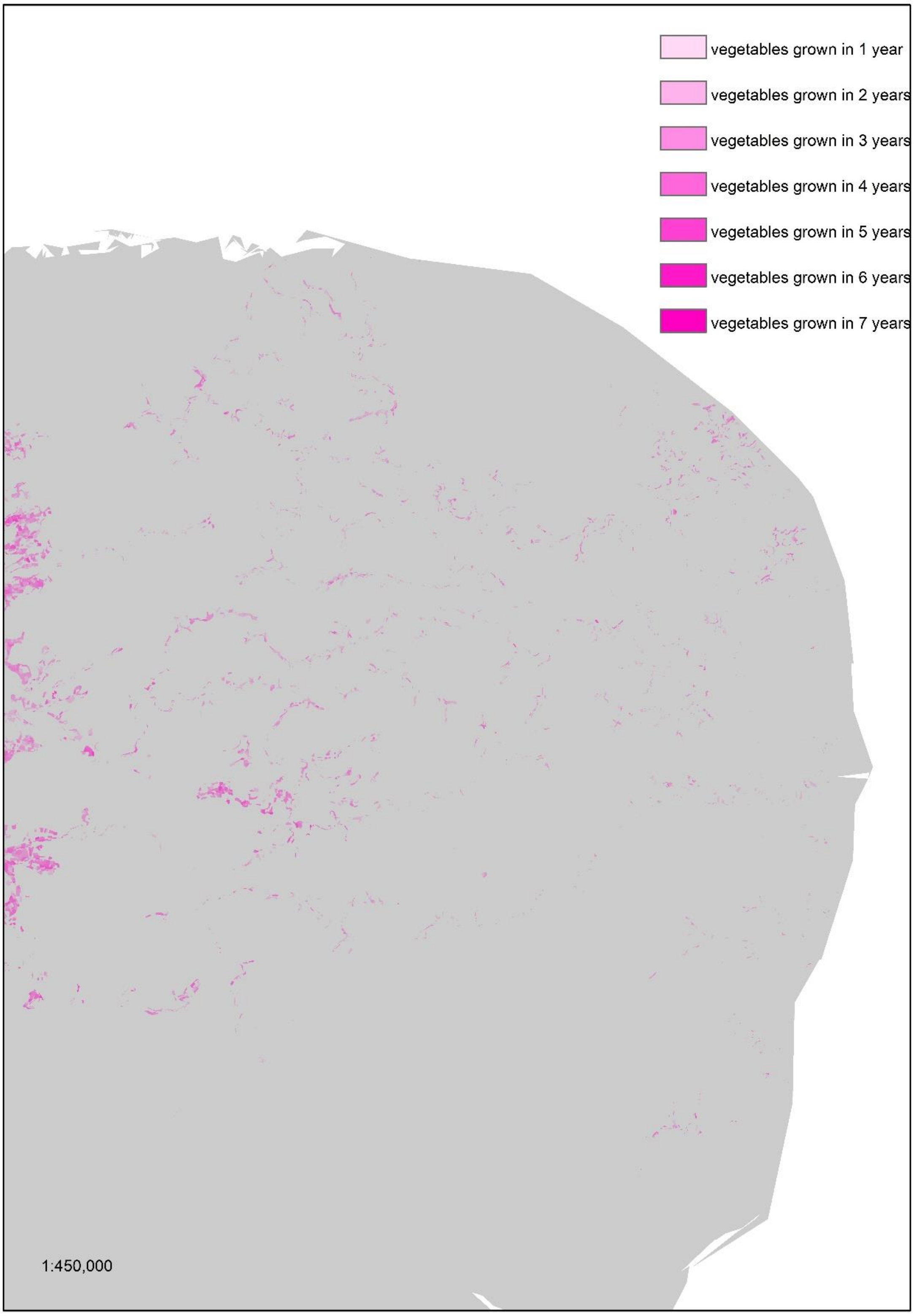

Figure A5 Vegetable production intensity in the Norfolk and Suffolk Broads between 2015 and 2021. Pink shading denotes the number of years a given field was under vegetable cultivation between 2015 and 2021

Table A1 Agricultural lowland peat in East Anglia (Cambridgeshire, Norfolk, Suffolk & Peterborough).

	Peat Condition													
	2015		2016		2017		2018		2019		2020		2021	
	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted
	(ha)													
Vegetables	6,998	29,180	7,021	28,479	7,580	32,429	6,484	27,671	7,454	28,510	7,824	30,841	7,902	29,166
Cereals	7,713	44,446	6,901	44,539	6,619	41,184	7,663	45,831	7,167	44,345	6,907	42,345	6,933	45,266
OSR	1,182	7,281	964	6,197	547	4,891	735	5,485	588	4,827	478	3,502	422	2,748
Maize	642	3,044	678	3,580	1,378	5,153	485	3,056	1,140	5,644	940	6,180	1,061	5,971
Grassland	8,393	19,850	9,084	20,289	8,523	19,427	9,254	20,986	8,217	19,666	8,416	20,113	8,249	19,832

Total	24,926	103,801	24,648	103,083	24,648	103,083	24,621	103,029	24,567	102,992	24,566	102,982	24,566	102,982

Appendix 1.2 Yorkshire and Humberside

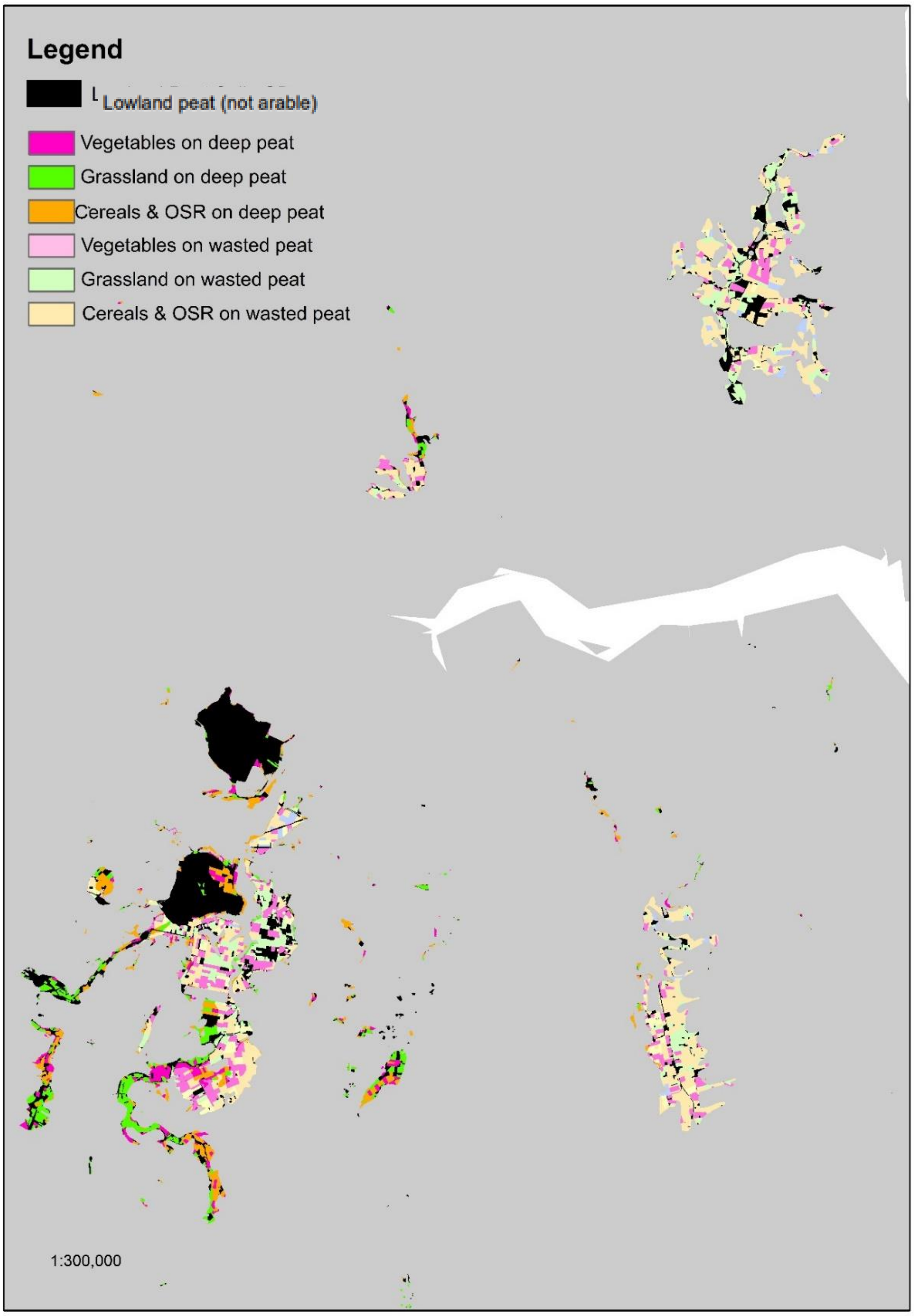

Figure A6 Lowland peat soils under cultivation for different crop types; grassland, cereal & oilseed rape (OSR) and vegetables in the Yorkshire / Humberside region in 2021. Black areas are peat under non-agricultural land-uses such as conservation management.

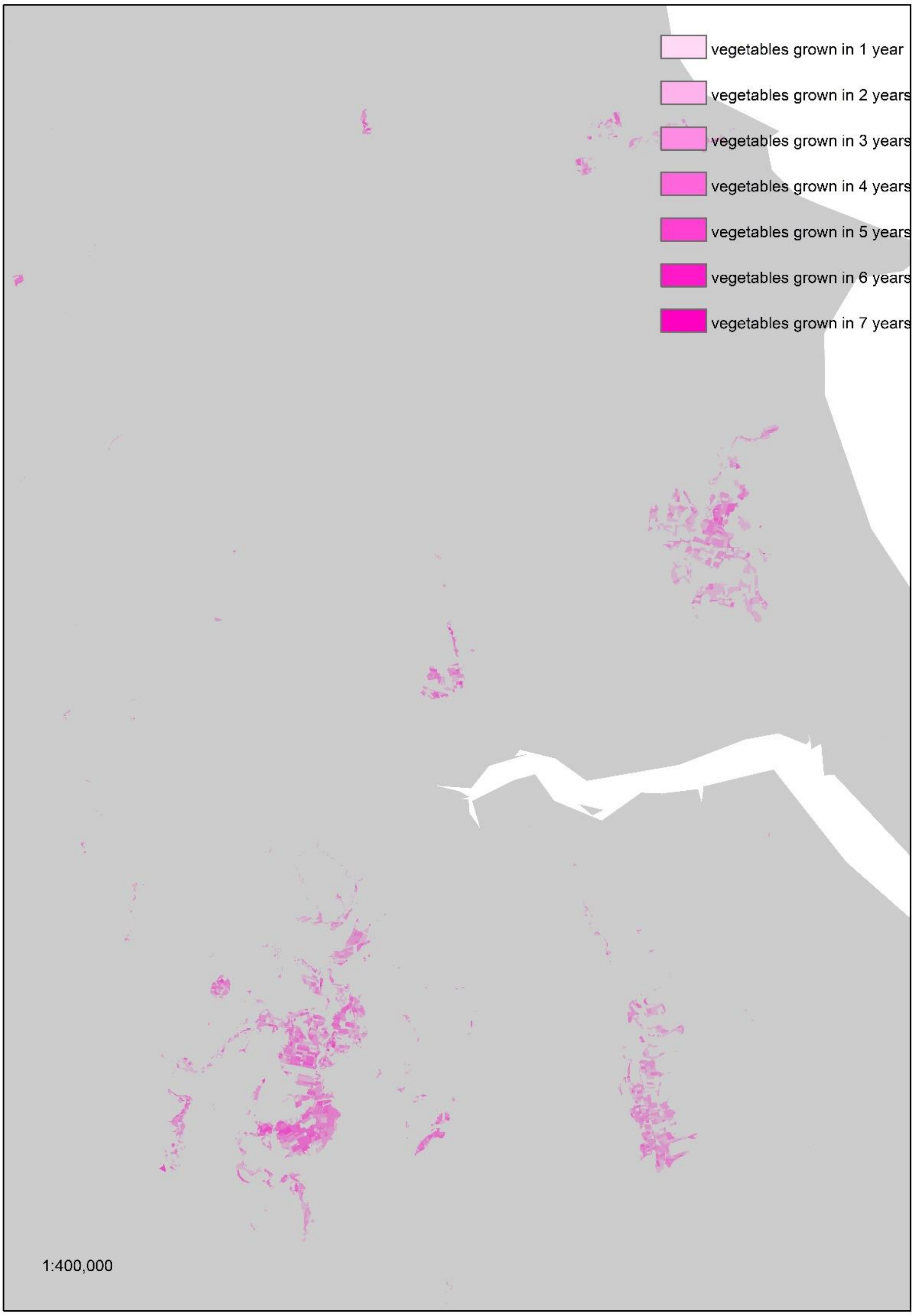

Figure A7 Vegetable production intensity in in the Yorkshire / Humberside region between 2015 and 2021. Pink shading denotes the number of years a given field was under vegetable cultivation between 2015 and 2021

Table A2 Agricultural lowland peat in the Yorkshire Humberside region, including the Humberhead levels (ha).

	Peat Condition													
	2015		2016		2017		2018		2019		2020		2021	
	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted
	(ha)													
Vegetables	692	1,449	1,502	2,685	711	1,853	698	1,760	535	1,922	1,123	1,929	707	1,606
Cereals	1,537	3,911	1,235	3,415	1,479	3,596	1,558	4,113	1,819	3,793	1,179	3,641	1,729	4,181
OSR	351	997	246	811	330	867	347	794	183	623	190	628	168	484
Maize	152	269	79	158	238	473	152	133	166	341	240	411	239	408
Grassland	3,295	2,350	2,879	1,887	3,182	2,166	3,180	2,147	3,210	2,249	3,181	2,319	3,061	2,250
Total	6,027	8,975	5,940	8,955	5,940	8,955	5,935	8,947	5,913	8,928	5,913	8,928	5,904	8,928

Appendix 1.3 Northwest England

Table A3 Agricultural lowland peat in the NW of England (ha).

	Peat Condition													
	2015		2016		2017		2018		2019		2020		2021	
	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted
	(ha)													
Vegetables	3,350	265	5,015	480	5,051	407	3,521	278	4,272	3,350	265	5,015	480	5,051
Cereals	3,681	789	3,366	740	4,530	925	4,560	876	5,236	3,681	789	3,366	740	4,530
OSR	396	32	253	76	245	39	175	24	383	396	32	253	76	245
Maize	339	138	366	70	624	124	2,170	276	1,025	339	138	366	70	624
Grassland	14,533	7,341	13,199	6,982	11,751	6,854	11,731	6,880	11,187	14,533	7,341	13,199	6,982	11,751

Total	22,299	8,565	22,200	8,349	22,200	8,349	22,158	8,334	22,103	22,299	8,565	22,200	8,349	22,200

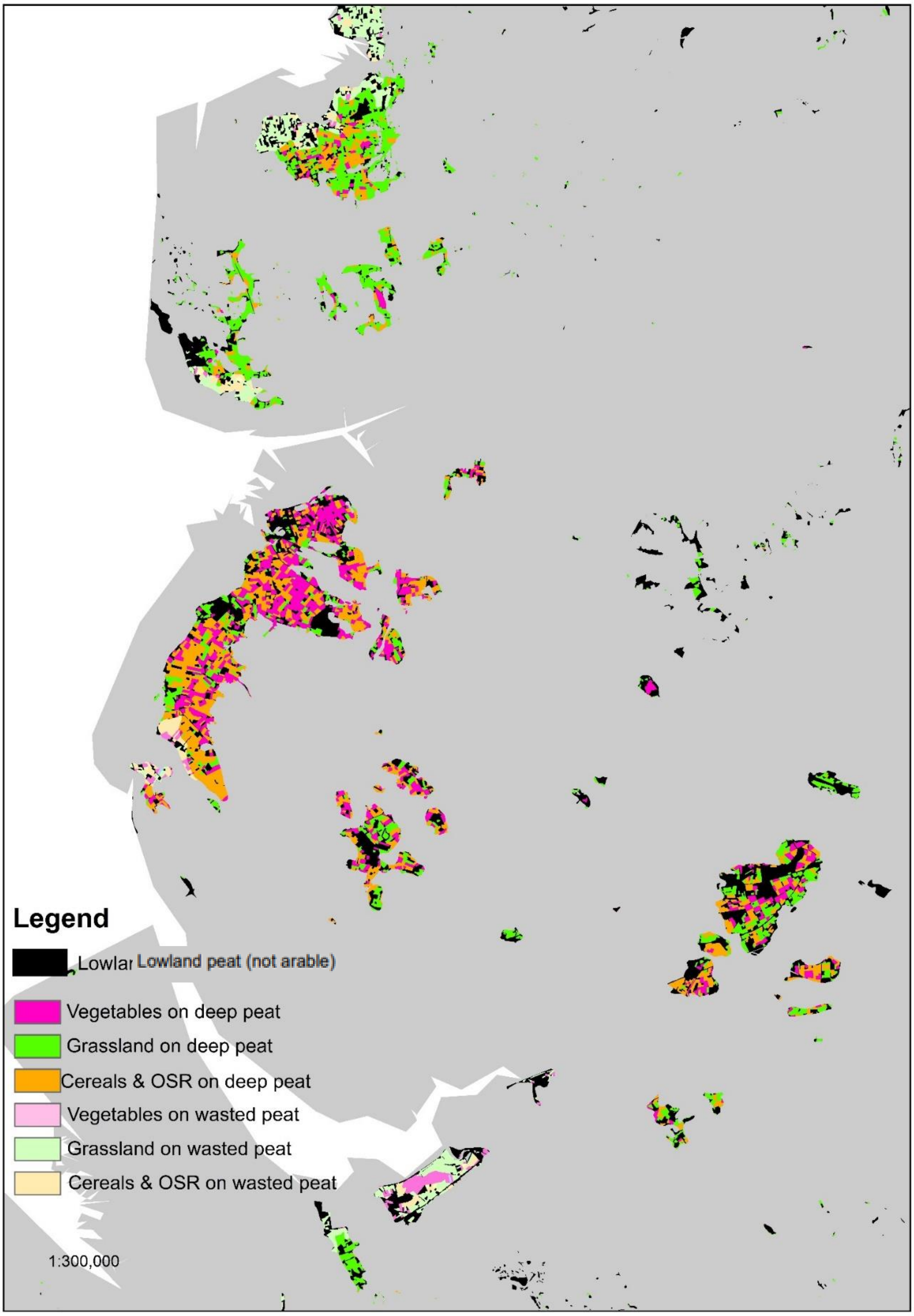

Figure A8 Lowland peat soils under cultivation for different crop types; grassland, cereal & oilseed rape (OSR) and vegetables in NW England in 2021. Black areas are peat under non-agricultural land-uses such as conservation management.

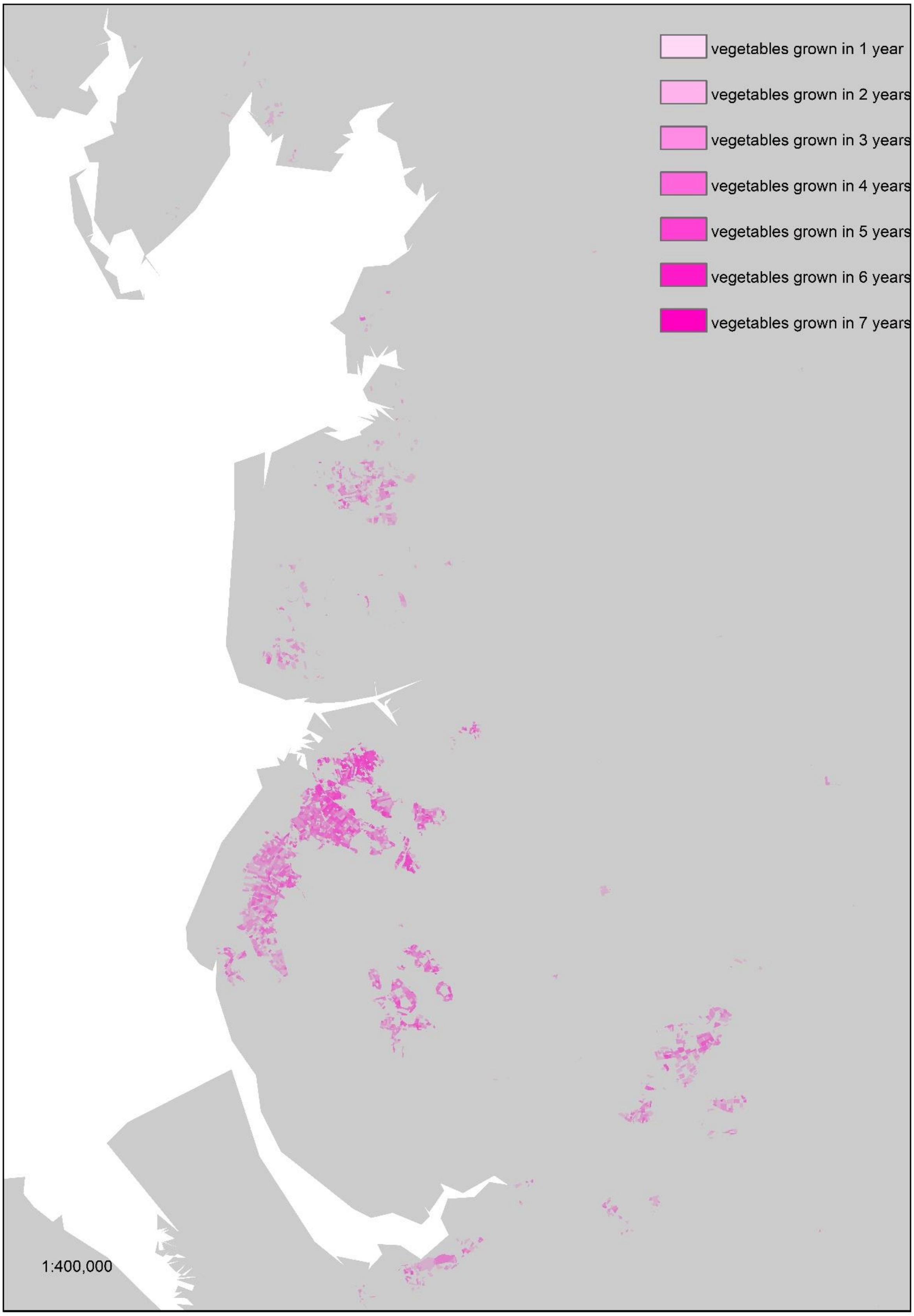
vegetables grown in 1 year
vegetables grown in 2 years
vegetables grown in 3 years
vegetables grown in 4 years
vegetables grown in 5 years
vegetables grown in 6 years
vegetables grown in 7 years
1:400,000

Figure A9 Vegetable production intensity in the NW England region between 2015 and 2021. Pink shading denotes the number of years a given field was under vegetable cultivation between 2015 and 2021

Appendix 1.4 English Midlands

Table A4 Agricultural lowland peat in the English Midlands.

	Peat Condition													
	2015		2016		2017		2018		2019		2020		2021	
	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted
	(ha)													
Vegetables	1,752	6,141	2,320	6,753	1,840	6,197	1,621	5,229	1,847	5,965	2,068	8,085	1,870	5,838
Cereals	2,977	11,830	2,817	11,728	3,045	12,145	3,429	13,104	3,282	13,652	3,062	11,627	3,707	14,769
OSR	905	3,994	794	3,661	894	3,298	715	3,797	614	2,875	569	1,804	381	1,166
Maize	390	808	468	1,344	572	1,757	529	1,431	616	1,056	654	2,014	556	1,620
Grassland	6,009	3,467	5,552	2,805	5,600	2,894	5,643	2,700	5,570	2,678	5,577	2,691	5,414	2,828

Total	12,033	26,238	11,951	26,291	11,951	26,291	11,937	26,262	11,930	26,227	11,930	26,221	11,929	26,221

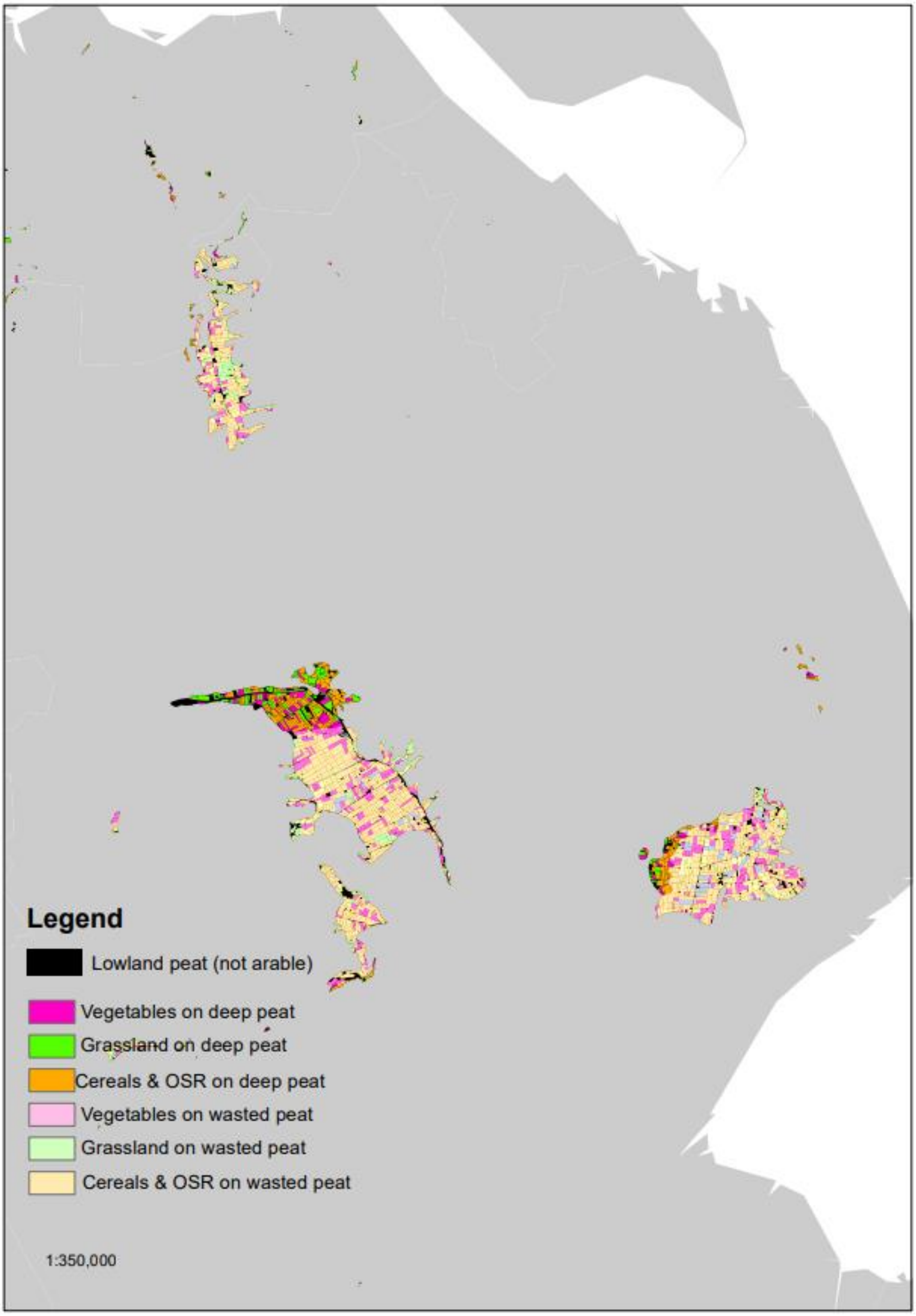

Figure A10 Lowland peat soils under cultivation for different crop types; grassland, cereal & oilseed rape (OSR) and vegetables in Lincolnshire in 2021. Black areas are peat under non-agricultural land-uses such as conservation management.

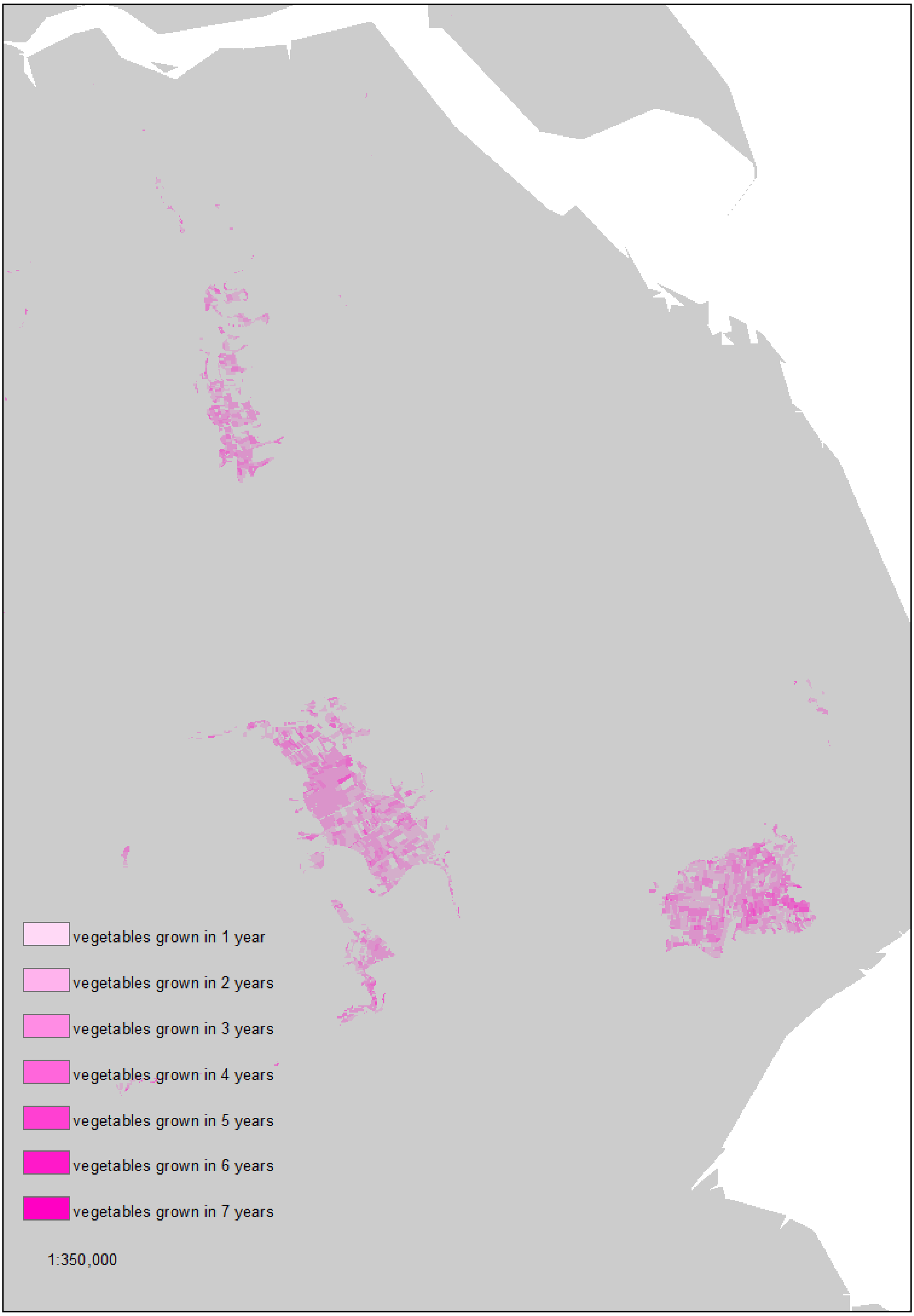

Figure A11 Vegetable production intensity in Lincolnshire between 2015 and 2021. Pink shading denotes the number of years a given field was under vegetable cultivation between 2015 and 2021

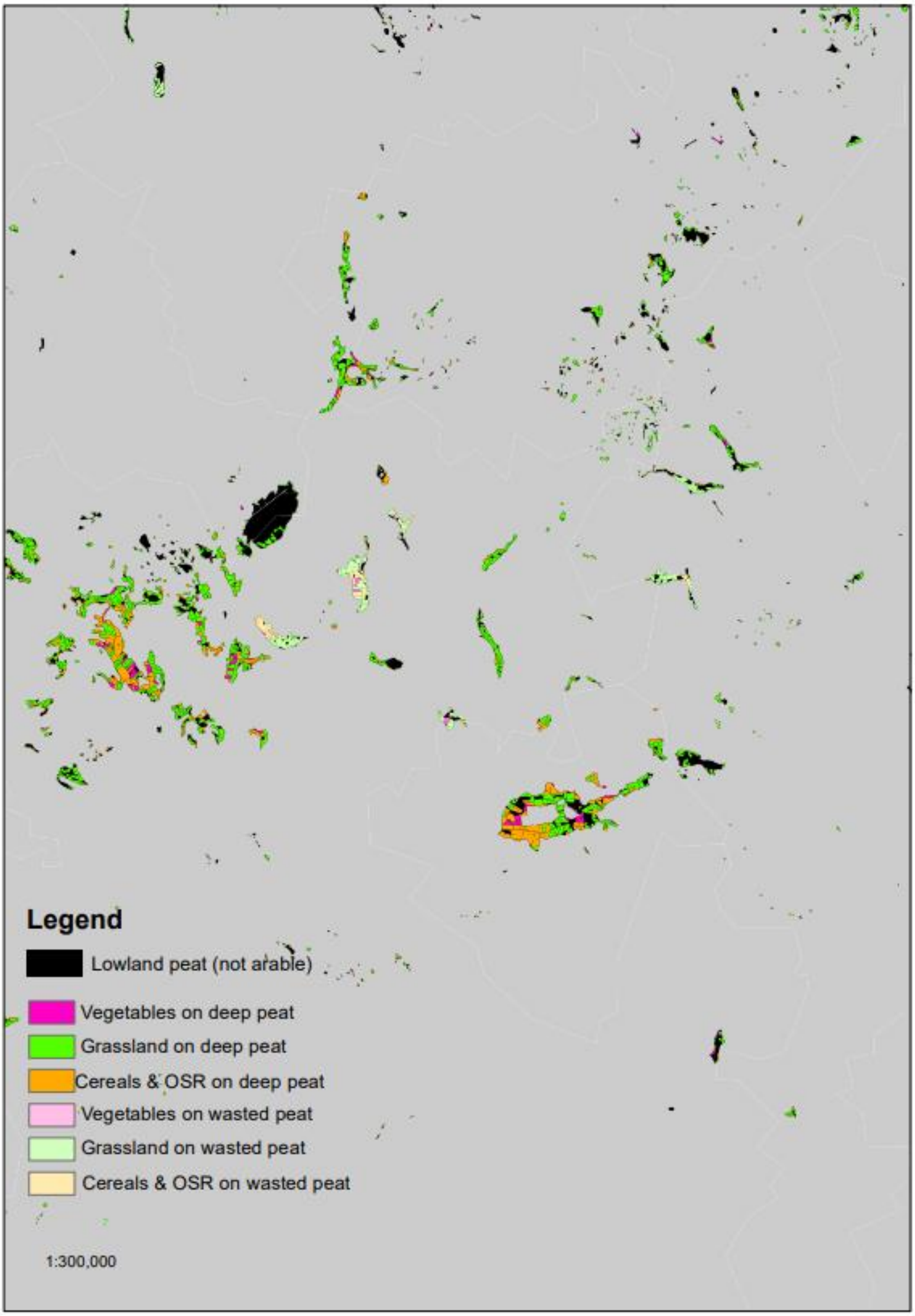

Figure A12 Lowland peat soils under cultivation for different crop types; grassland, cereal & oilseed rape (OSR) and vegetables in the West Midlands in 2021. Black areas are peat under non-agricultural land-uses such as conservation management. The area shown in black near the centre of the map is Whixall Moss, a conservation area previously used for peat extraction.

Figure A13 Vegetable production intensity in the West Midlands between 2015 and 2021. Pink shading denotes the number of years a given field was under vegetable cultivation between 2015 and 2021.

Appendix 1.5 Southwest England

In Southwest England the methodology used in this report mapped nearly 15,000 ha of arable land on lowland peat (Table A5), the majority of which is in the Somerset levels (Figure A14). Almost all the agricultural land within this area is mapped as grassland, with only small areas used to grow vegetables, cereals, maize and OSR (less than 10% of the total agricultural lowland peat in the southwest of England is in arable with over 90% in grassland).

Table A5 Agricultural lowland peat soils in SW England, including the Somerset levels.

	Peat Condition													
	2015		2016		2017		2018		2019		2020		2021	
	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted
	(ha)													
Vegetables	130	61	20	20	99	117	82	27	45	60	99	65	125	78
Cereals	221	165	147	234	185	187	113	229	163	150	108	174	209	188
OSR	29	72	8	6	14	27	12	14	5	2	24	0	0	2
Maize	117	97	155	154	154	120	129	144	191	175	178	196	241	206
Grassland	9,044	4,040	9,177	3,998	9,056	3,962	9,162	3,992	9,093	4,011	9,088	3,961	8,921	3,923

Total	9,541	4,434	9,508	4,412	9,508	4,412	9,499	4,405	9,496	4,398	9,496	4,396	9,495	4,396

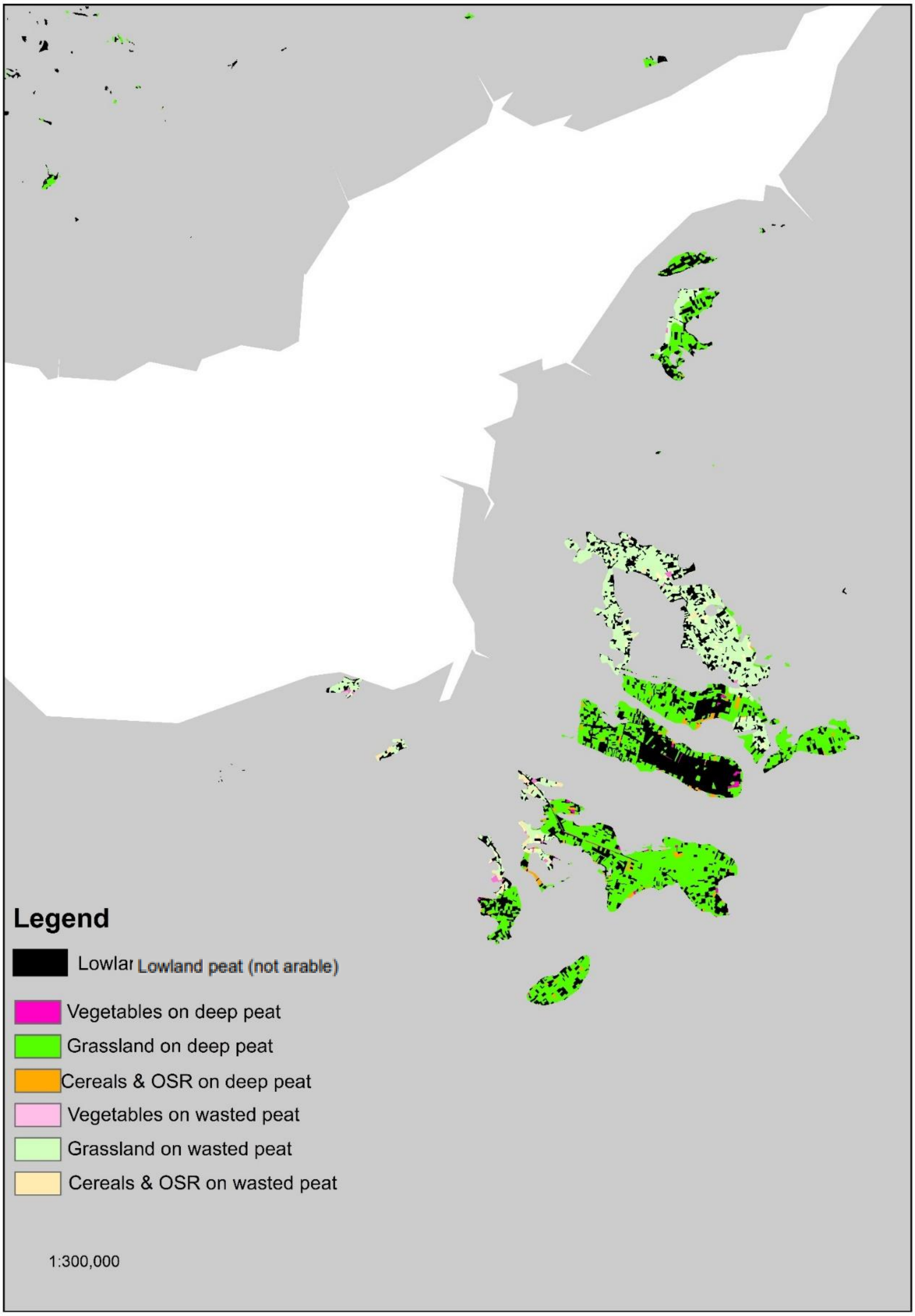

Figure A14 Lowland peat soils under cultivation for different crop types; grassland, cereal & oilseed rape (OSR) and vegetables in the Somerset Levels in 2021. Black areas are peat under non-agricultural land-uses such as conservation management. The large area in black in the centre of the map is the Avalon marshes, west of Glastonbury (previously a peat extraction site).

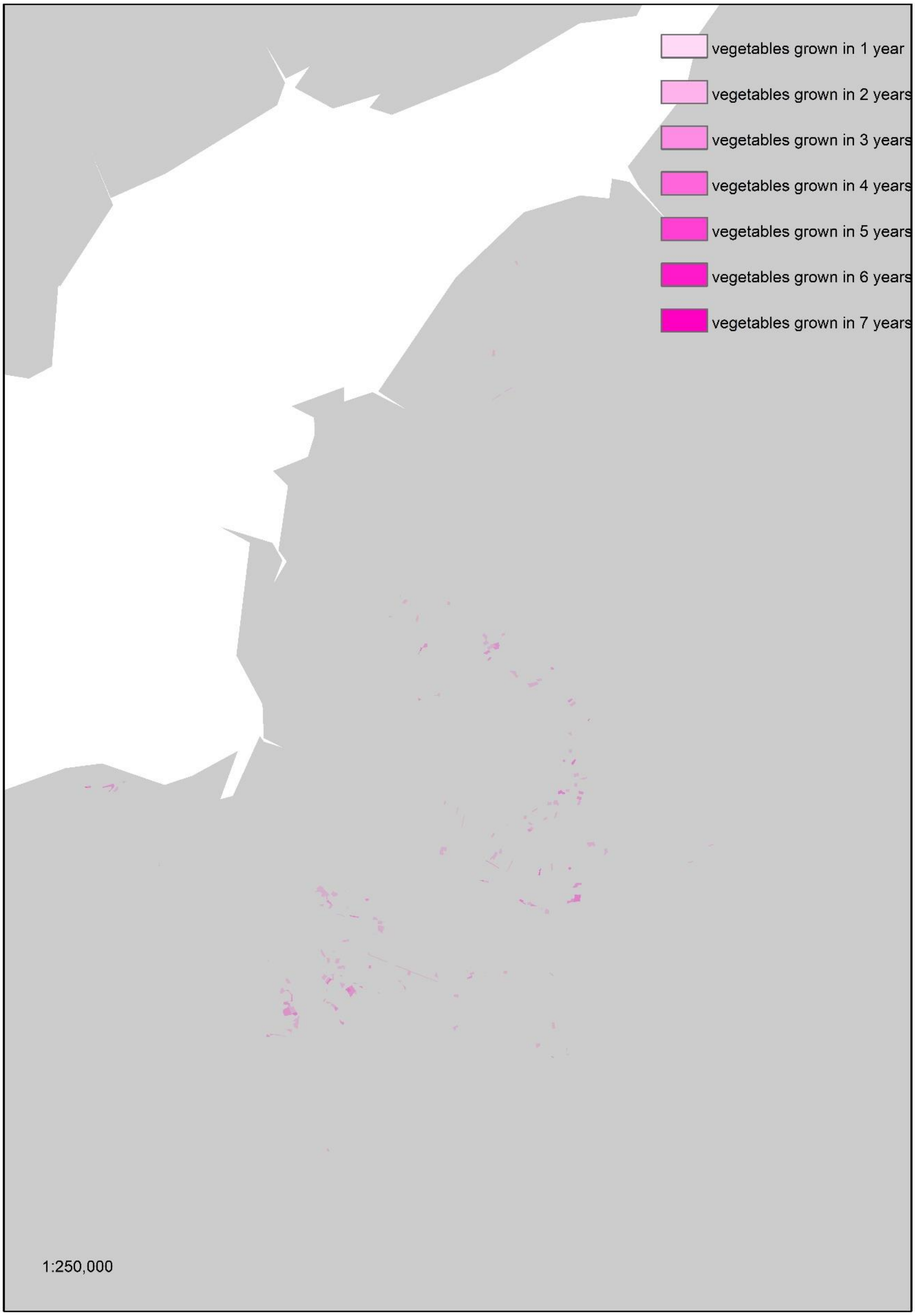
vegetables grown in 1 year
vegetables grown in 2 years
vegetables grown in 3 years
vegetables grown in 4 years
vegetables grown in 5 years
vegetables grown in 6 years
vegetables grown in 7 years
1:250,000

Figure A15 Vegetable production intensity in the the Somerset Levels between 2015 and 2021. Pink shading denotes the number of years a given field was under vegetable cultivation between 2015 and 2021.

Appendix 1.6 North East England, South East England and South Central England

There are few lowland peat soils under agriculture found in the remaining English regions – Southeast and South-Central England, and Northeast England. Of the approximately 4,700 ha across the three regions almost all the peat soils used for agriculture are used for grassland, with very little production of cereals, vegetables, maize or OSR (Tables A6-A8).

Table A6 Agricultural lowland peat soils under agriculture in Northeast England.

	Peat Condition													
	2015		2016		2017		2018		2019		2020		2021	
	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted
	(ha)													
Vegetables	60	0	24	0	107	0	9	0	34	0	60	0	24	0
Cereals	309	0	300	0	271	0	300	0	310	0	309	0	300	0
OSR	34	0	87	0	47	0	69	0	35	0	34	0	87	0
Maize	0	0	2	0	0	0	1	0	7	0	0	0	2	0
Grassland	1510	0	1466	0	1455	0	1500	0	1494	0	1510	0	1466	0
Total	1912	0	1880	0	1880	0	1880	0	1880	0	1912	0	1880	0

Table A7 Agricultural lowland peat soils under agriculture in Southeast England.

	Peat Condition													
	2015		2016		2017		2018		2019		2020		2021	
	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted
	(ha)													
Vegetables	25	0	27	0	24	0	13	0	15	0	25	0	27	0
Cereals	18	0	21	0	17	0	29	0	25	0	18	0	21	0
OSR	2	0	3	0	8	0	0	0	4	0	2	0	3	0
Maize	632	0	614	0	625	0	621	0	617	0	632	0	614	0
Grassland	11	0	5	0	5	0	1	0	3	0	11	0	5	0
Total	689	0	670	0	679	0	665	0	664	0	689	0	670	0

Table A8 Agricultural lowland peat soils under agriculture in South-central England

	Peat Condition													
	2015		2016		2017		2018		2019		2020		2021	
	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted	Deep	Wasted
	(ha)													
Vegetables	69	0	63	0	46	0	11	0	25	0	69	0	63	0
Cereals	70	0	57	0	75	0	110	0	43	0	70	0	57	0
OSR	18	0	1	0	3	0	9	0	5	0	18	0	1	0
Maize	45	0	40	0	11	0	47	0	91	0	45	0	40	0

Grassland	2053	0	2021	0	2048	0	2005	0	2014	0	2053	0	2021	0
Total	2254	0	2182	0	2182	0	2182	0	2178	0	2254	0	2182	0

Appendix 2. Regenerative vegetable production – all soils

In contrast to 'organic farming', for which a strong legal framework is in place in most countries worldwide, there is currently no legislative framework that defines the use of the term 'regenerative agriculture', in terms of either permitted or prohibited farming practices. In general, regenerative farming used as an umbrella term to describe farming systems that seek to building and maintain soil health. Regenerative agriculture also focuses on increasing biodiversity, enhancing ecosystem services, building resilience to climate change, and improving the water cycle, among other things. The main pioneer organisation for regenerative farming in the UK is Groundswell; this farm and agricultural conference/show has identified 5 principles that are considered to underpin regenerative agriculture (Figure A2-1):

6) Minimise soil disturbance
7) Keep the soil surface covered
8) Maintain living roots
9) Grow a diverse range of crops
10) Integrate livestock

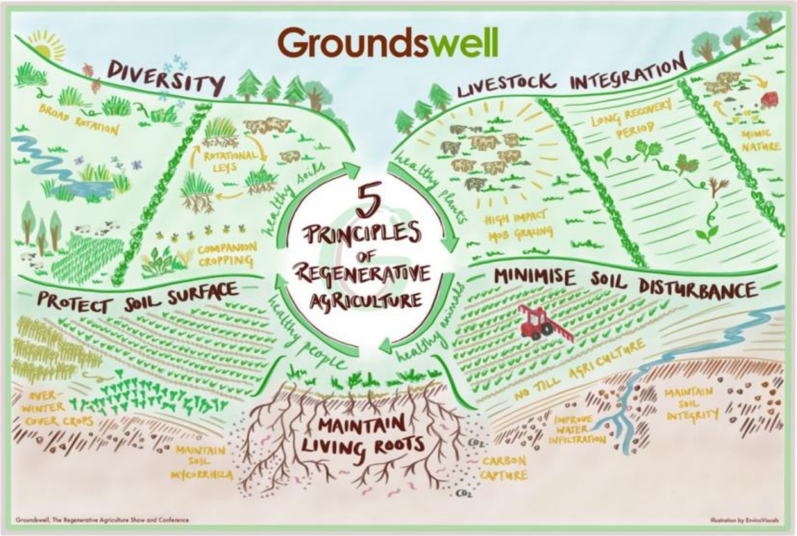

Figure A2-1 Infographic that highlights the 5 principles of regenerative agriculture, extracted from Groundswell (2021)*.*

These principles reflect those of a wider global movement which began with the Rodale Institute in the USA, which has been developed in practice on farms and ranches across the USA. Consequently, a sixth principle has recently been added, that of context (UnderstandingAG 2022). Understanding the business and environmental baseline for any farming systems is essential to allow for locally-adapted regenerative management approaches to begin; it is also important to note that for most practitioners, regenerative agriculture is regarded as a direction of travel not an absolute.

Interests in regenerative agriculture have been rapidly growing among public, private, and non-profit sectors. A meta-analysis by Newton et al. (2020) identified a range of definitions used for 'regenerative farming', based on either interventions (e.g., use of cover crops), outcomes (e.g., to sequester carbon) or a combination of the two. An outcome-focused perspective encompasses all practices that can deliver a desired end point, whilst intervention-based approaches are considered more prescriptive and inflexible (Grelet et al. 2021). It is important to consider that these conflicting definitions will have different implications on policy and stakeholder perceptions (e.g. policymaker v farmer).

Appendix 2.1 Learning from existing approaches to sustainable vegetable production

Previous research that explores sustainable practices and the growing development of regenerative principles (outlined briefly above) has mainly focused on arable cropping systems with relatively little focus on vegetable cropping systems. However, it is possible to identify two approaches that have partly included a consideration of the challenge of increasing sustainability in vegetable production and these are described briefly below.

Appendix 2.2 Organic vegetable production

Organic farming has a clear legislative basis and certification schemes for both production and processing. The legal basis of organic food certification in the UK are the retained EU regulations 834/2007, 889/2008, 1235/2008 and the Organic Products Regulations 2009 (DEFRA 2016) which outline permitted and prohibited practices. For example, organic farming prohibits the use of synthetic nitrogen fertilisers, synthetic pesticides, and genetically modified organisms, whilst encouraging the adoption of positive practices to benefit the environment, sustain soil health, fertility, and biodiversity (Niggli 2015; Seufert and Ramankutty 2017). Various reviews and meta-analyses provide evidence to suggest that organic farming plays an active role against biodiversity losses (Hole et al. 2005; Stein-Bachinger et al. 2021). Although organic crop production is associated with lower yields in comparison to conventional farms (Seufert et al. 2012), the farms often have higher profitability due to lower production costs and organic premiums (Smith et al. 2019).

Organic production of vegetables is usually specialised both in fields and greenhouses. Greenhouse and perennial systems are the most intensive cropping systems in organic farming, largely dependent on imported nutrients (e.g., from animal wastes). The key difference between organic and conventional vegetable production is the systems-based approach to soil fertility and pest management. The production of high value field vegetables is often performed on very specialised farms with little or no animal husbandry. The approach to soil fertility is based on an appropriate crop rotation design, including perennial green manures with legumes, cover crops, an appropriate management of crop residues and the application of permitted mineral and organic fertilisers (e.g., farmyard manures) preferably from the same farm or otherwise derived locally, to close in-farm or local nutrient cycles. Biological nitrogen fixation instead of synthetic nitrogen (N) fertilisers is a key element in the overall fertility management. Many of the vegetables grown (e.g., cabbage, celery, etc.) have moderate to high N demand, which is nearly impossible to meet through solid farmyard manure use and green manures alone. In addition, weed control in organic systems is cultural and, consequently, tillage is at least as intensive, and often more intensive, than in conventional vegetable production (Elizabeth A Stockdale et al. 2006). Seufert et al. (2012) showed large yield reductions for organic vegetable production systems in comparison with conventional vegetable production, which compromises the potential environmental and societal benefits as more land is then required to meet production demand. Importantly, organic farming rules do not include any specific consideration of peat soils or water level management; indeed, organic production on peatlands is likely to be facilitated by drainage due to the release of nutrients from the decomposing peat.

Appendix 2.3 Field-scale regenerative principles in vegetable production systems (mineral soils)

This section draws on the detailed synthesis and analysis of two previous major reviews of impacts of agricultural management practices (Emmett et al. 2022; E.A. Stockdale and Watson 2012). The detailed findings of those reviews are summarised and applied to the evaluation of the likely impacts of the adoption of regenerative principles in vegetable production systems on mineral soils in the UK (we discuss regenerative vegetable production for peaty soils in section 4). Currently the focus within vegetable production systems would be on reducing tillage intensity in the vegetable phases of the rotation, with no-till adopted where possible in the non-vegetable phases. The other regenerative principles can be adopted with care and attention to the local context (surrounding habitats, soil type, climate) within field vegetable systems. Overall, the evidence suggests that growers seeking to adopt regenerative principles in vegetable production on mineral soils would have positive benefits for soil health and biodiversity whilst maintaining productivity.

Appendix 2.4 Reducing tillage intensity

Tillage is the mechanical manipulation of soil properties practiced for seedbed preparation, weed and pest control, or the incorporation of soil amendments. Tillage operations are a major user of diesel on farm, hence reducing tillage intensity can lead to reduced costs and vehicle emissions, as long as weed control and seedbed preparation is still achieved effectively. Reduced cultivations often include using discs or tines rather than ploughing (aka inversion tillage) for primary cultivation (typically 10-15cm cultivation depth). For cereals, oilseed, and pulses direct drilling (e.g., no-till) may also be possible. However, for vegetable crops currently some cultivations are required. Reduction in tillage intensity can include reduction in numbers of operations (e, g. ceasing de-stoning), reducing depth of operations and changing speed (usually, reducing speed reduces tillage intensity). The impact of any tillage practice depends on the combination of equipment factors (including depth, energy input and speed) together with soil factors (including water content, texture, and residue cover). Therefore, the same operation can result in very different impacts on different days or with different operators.

Changes in tillage practices, especially the use of non-inversion techniques which maintain the continuity of macro-pores to the soil surface result in soil surface conditions which are likely to reduce runoff and associated sediment loss, especially overwinter. Biodiversity benefits from minimum tillage approaches can help support populations of key predatory ground beetle species within arable agriculture, where tillage impacts are larger for larger species. Earthworm numbers are also typically higher with reduced tillage intensity, having knock-on benefits for soil health and wider soil biodiversity. Increases in the duration of crop residues and weed seeds at the soil surface along with reduced tillage can improve food supplies for small mammals such as wood mice and seed-eating farmland birds. Reduced tillage in combination, if combined with reduced weed control may increase diversity of arable species in the short term. However, in the long-term this can lead to the build-up of problematic weeds, such as annual grass and a range of biennial and perennial weed species.

In the past, there have been mixed claims about the impact of reducing tillage intensity on soil organic matter content and overall C stock. A robust meta-analysis by Meurer et al. (2018) assessed the impact of reduced tillage intensity on soil C storage in the boreo-temperate zone. The study’s findings showed that reducing tillage intensity increases soil C storage in the topsoil (0-30 cm) only with effects detectable by field measurement after 10 years of implementation. However, the change in soil C storage were not detectable when a deeper soil profile is considered (0-60 cm depth) indicating that the changes in topsoil are mainly due to differences in stratification rather than an overall increase in the soil C storage. Under UK conditions, changes in the stratification of soil C storage as a result of reducing tillage intensity, rather than overall soil C storage have been confirmed (McKenzie et al. 2017). Reductions in fuel use through reduced tillage intensity will have a larger impact than changes in C storage in terms of the net C footprint of agricultural systems where tillage is minimised.

Any tillage operation immediately disrupts the connectivity of pores and water films in the soil. Reducing the occurrence or frequency of this disruption is likely to increase soil mesofauna biomass. Changes in tillage will also lead to changes in the proportion of time where there is active root biomass in the soil, and cover of soil by plants or residues as well as changes in stratification of organic matter inputs within the soil. Reducing tillage intensity has been associated with increased fungal biomass, especially arbuscular mycorrhizal (AM) fungi. These are plant mutualists that support plant growth through colonising roots and increasing their access to phosphorus and water. Reduced tillage also stimulates soil biota more generally as a result of increased OM inputs and increased stabilisation of niche habitats.

The possible range of impacts of changes in tillage intensity within vegetable rotations, which may include some crops where no-till can be implemented are described in Table A 2-1.

Appendix 2.5 Creating continuous cover (cover crops) and maintain living roots

Cover crops are plants grown between cash crops. As most vegetable crops are spring sown, there is an opportunity to use cover crops ahead of planting. This avoids periods of bare soil, which are associated with a greater risk of erosion, carbon losses and nitrogen leaching. A wide range of species are currently used for cover cropping which can be planted as a single species or a mixture of species. Cover crops can be terminated in winter or spring through herbicide use, cultivation, grazing or incorporated back into the soils by tillage to prevent competition with the following cash crop, and to promote mineralisation of organic N. They can also be left on the soil surface until a spring crop is direct-drilled, to provide weed control and N inputs. The majority of evidence on the impact of cover crops comes from arable systems; there is little evidence specifically on impacts of creating continuous cover in horticultural systems. Cover crops sown in spring as a one-year fallow are likely to provide stronger benefits for biodiversity as the crops are more likely to flower than winter cover crops. However, this may significantly reduce food production from the rotation. Information on the direct value of cover crops for supporting natural enemy species or controlling the outbreaks of pests and diseases in the UK is limited. The effectiveness of cover crops in providing this type of biocontrol of crop pests is dependent on the spatial and temporal dynamics of the crop cover within the farmed landscape.

Replacing fallow periods with cover crops is an effective management practice to withdraw soil N into the biomass of the cover crops and to reduce nitrate leaching, which is a cause of indirect N_2O emissions. Cover crops usually increase the duration of photosynthesis when considered across the rotation, which can increase soil organic matter as additional C is added to the soil through roots and in cover crop residues. Cover crops and green manures have been shown to have a wide range of positive effects on soil function and ecosystem services (Blanco-Canqui et al. 2015); practical guidance to support species/ variety selection and management is still limited. The possible range of impacts of integration of cover crops and green manures within vegetable rotations are described in Table A 2-1.

Appendix 2.6 Diverse crop rotations

Crop rotation involves the planting of a sequence of crops to control weeds, pests, and diseases; crop rotation can also be used as a tool to manage the fertility of the soil e.g., by integrating legume crops. The cultivation of different crops is usually associated with a range of other changes in management practices, as well as differences in relation to duration of crop cover and growing season, amount and quality of OM inputs. Longer and more diverse crop rotations are associated with higher butterfly and other insect abundance and higher biodiversity. A meta-analysis has shown that more diverse cropping systems (crop rotations, mixed crops, and inter-cropping systems) can generally result in a greater abundance of natural enemies of invertebrate pests, higher herbivore mortality rate, greater yield of the crop and lower crop damage (Letourneau et al. 2011). For vegetable crops, crop rotation and the length of the interval between crops of the same type is used to manage soil-borne pests and diseases by interrupting the population dynamics of pest invertebrates and weeds and providing an element of temporal biodiversity on a landscape level. Diverse crop rotations also challenge weed species, suppressing growth and reproduction. The possible range of impacts of increasing crop diversity within vegetable rotations, are described in Table A 2-1.

Appendix 2.7 Organic matter inputs (e.g., composts, manures)

Organic matter inputs (such as composts and manures) are usually part of an integrated nutrient management strategy. Other organic matter inputs used in agriculture include a diverse range of materials produced off-farm, including microbial, plant, and animal wastes, and by-products of the food processing industry. Whilst application of nutrients in organic material and chemical /mineral fertilisers may provide similar levels of nutrient supply, organic matter inputs also provide food for decomposers and are often beneficial for invertebrate communities. Increased use of organic matter inputs in regenerative cropping systems may occur where farmers are seeking to reduce use of chemical /mineral fertilisers. Application of livestock manures within cropping phases of rotations is common where livestock are integrated into the farming system and housed for part of the year (although this type of integrated farming system is rare in peatland areas used for vegetable production). Increased inputs of organic matter to soils have a range of positive benefits for soil function and the support of wider ecosystem services; these are described in Table A 2-1.

Appendix 2.8 Integrated pest and weed management strategies

Almost all farmers use integrated pest and weed management (IPM) to some level, i.e., they do not have a sole reliance on chemical control methods but use cultural approaches when these are perceived to be economically viable. Farmers take active steps in pest and disease prevention though crop choice, utilising disease-resistant varieties, and other cultural control methods including the timing of sowing and good crop hygiene. The management of field margins and other farm habitats can help to maintain populations of beneficial insects and thus have significant impacts on biological control.

The full implementation of IPM in high value crops (especially in protected systems) has proved more viable than in field vegetable and arable farming systems. This includes: 1) detailed planning focussing on identifying and monitoring pest populations, 2) use of action thresholds to define the point at which economic productivity is threatened; and 3) implementation of control methods only when threshold damage has been reached. This usually focuses on lower impact interventions first (such as mechanical control, disruptive pheromones or attract and kill traps) with the use of pesticides being a last option. Egan et al. (2020) proposed a systematic framework for ‘integrated pest and pollinator management' (IPPM) to address the diverse needs of crop pollination and pest control practices. Implementation of IPM within vegetable systems has been shown to reduce the use of soil sterilisation and reduce use of pesticides overall. The potential impacts of reducing pesticide use within vegetable rotations, are described in Table A2-1.

Cultural control of weeds, with reduced use of herbicides, includes crop variety choice (including use of allelopathic crops, where plants can inhibit the growth of another; for example, for weed control), seed cleaning, altering seed rate, under sowing, avoiding cultivation, avoiding weedy fields with certain crops, planning gaps in the rotation to control weeds and use of cover crops and managing non-cropped areas. In terms of direct control measures, mechanical weeding is the most predominant practice, which includes the use of harrows, inter-row hoes, steerage hoes, flail and rotary toppers, brush weeders, ridgers, rotovators and cultivators. This increases tillage intensity.

The process of mulching refers to the covering of soil to reduce water loss, supress weeds and improve crop yield. The use of mulches may also reduce wind erosion. Materials used to cover the soil vary and can be synthetic or organic. Polyethylene plastic mulch has become the most commonly used inorganic mulch worldwide and is common practise across vegetable farming. Organic mulches are based on straws, grasses, husks, compost, or manure. Plastic mulches are very effective at reducing the number and species diversity of weeds species in vegetable crops and some reduction in crop pest numbers has also been shown. However, plastic mulch also has negative impacts on non-target species with reductions in bird and butterfly species richness and abundance. Organic mulches are reportedly less effective for weed control than plastic mulches. However, they do not have the negative impacts on non-target species seen for plastic mulches.

Table A2-1 Expected impacts of key management practices in horticultural systems on soil biota and soil function in relation to agriculture and other ecosystem services derived from expert judgement following detailed literature review. The list order does not reflect any prioritisation in likely uptake or effectiveness. Adapted and updated from a table presented in Stockdale and Watson (2012) to focus on horticultural systems.

Land management practice	**Direct impacts on soil biota**	**Other impacts on soil which are likely to affect soil biota**	**Likely impacts on soil function for agriculture and other ecosystem services**
Reducing tillage intensity			
• Minimum intensity tillage	• All tillage operations kill soil macrofauna – largest impacts on earthworms and beetles; reduced numbers of tillage operations lead to significant increases in earthworm populations. Earthworms in peat are also an indication of drainage.	• All tillage operations that mix soil reduce connectivity of transmission pores to depth • Changes pore size distribution, disrupts pore connectivity • Mixes OM inputs throughout tilled soil	• Improve soil structure – reducing sediment loss • Improves water balance, regulate water flows • Reduces energy requirements of cropping
• No till includes non-inversion tillage compared with minimum tillage	• Allows development of anecic earthworm populations towards site carrying capacity. Earthworms in peat are also an indication of drainage.	• Increases connectivity of transmission pores from surface to depth • Increased profile stratification; higher • OM contents in surface soils • Surface mulch of residues provides more suitable end of season habitat for surface dwelling arthropods	• Improves soil structure and its stability – reducing sediment loss • Improves water balance, regulate water flows • Increases soil C content – C storage

			• Diversifies farmed landscapes overwinter; provides feeding habitats for seed-eating birds • Reduces energy requirements of cropping
• Permaculture techniques • No dig and deep mulching for small-scale intensive horticulture	• No tillage – positive impacts for anecic earthworms and beetles. Earthworms in peat are also an indication of drainage. • Surface resides and mulches provides energy / nutrient source for soil food web and supports increased biomass • May increase species richness and evenness depending on OM quality	• Permanent perennial root system providing energy and nutrient inputs below ground through root exudation and root turnover • Increased variety in rooting patterns • Increases connectivity of transmission pores from surface to depth • Increased profile stratification; higher OM contents in surface soils	• Increases soil C content – C storage • Improves soil structure and its stability; permanent soil cover– reducing sediment loss • Improves water balance, regulate water flows

Land management practice	**Direct impacts on soil biota**	**Other impacts on soil which are likely to affect soil biota**	**Likely impacts on soil function for agriculture and other ecosystem services**
Creating continuous cover, maintain living roots			
• Integration of cover crops or green manures into crop rotations	• Provides additional OM inputs as energy / nutrient source for soil food web • Supports increased biomass • May change species richness and evenness depending on quality – C/N ratio etc • Depending on crop species provides hosts for mutualistic soil organisms	• Increased variety in root biomass, rooting patterns, amount and quality of root exudates, amount and quality of residue inputs • Increased duration of ground cover	• Increased duration of soil cover– reducing sediment loss by wind and water erosion • Increases soil C content – C storage • Improves soil structure and its • stability • Diversifies farmed landscapes
• Fumigation green manure crops e.g mustard incorporated to provide soil fumigation effects • Additional effects to “Use of cover	• Root exudates and decomposition products with both positive and negative allelopathic effects on soil biota observed	• Root exudates and decomposition products with allelopathic effects on seed germination restricting root growth and hence affecting associative soil biota.	• May allow reduced use of pesticides and/or sterilisation

crops/green manures" above			
Diverse crop rotations			
• Locally adapted rotations with grass/clover leys compared with monoculture or minimal break crops	• Diversifies amount and quality of residue inputs modifying energy / nutrient sources for the soil food web	• More variety in timing and type of cultivation practices and duration of ground cover • Increased variety in rooting patterns • Increased diversity of hosts to support persistence of plant-associating organisms	• Diversifies farmed landscapes • Increases soil C content – C storage • Improve soil structure – reducing sediment loss

Land management practice	Direct impacts on soil biota	Other impacts on soil which are likely to affect soil biota	Likely impacts on soil function for agriculture and other ecosystem services
Managing amount and quality of organic matter inputs			
• Use of green waste compost, mushroom compost, paper waste, coffee grounds i.e., application of (local) waste organic matter. • Repeated applications	• Provides energy / nutrient source for soil food web • Supports increased biomass • May increase species richness and evenness depending onOM quality – C/N ratio etc	• Stimulates structural formation processes after disturbance • Improves structural stability in many • soils • Improves drainage in poorly drained • soils • Improves water holding capacity in sandy soils • Fertiliser effects of nutrients supplied stimulate plant growth and C inputs via roots and residues	• Improves nutrient supply for plant growth • Improves soil structure and its stability – reducing sediment loss • Increases soil C content – C storage • Improves water balance, regulate water flows • Increases greenhouse gas production – increase soil respiration – CO_2 production, if soils become waterlogged increase N_2O production
• Application of seaweed	• Provides energy / nutrient source for soil food web	• Improves structural stability in many soils through release of algal • polysaccharides	• Improves nutrient supply for plant growth

			• Improves soil structure and its stability – reducing sediment loss • Improves water balance, regulate water flows
• Vermicomposting	• Provides energy / nutrient source for soil food web • May increase species richness and evenness depending on “quality” – potentially manipulated through feedstocks	• Fertiliser effects stimulate plant growth and C inputs via roots and residues • As for repeated application of OM above	• As for repeated application of OM above

Land management practice	**Direct impacts on soil biota**	**Other impacts on soil which are likely to affect soil biota**	**Likely impacts on soil function for agriculture and other ecosystem services**
Specific target interventions			
Not employing soil sterilisation	Cessation should increase biomass, activity and diversity of soil biota. Fumigation shows immediate negative impacts on the activity of soil biota; repeated use leads to reduced biomass and species richness of all soil biota. Long-term fumigation may lead to cumulative impacts on community structure, which may not naturally return on cessation.	None expected	Few impacts expected; cessation of sterilisation approaches is likely to be linked to other cropping or management changes which may have effects
Reduced use of pesticides,	Limited direct impacts expected, little evidence of	Reduced use of herbicides increases weediness, and hence increases variety in root biomass, rooting patterns,	Few impacts expected; reduced use of pesticides may be linked to other management

including copper sulphate (used in organic farming)	negative effects at field rates of application • Some benefits may result from fewer applications of insecticides • Reduction or cessation of Cu inputs may not reduce impacts on earthworm populations if Cu toxicity has developed	amount and quality of root exudates and duration of soil cover. • Reduced glyphosate application may increase decomposability of crop residues	changes which may have effects • Reduces pesticide losses to water
• Targeting inputs of fertiliser and pesticides = precision farming	• No direct effects expected	• Few expected; minimises any negative impacts of inputs	• Few impacts expected; increase targeting of inputs may be linked to other management changes which may have effects • May improve nutrient use efficiency, and reduce nutrient leaching risk

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