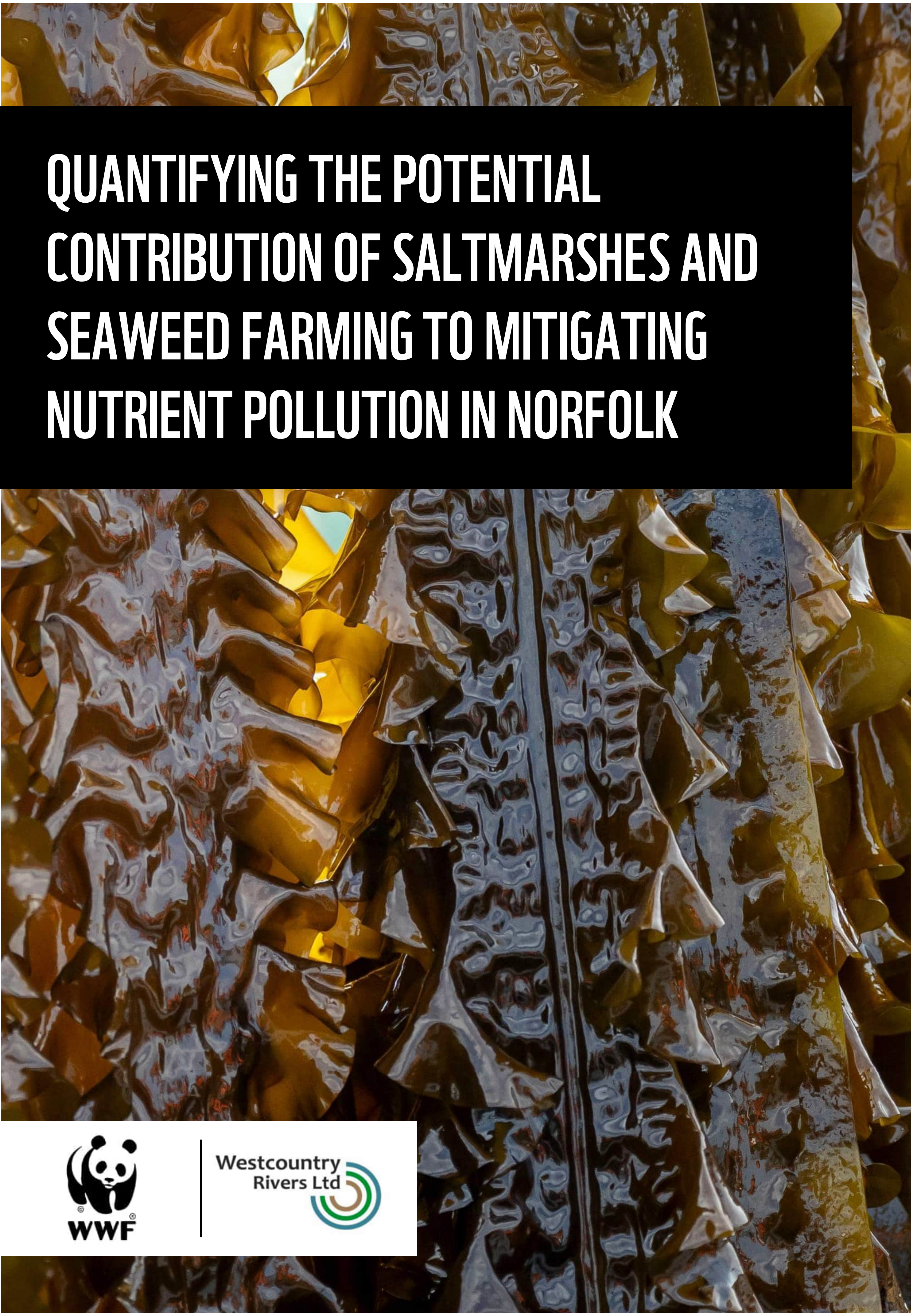
QUANTIFYING THE POTENTIAL CONTRIBUTION OF SALTMARSHES AND SEAWEED FARMING TO MITIGATING NUTRIENT POLLUTION IN NORFOLK



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Westcountry Rivers Ltd

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This report has been written and prepared by Westcountry Rivers Limited: Freya Stacey and Emily Howard-Williams. The report was commissioned by WWF-UK.

Primary WWF-UK Contributors: Tom Brook, Mollie Gupta and Piers Hart

Acknowledgements: Daisy Durden, Lucy Lee, Conor Linstead, Tom Stuart and Simon Walmsley

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EXECUTIVE SUMMARY

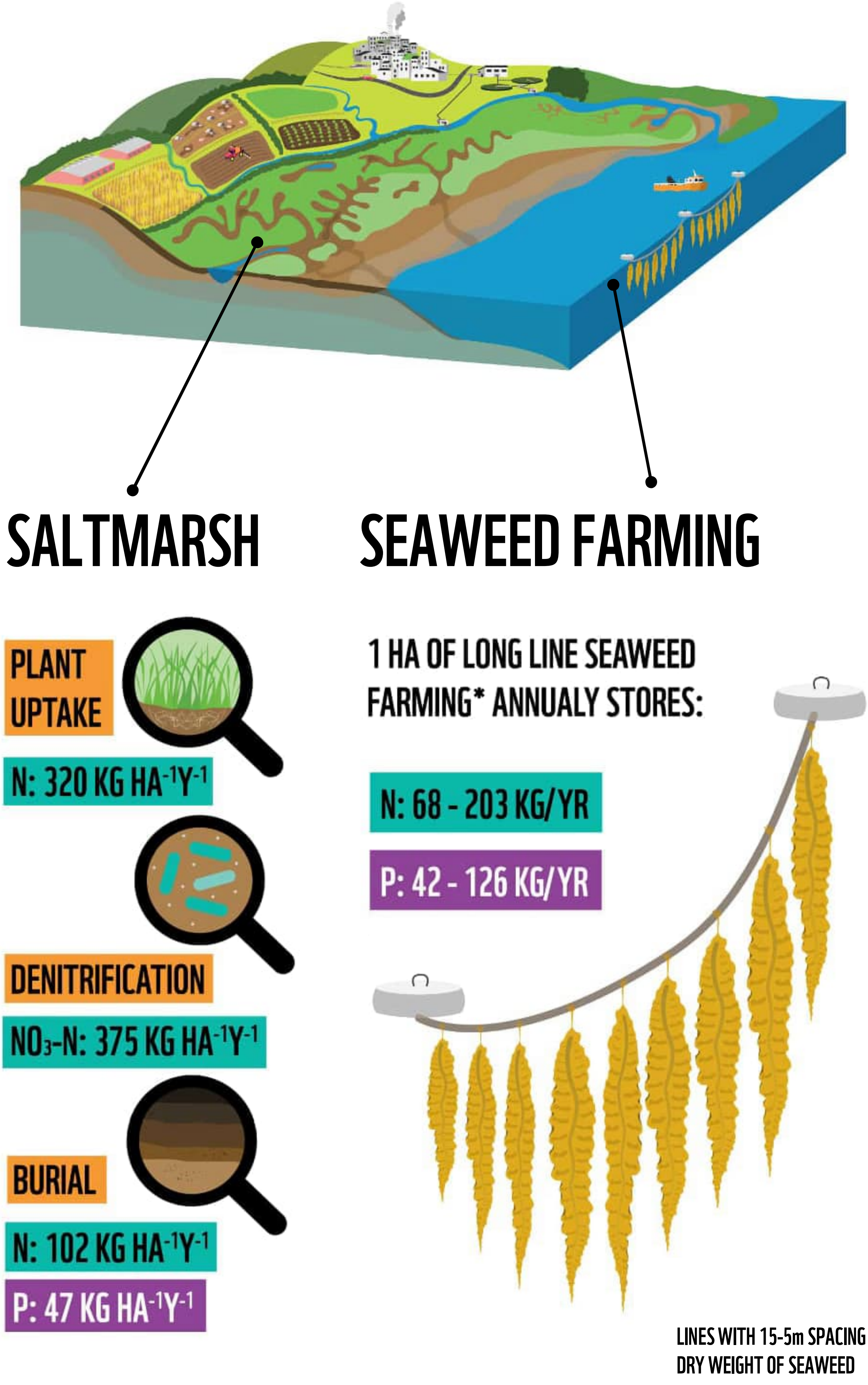
In 2021 WWF and 3keel estimated that the United Kingdom's (UK) per capita Nitrogen (N) and Phosphorus (P) footprints would need to be reduced by more than 80% to meet planetary boundaries. This would bring levels back down to within the limits of environmental self-regulation. Nutrient pollution is a widespread issue across the UK, with growing levels of concern in the general public and is key for the water, environmental, planning, and agricultural sectors, amongst others. The interactions between land-use, landform, nature and source of nutrient pollution means the issue can vary significantly between and within catchments, as can the resulting negative impacts. When reviewing nutrient pollution problems and potential mitigation opportunities, it is essential to take a targeted, local approach.

Norfolk is a highly productive county whose landscape is dominated by agriculture. The combination of nutrient pollution associated with agricultural and urban sources across the county demonstrates that Norfolk, 90% of which is designated as a Nitrate Vulnerable Zone, would benefit from a local scale review of nutrient pollution. This is evident from the surface water quality statuses classified by the Environment Agency and the application of Natural England's nutrient neutrality planning principles. Part 1 of this report describes the problem of excess nutrients, specifically N and where possible, P, and presents the key sources, pathways and sinks of nutrients from catchment to coast in the Norfolk focus area. Part 2 then presents the potential of saltmarsh restoration/creation and seaweed farming, previously under-explored in-situ measures, to mitigate the impacts of excess nutrients on coastal waters through bioremediation.

Part 1 illustrates that nutrient pollution is a significant issue affecting the majority of Norfolk. Nutrients entering the water network are primarily associated with sewage, agriculture, industrial processes, and transport. The highest levels of nutrient risk were found in the west of the county, due to the underlying soil type, presence of higher risk arable agriculture, and greater levels of surface water connectivity. This area corresponds with the highest levels of nutrients modelled in the coastal environment. Without a decrease in inputs across the catchments of Norfolk, as per the primary management option for nutrient pollution, no tangible water quality improvements will be realised.

In Part 2, the bioremediation estimates illustrate that there is great potential for saltmarsh restoration and seaweed farming to support mitigation of local nutrient levels. For instance, combining the three pathways by which saltmarsh can remediate nutrients - plant uptake, denitrification and burial - it is possible that approximately 800 kg of nitrogen, and 47 kg of phosphorous could be removed per hectare annually. In comparison, a dense sugar kelp (*Saccharina latissima*) farm could annually remediate up to 203kg of nitrogen, and 126 kg phosphorous per hectare. Whilst the nitrogen remediation potential is modest in comparison to saltmarsh figures, phosphorous remediation may be more favourable. Additionally, seaweed farms could offer an opportunity to provide local sources of native seaweed biostimulant, which could in future be used to support reductions in fertiliser inputs on farms, subject to appropriate field trials.

There is potential for bioremediation to act as a secondary management option for the nutrient pollution issues in Norfolk, but there are key areas where further work is required before the true potential of saltmarsh and seaweed farming can be fully understood and realised. Nutrient pollution is one of the key challenges facing the UK, and future policy and remediation efforts will need to be underpinned by robust evidence. This report provides a case study exploration of nutrient sources and flows in Norfolk. It also highlights future areas of research required to maximise the potential to use bioremediation measures, such as a saltmarsh restoration and seaweed farming, to mitigate such nutrient issues. With more knowledge, these methods could deliver tangible water quality and ecosystem benefits, both in Norfolk and more widely across the UK. Meanwhile, reducing input at catchment level continues to be the first priority.



SALTMARSH

PLANT UPTAKE

N: 320 KG $HA^{-1}Y^{-1}$

DENITRIFICATION

NO_3-N: 375 KG $HA^{-1}Y^{-1}$

BURIAL

N: 102 KG $HA^{-1}Y^{-1}$

P: 47 KG $HA^{-1}Y^{-1}$

SEAWEED FARMING

1 HA OF LONG LINE SEAWEED FARMING* ANNUALY STORES:

N: 68 - 203 KG/YR

P: 42 - 126 KG/YR

LINES WITH 15-5m SPACING
DRY WEIGHT OF SEAWEED

INTRODUCTION

Balancing the needs of people, while tackling climate change, biodiversity loss and nature restoration is one of our greatest challenges. Being able to meet societal needs is intrinsically linked to, and underpinned by, the ecosystem services and benefits that the natural environment provides. The provision of ecosystem services such as clean and plentiful water, is dependent on healthy and in the most part, naturally functioning ecosystems. When the normal balance is disrupted, the provision of these services are at risk. One of the issues inherently linked to meeting the needs of people and causing an imbalance is the increased production, use and subsequent availability of nutrients, specifically nitrogen (N) and phosphorus (P), resulting in nutrient pollution in fresh and coastal waters.

It was recently estimated by WWF and 3keel that to meet planetary boundaries, the United Kingdom's (UK) per capita N and P footprints need to be reduced by more than 80% (Jennings et al., 2021). This estimate only considered the agricultural elements of nutrient use, which is responsible for the highest proportion of pollution, but it is important to consider the other sources as well, such as sewage and industrial processes. While there are a whole suite of additional pollutants that arise from these three key sources, N and P comprised two of the three pollutants that needed the most reduction to meet planetary boundaries identified by WWF and 3keel (89 and 85% respectively). The largest component of N pollution in the UK is the portion lost to aquatic systems (in both mineral and organic forms) at ~712 kt N a^{-1}. The interactions between land-use, landform and sources of nutrient pollution means losses can vary significantly across catchments, as can the resulting negative impacts. So, when reviewing nutrient pollution and potential mitigation opportunities a targeted, local approach is favoured, such as county level.

Norfolk is a highly productive county whose landscape is dominated by agriculture. As with much of the east of England it has a long history of draining low-lying areas and reclaiming land from the sea to provide additional farmland. The combination of this with other agricultural and urbanisation impacts means that Norfolk is an example of an area that would benefit from a local scale review of nutrient pollution, including the sources and risks of nutrient pollution, as well as the opportunities to mitigate the associated negative impacts. This report provides an overview of water quality risks and opportunities in Norfolk. Part 1 describes the problem of excess nutrients, specifically N and where possible, P and presents the key sources, pathways and sinks of nutrients from catchment to coast in the Norfolk focus area. Part 2 then presents the potential of previously under-explored *in-situ* measures to mitigate the impacts of excess nutrients on coastal waters.

THE ROLE OF NITROGEN AND PHOSPHORUS

Nitrogen (N) and phosphorous (P) are fundamental, life sustaining nutrients for all organisms. N is an essential element of all the amino acids in plant structures, and it is vital in the growth and development of plant tissues and cells, making it essential for photosynthesis (Cai, 2018). P is an important component of DNA, it is a vital building block for cell membranes and is used in any biological process that uses energy. As they are both essential nutrients for healthy plant growth, they are very important for sustaining productivity in modern agricultural systems. Agriculture is the biggest source of excess N in the UK, followed by industrial processes, the water industry, transport and public heat and electricity generation. This report focuses on just one part of N lost to the environment, the flux of N from land to water (Figure 1). If these nutrient losses are concentrated, they can have a damaging impact on receiving fresh and coastal water ecosystems and the organisms that depend on them.

N and P are found in numerous forms in the natural environment, and in addition to these elemental forms, other forms discussed include - nitrate (NO_3); nitrate as N (NO_3-N); nitrous oxide (N_2O); nitrous oxide as N (N_2O-N); phosphate (PO_4); phosphate as P (PO_4-P). When -N or -P follows the chemical formula, this means molar weight of the compound without the oxygen is being reported.

THE IMPACT OF EXCESS NUTRIENTS

In a naturally cycling system the availability of N and P will determine the growth potential of plants; in marine ecosystems where N is limited or freshwater systems where P is limited, plant growth, will in turn be limited. This limitation results in a balanced and naturally functioning ecosystem. However, this balance is easily disrupted when more nutrients are available than are required, which is normally a consequence of increasing anthropogenic pressures from agriculture, industry or waste management. These additional nutrients can be transported either directly or indirectly to the water network where they can accumulate, and nutrient enrichment can occur.

Nutrient enriched freshwater and marine waters can lead to eutrophication, this is where phytoplankton and algal communities use the additional nutrients and grow excessively, causing blooms which can physically and chemically disrupt habitats. Where the biomass of a bloom becomes excessive, the water's surface can be completely blanketed which limits the amount of sunlight able to penetrate through the water column, in turn decreasing the ability of other plants to photosynthesise. When the algae dies, aerobic bacteria consume the oxygen in the water as they breakdown the dead material, effectively suffocating other aquatic life.

Eutrophication can be reduced by limiting the input of these nutrients within the catchment, this is always the primary solution. As shown in Figure 1, the greatest source of N lost to water is from agriculture, followed by the water industry then other industrial processes, therefore measures to reduce the input across these categories should be the primary solution to nutrient enrichment of fresh and marine waters. However, in addition to targeted reductions at source there are further *in-situ* measures that could also mitigate the impact of nutrient enrichment locally. This report explores the potential for saltmarsh restoration and seaweed farming to mitigate nutrient pollution in Norfolk.

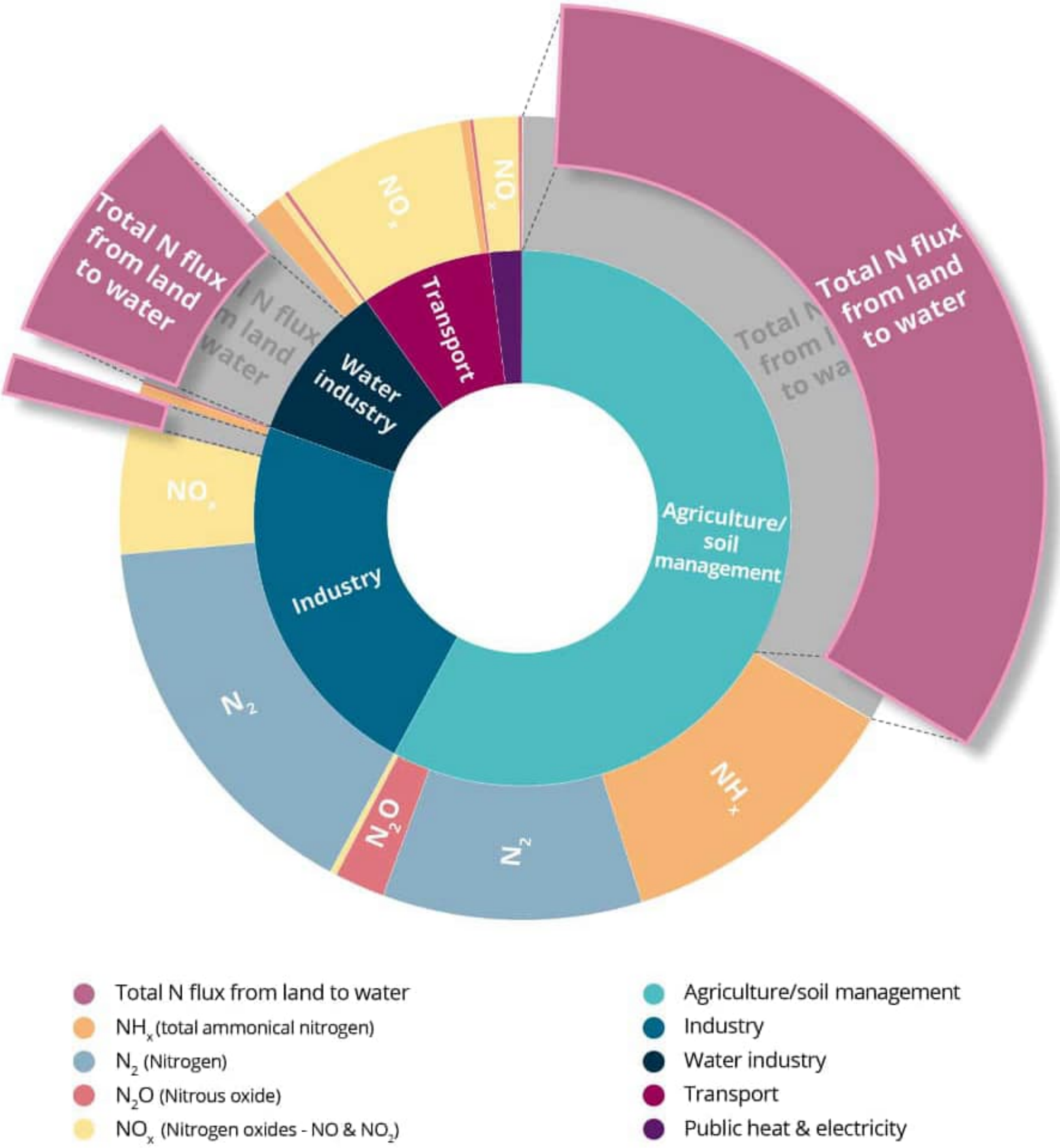


Figure 1. An adaptation of Figure ES1 from the WWF's 'Finding the Balance' report (Hicks et al., 2022), which highlights the losses of nutrients from land to water. The figure shows the relative magnitude of estimated rates of loss to the environment for the major nitrogen cycle pollutants by source and by chemical species. This chart, based on the data in Table ES1 from the WWF's 'Finding the Balance' report (Hicks et al., 2022), shows the magnitude of losses by weight of nitrogen, but not the importance of their impacts, which vary from human health, through global warming, to waste of resources.

PART 1:

FLUX OF NUTRIENTS FROM LAND TO WATER: NORFOLK

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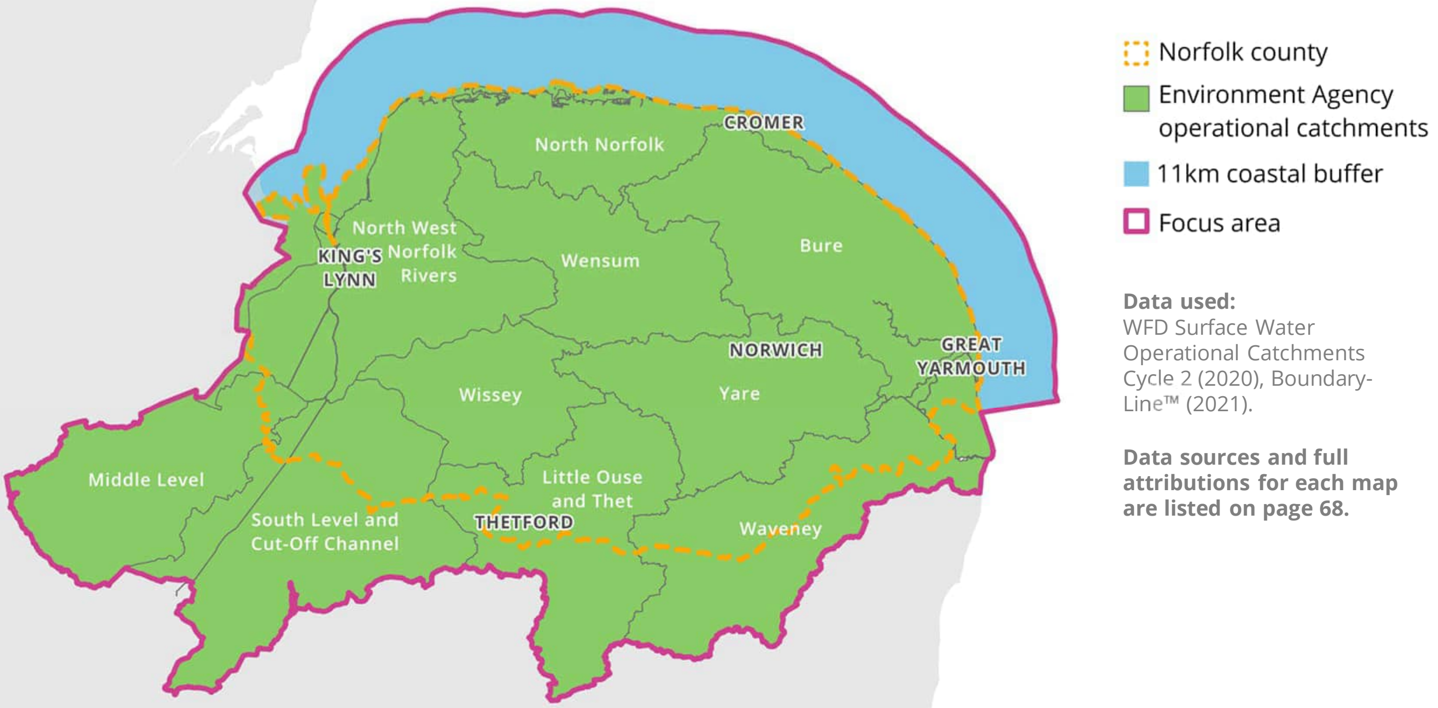
NORFOLK LANDSCAPE

Figure 2. A map of England highlighting the location of the focus area for this report.

Norfolk is located on the east coast of England and is bordered by the North Sea (Figure 2). This area has a long history of human activity with some of the earliest evidence of human occupation of what we now know as Great Britain. From flat plateaus, undulating hills, low-lying floodplains and coastal margins, the landscape of Norfolk is a representation of its underlying geology combined with the influence of the sea and the interactions of people. Flat, low lying, open coastal plains gradually rise inland to the mosaic of arable field parcels, dissected by lush pastural river valleys with internationally rare chalk streams, and bordered to the east and west by large areas of low-lying wetlands. The agricultural landscape is based on a long history of drainage to enable the wet low-lying areas to be worked and grazed. There are vast networks of drainage channels, dikes and rivers that slowly drain water towards the coastal mudflats and shingle beaches that stretch out towards the sea.

The coastline is characterised by three distinct forms, in the west the terrestrial land butts onto saltmarshes behind which sit shingle beaches, including the famous shingle ridge that forms Blakeney Point spit. Much of this coastal fringe has been artificially modified through diking systems and sluices to reclaim the land for agriculture at the expense of natural saltmarsh habitat. The next distinct form of coast is characterised by soft cliffs comprised of mix of silts, sands, clays and gravels deposited during the glacial period. These cliffs provide little protection from the power of the sea and are susceptible to erosion. The final section of the coastline within our focus area is defined by sand dunes which are all that separates the low-lying Norfolk Broads from the sandy beaches.

The focus area of this report is the county of Norfolk but with some additional areas that lie within the Environment Agency's operational catchment boundaries that overlap the county border, and an 11km coastal buffer, as shown by Figure 3.

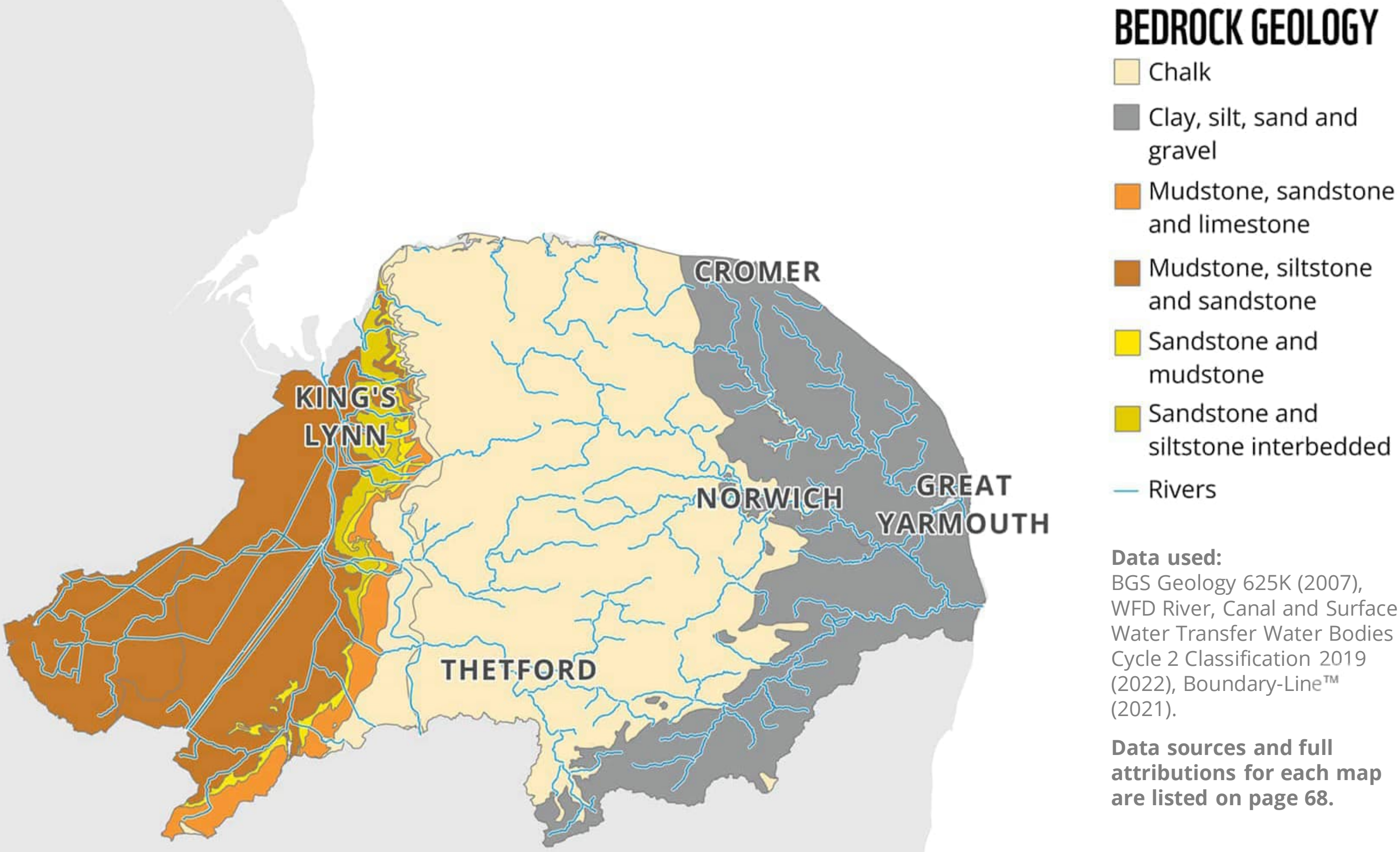


Data used:
WFD Surface Water Operational Catchments Cycle 2 (2020), Boundary-Line™ (2021).

Data sources and full attributions for each map are listed on page 68.

Figure 3. A map of the focus area showing its constituent parts; the county boundary of Norfolk, the Environment agency operation catchments and the coastal buffer zone.

The underlying geology of any area will, to some extent, influence the hydrology, habitats and species that are found there. As Figure 4 below shows the dominant bedrock geology in Norfolk changes from sandstone and mudstones in the west, through a large area of chalk in the middle of the county, to clays and silts in the east.



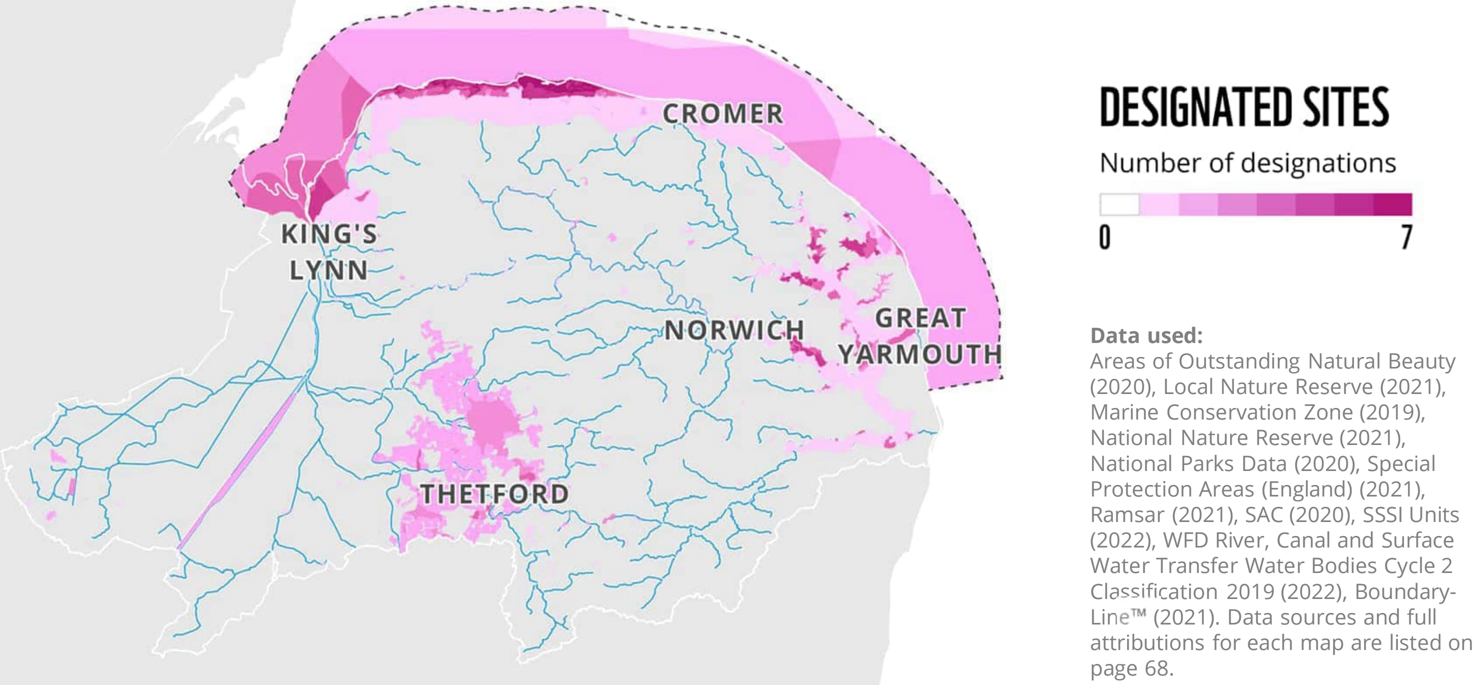
Data used:
BGS Geology 625K (2007), WFD River, Canal and Surface Water Transfer Water Bodies Cycle 2 Classification 2019 (2022), Boundary-Line™ (2021).

Data sources and full attributions for each map are listed on page 68.

Figure 4. The bedrock geology within the focus area. Geological components impact how catchments function hydrologically.

Lying below the chalk, sandstones and mixed clay, silt, sand and gravel areas are important aquifers which supply the many internationally rare chalk-fed rivers. These are exceptional ecosystems that provide a habitat haven that allows a large variety of fauna and flora to thrive including Eurasian otter *Lutra lutra*, Starworts *Callitriche*, Brown trout *Salmo trutta* and White-clawed crayfish *Austropotamobius pallipes*.

Many of the habitats found in Norfolk, including aquatic, terrestrial and coastal, are protected by national and international designations. As shown by Figure 5 much of the focus area is covered by designations, many sites with more than one as there is often considerable geographic overlap between them. For example, many sites are designated as SSSI, SAC and SPA, almost all Ramsar sites are underpinned by the SSSI designation, and most Ramsar sites are also SPAs. Table 1 shows the area (ha) of each type of designation within the focus area. A designation does not necessarily indicate optimum condition. Within the project area just 49% of SSSI designated areas are classed as in 'favorable' condition, which indicates habitats and features are in a healthy state and are being conserved by appropriate management.



Data used:
Areas of Outstanding Natural Beauty (2020), Local Nature Reserve (2021), Marine Conservation Zone (2019), National Nature Reserve (2021), National Parks Data (2020), Special Protection Areas (England) (2021), Ramsar (2021), SAC (2020), SSSI Units (2022), WFD River, Canal and Surface Water Transfer Water Bodies Cycle 2 Classification 2019 (2022), Boundary-Line™ (2021). Data sources and full attributions for each map are listed on page 68.

Figure 5. The designated areas present within the focus area. These areas are protected for their natural or heritage of landscape features.

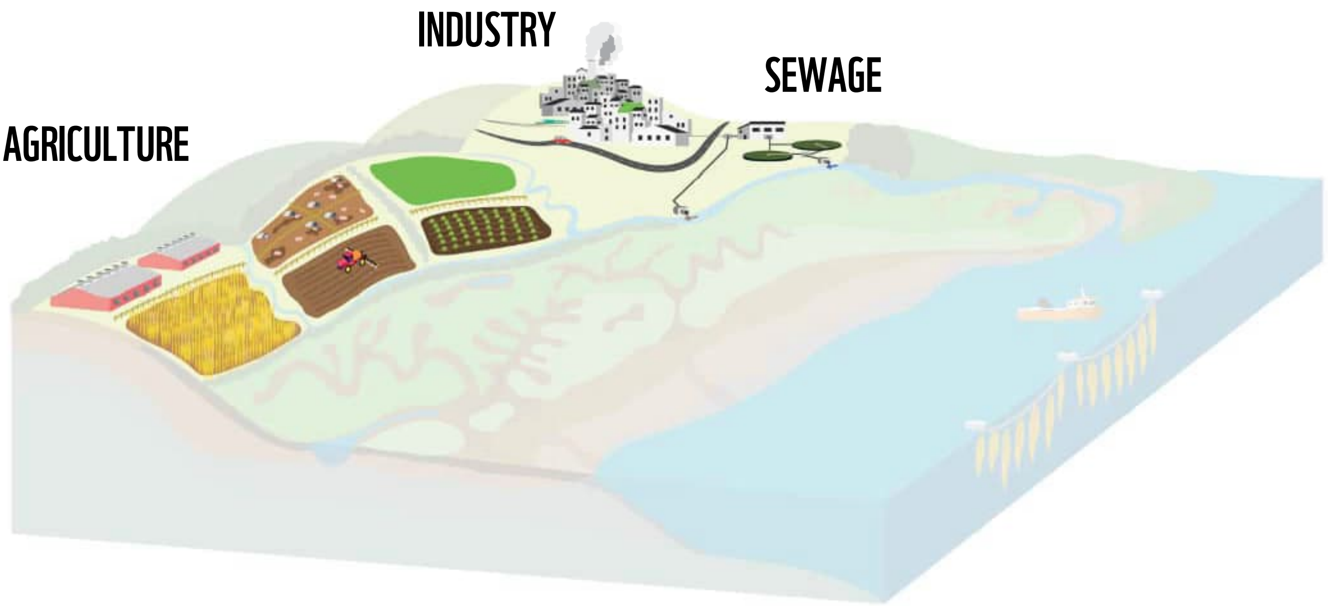
Table 1. Designations present in the focus area and the total area designated in hectares (ha).

	DESIGNATION		DESCRIPTION	AREA (ha)
Nature conservation	Ramsar sites		Wetlands of international importance	**48,103**
	Sites of special scientific interest	**SSSI**	Areas containing rare species of flora or fauna, geological or physiological features	**65,939**
	Special areas of Conservation	**SAC**	Areas protected under the Conservation of Habitats and Species Regulations 2017, Conservation of Offshore Marine Habitats and Species Regulations 2017	**150,723**
	Special protection Areas protected	**SPA**	Areas for birds under the Conservation of Habitats and Species Regulations 2017, Conservation of Offshore Marine Habitats and Species Regulations 2017	**216,655**
	Marine Conservation zones	**MCZ**	Nationally important habitats and species in territorial and offshore waters	**32,048**
	National nature reserves	**NNR**	Areas designated as key places for wildlife and natural features in England. Established to protect the most significant areas of habitat and of geological formations.	**17,937**
	Local nature reserves	**LNR**	A protected area of land designated by a local authority because of its special natural interest and/ or educational value	**1,080**
Natural heritage conservation	National Park	**NP**	Large areas of land protected by law for the benefit of the nation, originally established by the 1949 National Parks and Access to the Countryside Act.	**30,151**
Landscape conservation	Area of outstanding natural beauty	**AONB**	Land protected by the Countryside and Rights of Way Act 2000, to conserve and enhance natural beauty.	**44,591**

SOURCES OF NUTRIENTS LOST TO WATER

When it rains excess nutrients can wash into the river network, and percolate down through the ground to accumulate in groundwater. These nutrients can have negative impacts within the river network as well as travelling through catchments to the sea where they can also cause similar issues in coastal waters.

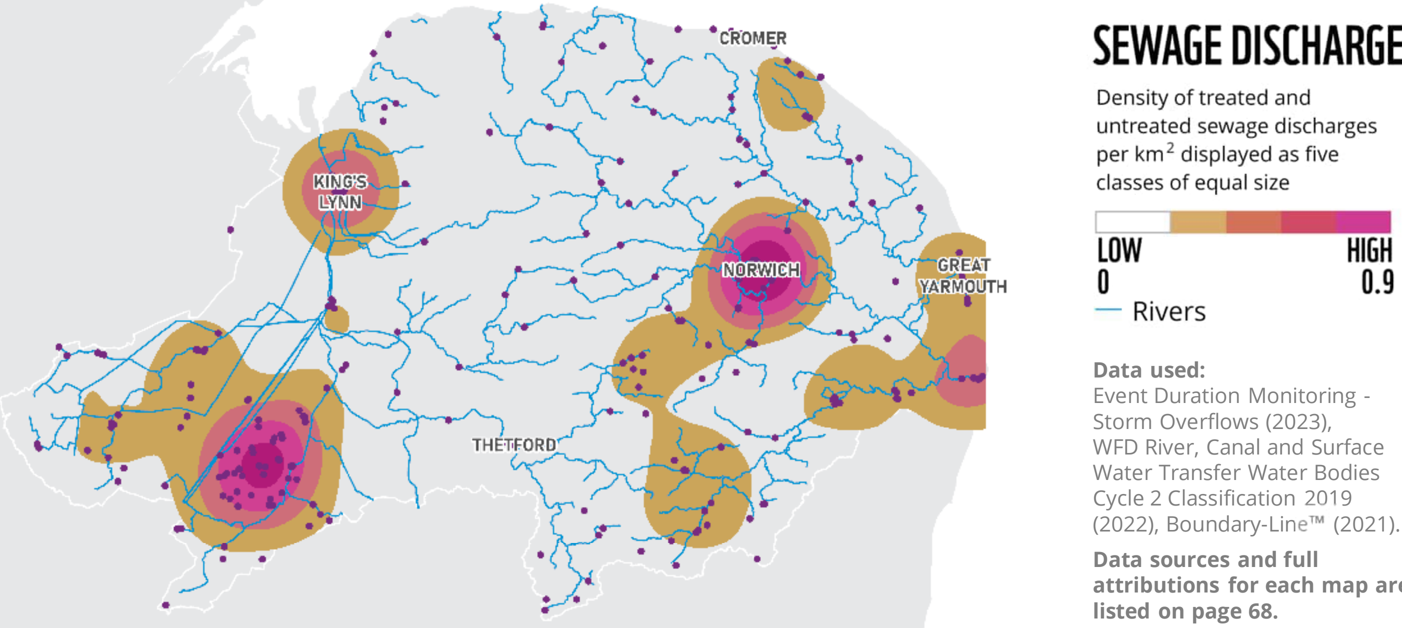
Norfolk and the wider focus area contains a large portion of farmland. Agricultural practices are significant sources of excess nutrients lost to the environment. There are three main sources associated with agricultural practices that are likely to be relevant to this area. These are the inefficient management of synthetic fertilisers in arable crop production, poor animal waste management practices, and intensive arable crop production on drained and degrading peaty soils. Other sources that contribute to nutrient pollution include domestic and industrial sewage, either from spills of raw sewage or discharges of treated effluent (although water is treated to legal standards, the levels of treatment are not always adequate to protect river health), and industrial processes including transport and energy production. The transport and industry sector are key sources of excess N via combustion and other processes, particularly the combustion of fossil fuels. The main forms of N emitted in this way are gaseous forms of nitrogen oxides (NOx) (nitric oxide (NO) and nitrogen dioxide (NO_2)). Gaseous forms of N can precipitate out onto the land surface where it can then also be lost to water via surface flows into the river network. It is not possible to identify the sources of nutrient pollution from atmospheric deposition with the data available. Although it may add to the nutrient loading, we have not included it this analysis. Data on atmospheric deposition is available at the UK Air Information Resource.



SEWAGE

Sewage effluent contributes between 25-30% of NO_3 inputs to water in the UK, it also a major source of phosphate (Hicks et al., 2022). Treated effluent from wastewater treatment works is regulated by thresholds, but these vary according to population size and whether the receiving waters are in designated areas such as Ramsar/Natura sites. However, it is not only treated effluent that enters rivers. In England much of the sewer network is a combined system. This means that rainwater and wastewater from toilets, bathrooms and kitchens are transported in the same pipe to a sewage treatment works. During heavy rainfall, the capacity of these pipes can be exceeded so combined sewer overflows (CSOs) were developed as overflow valves to reduce the risk of sewage backing up and causing flooding. This means that in some situations untreated sewage is discharged into rivers and coastal waters. Small private sewage treatment systems are often exempt from permits and gaining an accurate assessment of the exact number of small sewage discharges is difficult as it depends on the owner registering its existence. The effective functioning of these systems is also reliant on the owner. As such septic tank numbers could play a larger role in catchment nutrient budgets than can currently be estimated.

Figure 6 shows the location and density of combined sewer overflows (CSOs) per km^2. The areas with the highest number of overflows could indicate that nutrient pollution is more likely. However, the data presented in this map does not indicate the level of nutrient inputs from discharges or the risk to surface waters. The overflows mapped only include water company owned CSOs that have monitoring equipment installed, while that is the majority it is not all of them. Other sources of raw and treated sewage inputs have not been included due to the lack of available data.



SEWAGE DISCHARGES

Density of treated and untreated sewage discharges per km^2 displayed as five classes of equal size

Data used:
Event Duration Monitoring - Storm Overflows (2023), WFD River, Canal and Surface Water Transfer Water Bodies Cycle 2 Classification 2019 (2022), Boundary-Line™ (2021).

Data sources and full attributions for each map are listed on page 68.

Figure 6. The density of combined sewer overflows (per square kilometre). The data used to produce this density heat map shows water company owned combined sewer overflows that have monitoring equipment installed, while that is the majority it is not all of them. Other sources of raw and treated sewage inputs have not been included due to the lack of available data. Sewage is a major source of nutrient pollution, both raw and treated wastewater can contribute to nutrient pollution.

AGRICULTURE

The east of England is a productive area, often referred to as Britain's breadbasket, with 83% of farmland under arable production which is the greatest proportion across all regions. In Norfolk specifically, 76% of the county is devoted to farming, of which 79% is classed as arable, 12% as livestock production, 5% as mixed agriculture, 3% as horticulture and 1% as 'other' (Defra, 2021). In the UK the majority of N losses from land to water come from the farming sector (about 70%) (Environment Agency, 2019) and in general, NO_3 concentrations are greatest in the drier, arable-dominated southern and eastern areas of England. In 2019, 55% of England was designated as a Nitrate Vulnerable Zone (NVZ) due primarily to elevated NO_3 concentrations in groundwater and rivers, and to a lesser degree because of eutrophication of estuaries and lakes/reservoirs (Defra and Environment Agency, 2021). In Norfolk this designation covers 90% of the county.

Nitrate Vulnerable Zones have additional rules regarding the use and storage of N fertilisers that farmers must follow in addition to the cross compliance rules required under the rural payment schemes (farm subsidies). The Department for Environment, Food and Rural Affairs (Defra) reviews NVZs every four years to account for changes in NO_3 concentrations. The last review was in December 2020 and it did not find substantial changes in the patterns of NO_3 pollution in England, so the NVZ areas remain the same for 2021 to 2024.

Livestock waste in the forms of manure and slurry (manure in liquid form) are also spread on fields to improve soil or support crop growth, as with synthetic fertilisers this can lead to excess nutrients being lost to the water network. Although there are various rules and regulations that pertain to the storage and use of animal waste on fields (The Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018, Rules for Storing Silage, Slurry and Agricultural Fuel Oil (SSSAFO), as well as additional rules in NVZs) this is still a major source of nutrient pollution in rivers.

Another source of excess nutrients from the farming sector comes from the draining of wet peaty soils to enable crop production. Norfolk has around 160,000ha of peaty soils, mostly located in the fens in the east of the county, but also within the river valley network. Peat is formed by the accumulation and decomposition of plant materials under waterlogged conditions. They are generally classed as containing above 75% organic content. During the course of agricultural intensification many of the lowland peat soils in England have been drained. These drained fen or light peat soils are among the most fertile arable soils. Crops such as potatoes, sugar beet, celery, onions, carrots, lettuce and other salad crops are commonly grown. On light undrained peats, or where the water table remains high, the main crop is grass, such as the river valley areas in Norfolk where pasture is the dominant land use. The drainage of these soils induces the decomposition of the peat which releases the stored N allowing easier uptake by plants but also leads to N losses in the drainage water and to the atmosphere (Wang et al., 2022). Degraded soils are vulnerable to erosion, which also causes nutrient loss as nutrients bound to soil particles are washed into rivers. The decomposition of the peat also releases substantial amounts of methane and carbon dioxide. This land-use change has been a major source of carbon emissions since the industrialisation period (Kasimir-Klemedtsson et al., 1997).

ARABLE FARMING

Arable is the dominant farming type across Norfolk and within this sector the largest portion of land is used to grow barley, wheat, beets and maize (Defra, 2021). While these crops are often used to feed livestock in the UK, only 7% of crops in Norfolk are grown exclusively for animal feed (Defra, 2021). Many arable crops are grown intensively in the UK and this usually involves using synthetic fertilisers that, when managed inefficiently, can have negative impacts on the environment. The arable crops that pose the greatest risk of nutrient pollution have been identified through a combination of the level of fertilisers required during growth as well as the soil erosion risk associated with production. Table 2 shows the crops that are considered as 'risky' in this report (Defra and Environment Agency, 2021; Defra, 2023), all of which are grown in Norfolk, although in varying amounts. Figure 7 shows the potential sources of excess nutrients from arable farming within the project area. The map shows where 'risky' crops were grown in 2021, this is the most up to date available data on crop type from Defra at the time of writing. As shown by Figure 7 arable farming dominates the area and there is a relatively uniform coverage other than some distinct exceptions. These are mostly occupied instead by pasture, woodland and urban areas, and along the north coast by saltmarsh and beaches.

Table 2. The classification of 'risky' crops for the purpose of this report, where risk indicates that nutrient pollution may occur where these crops are grown. The crops tend to be grown intensively with higher fertiliser requirements and soil erosion impacts. Fertiliser application rates were taken from Defra (2023). Higher rates were determined as greater than or equal to the average application rate (of nitrogen and phosphorus separately), which was calculate from the crops listed within the report. In addition to the fertiliser requirement, crops with high soil erosion risk were taken from Defra (2019).

CROP	POTENTIAL RISK FACTOR		
	N APPLICATION	P APPLICATION	EROSION
Potatoes	X	X	X
Winter wheat	X		X
Winter oilseed rape	X		X
Winter barley	X		X
Rye/triticale/durum wheat	X		
Oats	X		
Spring wheat	X	X	
Spring barley	X	X	
Vegetables (brassica)		X	
Maize			X
Beets			X

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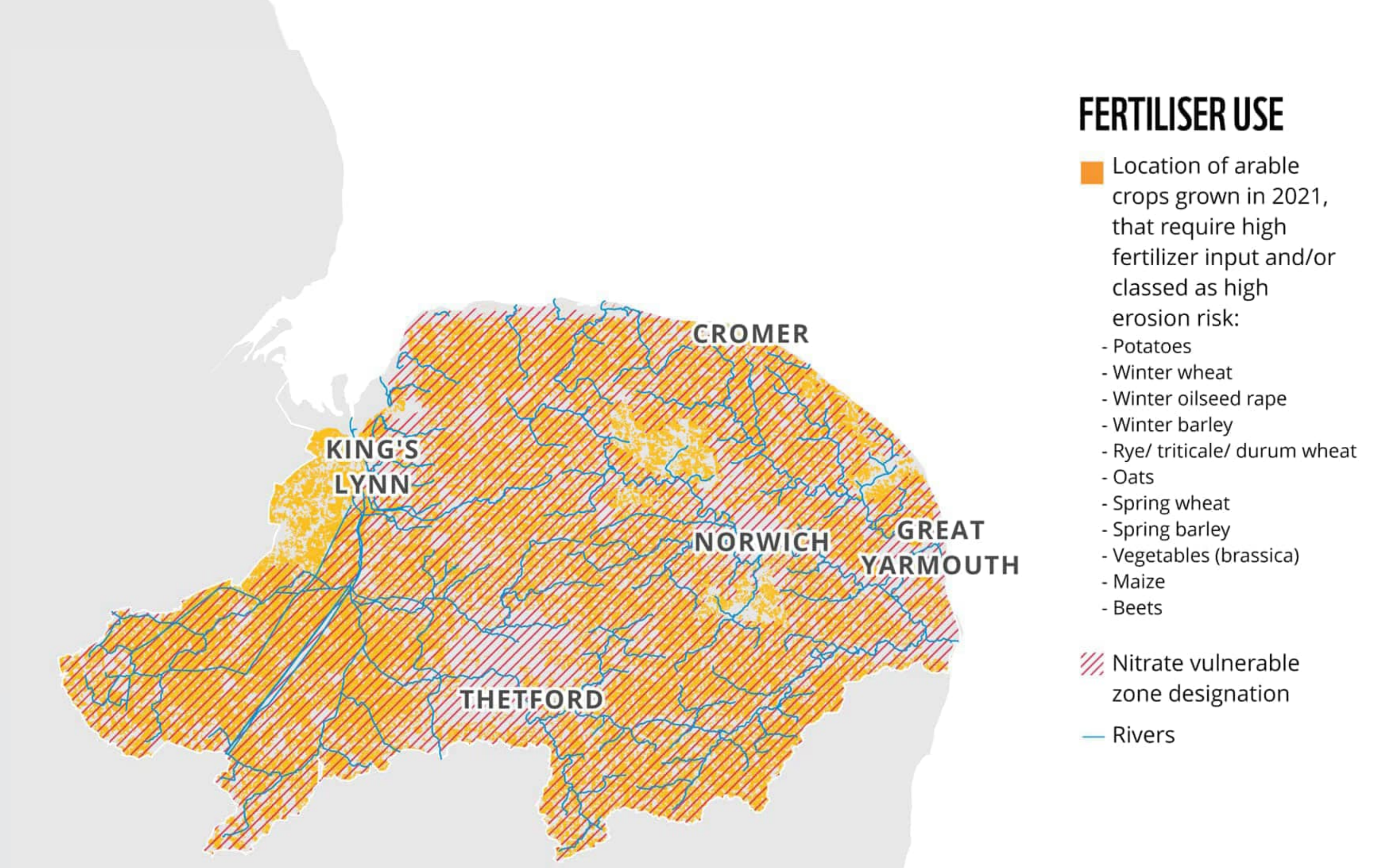


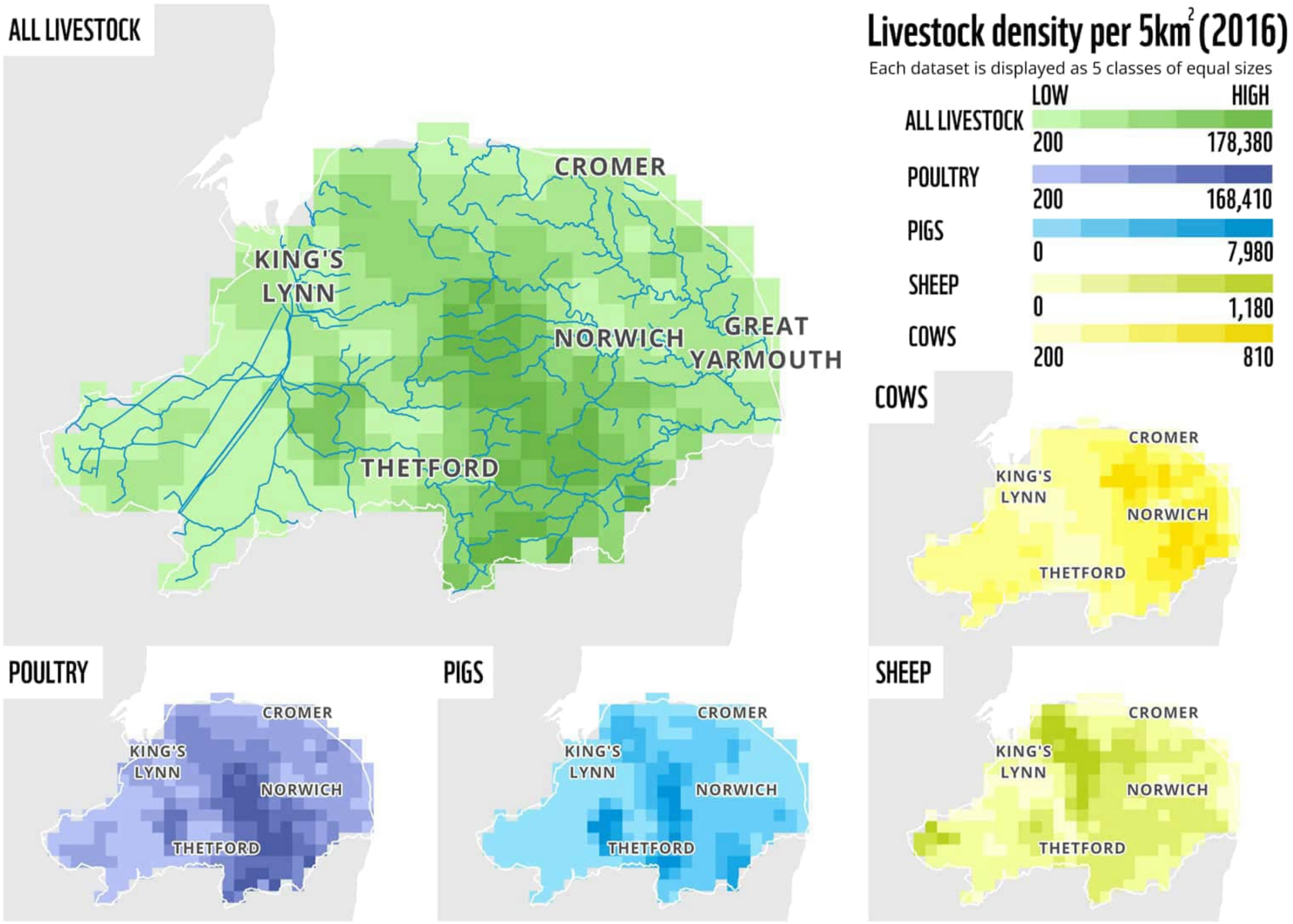
Data used:
Crop Map of England (CROME) 2021 (2022), Nitrate Vulnerable Zones (2017), WFD River, Canal and Surface Water Transfer Water Bodies Cycle 2 Classification 2019 (2022), Boundary-Line™ (2021).

Data sources and full attributions for each map are listed on page 68.

Figure 7. Areas where crops that pose a risk of nutrient pollution and/or soil erosion were grown in 2021.

LIVESTOCK WASTE

Livestock waste is spread on fields as a fertiliser for grass and other crops and to improve soil health. Poor storage and nutrient management practices regarding livestock waste can result in contributions to the nutrient pollution problem. Although just 12% of the farmland in Norfolk is used for livestock production the density of both pigs and poultry per hectare is higher than the average across all regions in England (Defra, 2021). Pigs and poultry are often reared intensively, which produces large amounts of livestock waste in a small area. There are also cattle, sheep and other livestock present within the area though at lower densities than average. Due to logistical complications with transportation livestock waste is often utilised within the local area. However, no information was available at the time of this report to determine where this is spread across the study area, at what concentrations, and the implications for nutrient pollution. Figure 8 shows densities of the top four types of livestock per 5km^2 within the focus area. The map uses Defra farm census data from 2016 (the most up to date data of this kind available spatially at the time of writing). Figure 8 illustrates that the highest densities of livestock occur predominately within the middle section of the focus area, this is principally due to the high numbers of poultry and pigs. Cattle are present in highest numbers in the east and sheep are highest in the north.



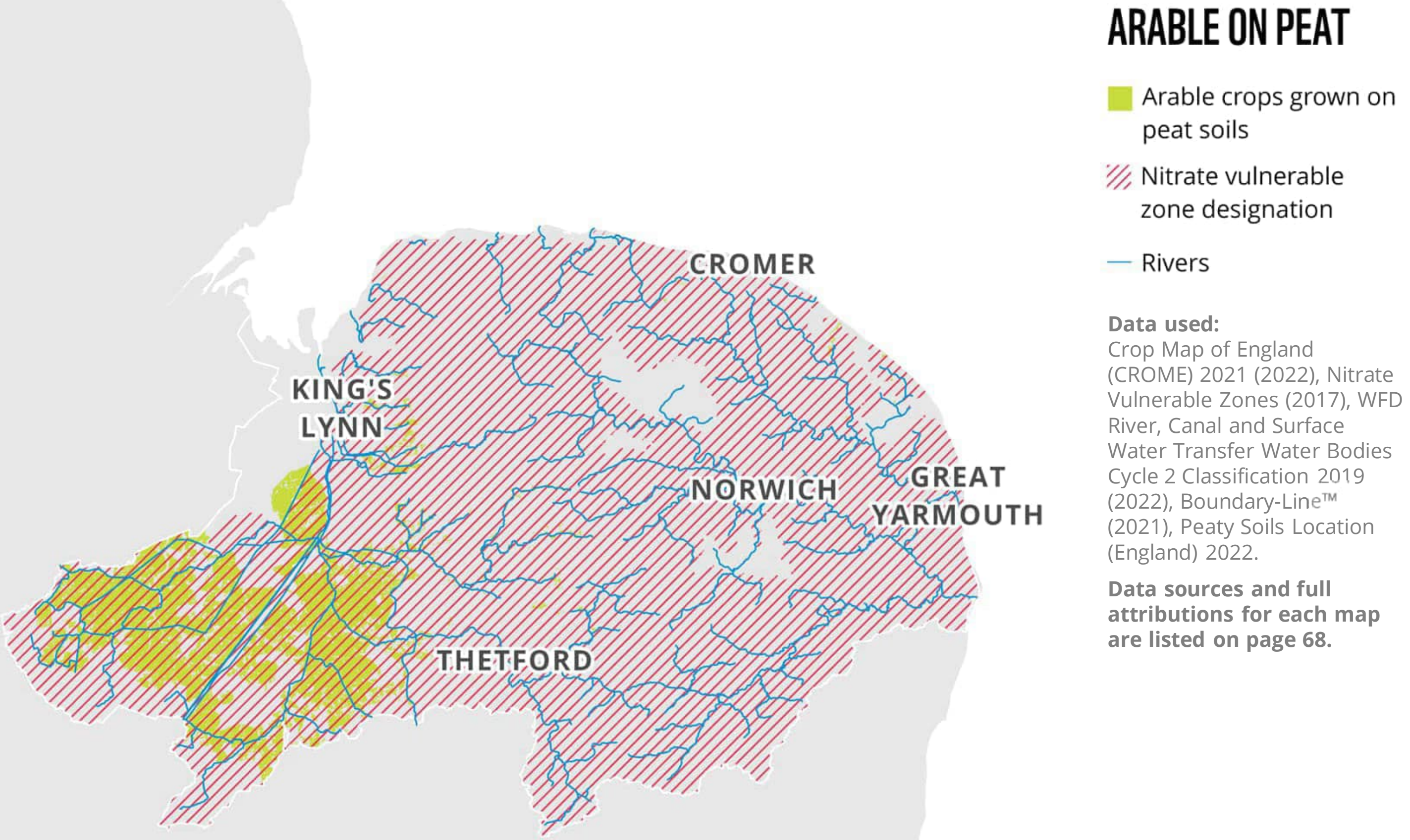
Data used: WFD River, Canal and Surface Water Transfer Water Bodies Cycle 2 Classification 2019 (2022), Boundary-Line™ (2021), Agcensus (2016).

Data sources and full attributions for each map are listed on page 68.

Figure 8. The density (number of livestock per 5 square kilometres) of poultry, cows, sheep and pigs, as well as the density of all livestock combined in 2016. The data comes from EDINA which creates spatial datasets from Defra's agricultural censuses. Algorithms developed by EDINA convert small area data provided by the government agencies into grid squares to visualise the data consistently. Note: each map has its own scale, visible in the legend. Livestock waste is a major source of nutrient pollution, and it is more likely to occur in areas where there are high densities of livestock, either through the use of the waste as a soil amendment or through poor storage management.

ARABLE FARMING ON PEAT SOILS

There are approximately 87,000ha of arable farmland on peaty soils within the focus area. The water drained from these soils can contain elevated nutrient levels which can impact local waterbodies and coastal environments. Figure 9 shows the location of arable crops grown in 2021 over peaty soils (these were the most recent available data on crop type at the time of writing this report), as well as the full extent of peat soils within the focus area. Arable crops grown on peat soils are nearly all located in the fen area to the west. Around 90% of the crops grown in this area are 'risky' for nutrient pollution, as described on page 19. There are additional areas of peat soils within the river valleys across the rest of the focus area, however these areas are predominately pasture, this also correlates with the higher densities of cattle in these areas, as shown by Figure 8. There will be some level of drainage within pasture over peat, but the degradation will be greater under arable management as erosion risks are higher.



Data used:
Crop Map of England (CROME) 2021 (2022), Nitrate Vulnerable Zones (2017), WFD River, Canal and Surface Water Transfer Water Bodies Cycle 2 Classification 2019 (2022), Boundary-Line™ (2021), Peaty Soils Location (England) 2022.

Data sources and full attributions for each map are listed on page 68.

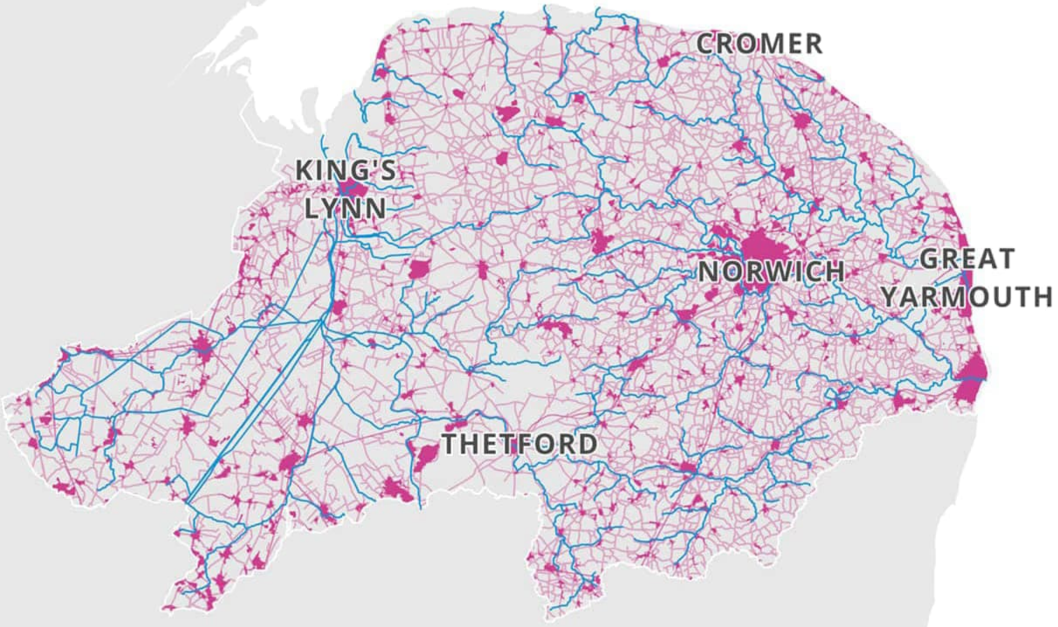
Figure 9. Areas where arable crops were grown on peat soils in 2021. Greater losses of nutrients to the surface water network may occur here as peat soils are known to leach nutrients when they are drained for agriculture and arable farming increases soil erosion risk.

INDUSTRY AND TRANSPORT

Despite a drop of more than 70% in emissions since the 1970s, NOx emissions from combustion of fossil fuels are currently still the largest source of atmospheric N pollution in the UK, accounting for approximately 250 kt N yr^{-1} (Hicks et al., 2022). Atmospheric deposition of reactive forms of N (Nr) can contribute to the losses to aquatic systems through soil erosion and surface runoff after atmospheric deposition has occurred. Figure 10 below shows the main industrial areas and major transport networks across the focus area, this is where combustion is most likely to occur. There is little research that looks specifically at the effects of gaseous NO$_x$ on freshwaters. The major role of NO$_x$ as a pollutant is its conversion in the atmosphere to nitric acid (HNO$_3$) vapor and NO$_3$ particles which are deposited directly or in precipitation, often many hundreds of km from sources (Hicks et al., 2022). This makes it difficult to determine what risk industry presents to nutrient pollution in the region (including the influence of NO$_x$ transport from outside the county). Some nutrients lost to water from the industrial sector with be in the form of industrial effluent that is discharged to surface water (under permits managed by the Environment Agency). The presence of nutrients in industrial discharges will depend on the type of industrial activity and will often be present alongside other harmful pollutants such as heavy metals.

INDUSTRY

- 🟪 Urban areas
- — Railway network
- — Road network
- — Rivers



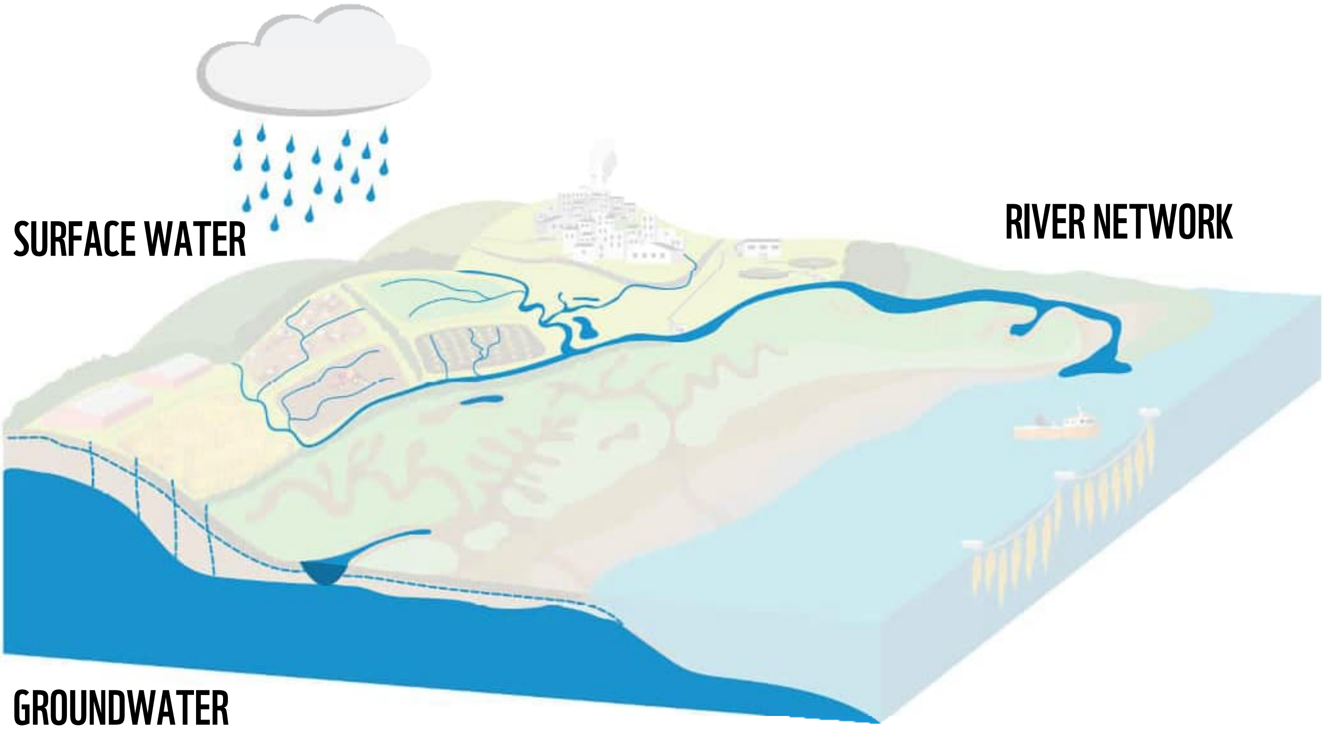
Data used:
Built Up Areas (2017), OS VectorMap District (2020), WFD River, Canal and Surface Water Transfer Water Bodies Cycle 2 Classification 2019 (2022), Boundary-Line™ (2021).

Data sources and full attributions for each map are listed on page 68.

Figure 10. Major urban areas, roads and railways across the focus area. These features indicate where NO$_x$ emissions are most likely to occur.

PATHWAYS OF NUTRIENTS LOST TO WATER

All water flows towards the sea, though depending on its journey this may take a matter of days or years. There are two key pathways in which nutrients lost to aquatic systems can reach the coast, via the surface water network and the groundwater network. Each pathway is not necessarily distinct and there will usually be elements of both involved and this will depend on the landscape above and below the ground level.



GROUNDWATER PATHWAYS

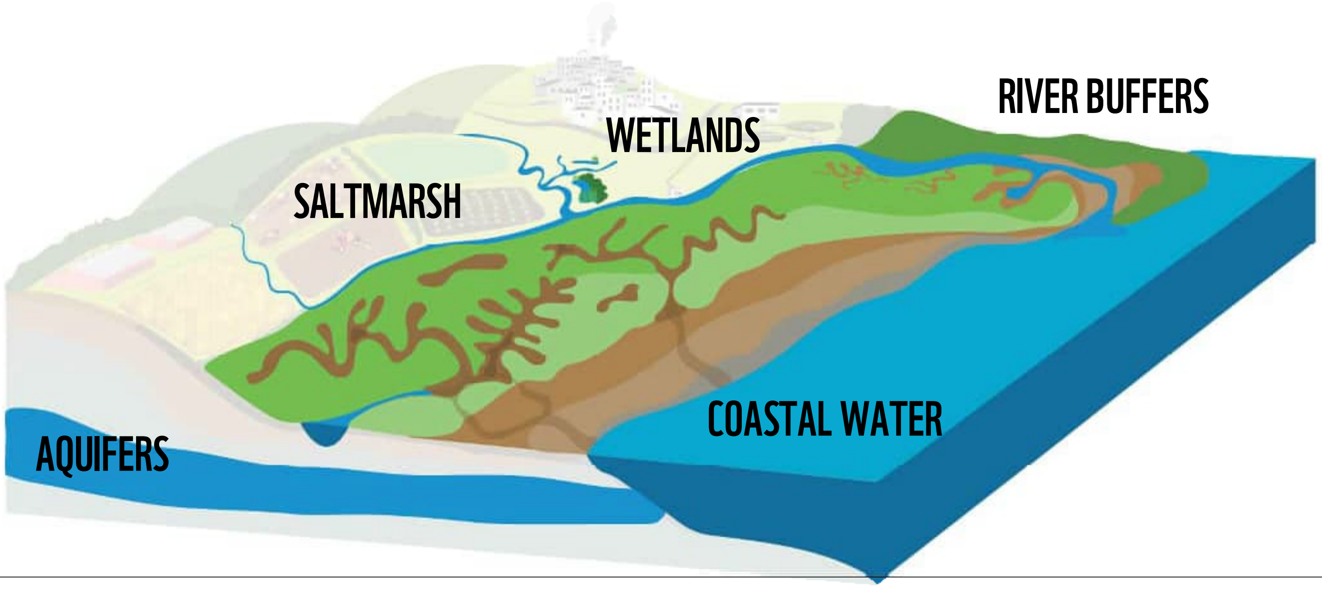
On permeable soils nutrients dissolved in rainwater percolate down through the soil structure into groundwater (water that exists below the land surface). These groundwater bodies can move into deeper layers of permeable geology such as the chalk bedrock in Norfolk, into large aquifers, or return to the surface via springs. The subsurface pathways of water to aquifers and ground fed rivers are determined by the characteristic of the substrate. Chalk is a permeable rock that allows groundwater to flow both through the matrix structure itself and through an interconnected network of fractures. Appendix A shows the groundwater bodies defined by the Water Framework Directive (WFD) within the focus area. These are subdivisions of large geographical areas of aquifers to enable effective management to protect the groundwater and linked surface waters. They are hydraulically continuous entities and are linked to surface water bodies above. Groundwater bodies are not present in areas where there is very low or no abstraction and where there is no influence on surface water bodies. There are six distinct groundwater bodies in the project area, these relate to the aquifers shown in Appendix B.

SURFACE WATER PATHWAYS

When heavy rain falls on saturated ground, water moves over the land surface via preferential flow pathways determined by topographical features such as slopes and depressions. As the water moves it can pick up contaminants and pollutants such as excess nutrients from agricultural land. The surface flows accumulate until they reach the river network where they continue to flow towards the sea. Discharges directly into the river network and drainage water will also follow this downstream movement. Appendix C shows the surface water network across the focus area. This is made up of the lakes, ponds, ditches, streams and rivers as well as the preferential surface flow pathways modelled using the SCIMAP diffuse pollution and flood water source mapping software (Durham University 2013). Great Yarmouth and King’s Lynn are located either side of the focus area and both are in the areas where the greatest confluence of pathways join to meet the sea. The coastal waters in these locations would be expected to have higher nutrient levels than other section of the coast as a result of the influx from the catchments upstream. This trend is seen in the marine nutrient data shown in Figure 14.

SINKS OF NUTRIENTS LOST TO WATER

Nutrient sinks describe features that accumulate nutrients along their pathways to the sea, such as vegetated river buffers, freshwater and coastal wetlands (saltmarsh), aquifers and coastal waters. Nutrients maybe be stored or utilised within a sink habitat, helping to reduce the level of nutrients circulating through the water network.



-

Nutrients travelling through the groundwater network will predominately accumulate in the aquifers deep underground. In Norfolk there is a highly productive aquifer under the chalk geology, this is one of the UK's principal aquifers supplying water for human consumption as it has a high permeability and water storage capacity. There are also some areas of moderately productive aquifers over the mudstone to the west and silts to the east. Excess N in water is harmful to human health and in the UK the levels are controlled by a legal standard for the level of NO_3 in drinking water, 50 mg/L (Drinking Water Inspectorate, n.d.; Defra, 2012). When levels are elevated drinking water requires further treatment processes to ensure it is safe for consumers. Nutrients in groundwater will also accumulate in groundwater fed rivers and subsequently coastal areas where they can cause eutrophication. Appendix B shows the designated aquifers in the focus area, these are where excess nutrients lost to water will accumulate although as water can move much slower underground there is often a significant time lag between pollution and accumulation.

FRESHWATER AND MARINE HABITATS – SURFACE WATER NUTRIENT SINKS

Nutrients will accumulate in the surface water network and although natural processes, described below, will remove some, the majority will reach the sea and accumulate in coastal waters. Freshwater wetlands connected to the river network will also act as a sink for the nutrients as they act as a buffer, intercepting surface run off and subsurface flows, slowing water down and holding it in the landscape for longer. Wetlands can remove N and P through a combination of physical, chemical, and biological processes. These naturally occurring processes adsorb, absorb, transform, sequester, and remove the nutrients and other chemicals while the water dwells in the wetland. Nutrient cycling is just one of the ecosystem services that wetlands deliver, but it is a key reason why habitats such as saltmarshes and freshwater wetlands have huge remediation value when it comes to nutrient pollution. The key remediation process include:

- Sedimentation - when water velocity is slowed by the complex vegetation, the suspended contaminants can settle and be deposited.
- Burial – when layers of settled sediments become piled upon another, the sediments beneath are buried.
- Biofiltration - the vegetation found within the wetland acts as a filter and traps pollutants.
- Chemical precipitation the binding of phosphates removes dissolved phosphate from the water column and stores it within the wetland sediments.
- Denitrification - when nutrients biodegrade via microbial activity. This plays an important role in reducing the amount of N from leaching into groundwaters.
- Nutrient uptake - either by direct uptake into biofilm or from metabolism by the plant following denitrification by the biofilm on the plants structure and once denitrification occurs (see above) the resulting compounds (e.g., NO_3) can be taken up by the plants.

N and P are present in many forms, and each undergo different processes within wetlands. Volatile forms are released into the atmosphere, others sink to the bottom of the wetland, and others are used by plants and microorganisms that live within the wetlands. There are many variables, such as oxygen level and season, that will determine the flow of the different processes. The uptake of N and P by plants only provides temporary storage of the nutrients. Most of these assimilated nutrients are released back into the water and sediments when plants die and decompose. Around 10–20% of nutrients will remain stored in woody plant litter that decomposes slowly and becomes permanently incorporated in wetland soils.

The dominant sustainable process removing N is denitrification performed by bacteria. P, on the other hand, is removed primarily through physical and chemical processes. The dissolved form of P accumulates quickly in sediments, but wetland soils have a limited amount of P they can hold before the negative impacts of excess nutrients occur. In a naturally functioning wetland, new soil needs to be “built” from residue plant material and undecomposable parts of wetland to support continual removal of P. The growth, or accretion, of new material in the wetland is the only sustainable removal and storage process for P (Kostel, n.d.).

Appendix D shows the main surface level sinks for nutrients lost to water. The maps shows the sinks are widespread in the low-lying western fen area and the Broads in the east where there are higher densities of surface water network features (as shown by Appendix C). Across the rest of the focus area the sink habitats are more localised to the main river network.

POTENTIAL RISK OF NUTRIENTS LOST TO WATER

This section draws together the sources of excess nutrients and looks at them in combination to indicate the likelihood of nutrient pollution across the focus area. It does not infer the level of the risk posed by the level of nutrient loading, just the potential for the risk of pollution to be present due to the presence of multiple known nutrient pollution sources. Finer scale data including specific farming practices, discharge permit information and water sampling would be required to create estimates of the amount of nutrients lost to surface water. Nevertheless, this is still a useful step to help understand the nutrient pressures across the landscape and is a valuable tool to direct remedial actions and target mitigation at a strategic level. It can highlight areas that may be exposed to multiple sources which may warrant a prioirtisation of effort or funds to investigate further and ultimately deliver maximum benefits.

Figure 11 shows the potential risk of nutrients entering the surface water network using the sources identified earlier in this report; sewage discharges, risky arable crops (those with high fertiliser requirement and or erosion risk), arable farming on peat soils and high livestock density. While a small portion of the nutrients lost to aquatic systems is attributed to the industrial sector these are initially emitted in gaseous forms in gaseous forms. These can precipitate out and wash into the river network, but there are many climatic variables that will determine where they may precipitate, and it could be 100s of kilometres away. The risk posed by industrial discharges to surface water will also vary significantly depending on the processes involved, and without more detailed information of these activities it is not possible to infer where these sources might be in the focus area. Consequently, industrial sources have not been included in this analysis of pollution risk to surface waters. Furthermore, only the surface water pathways were considered as it is not possible to accurately trace the influence of groundwater pollution from sources to sinks.

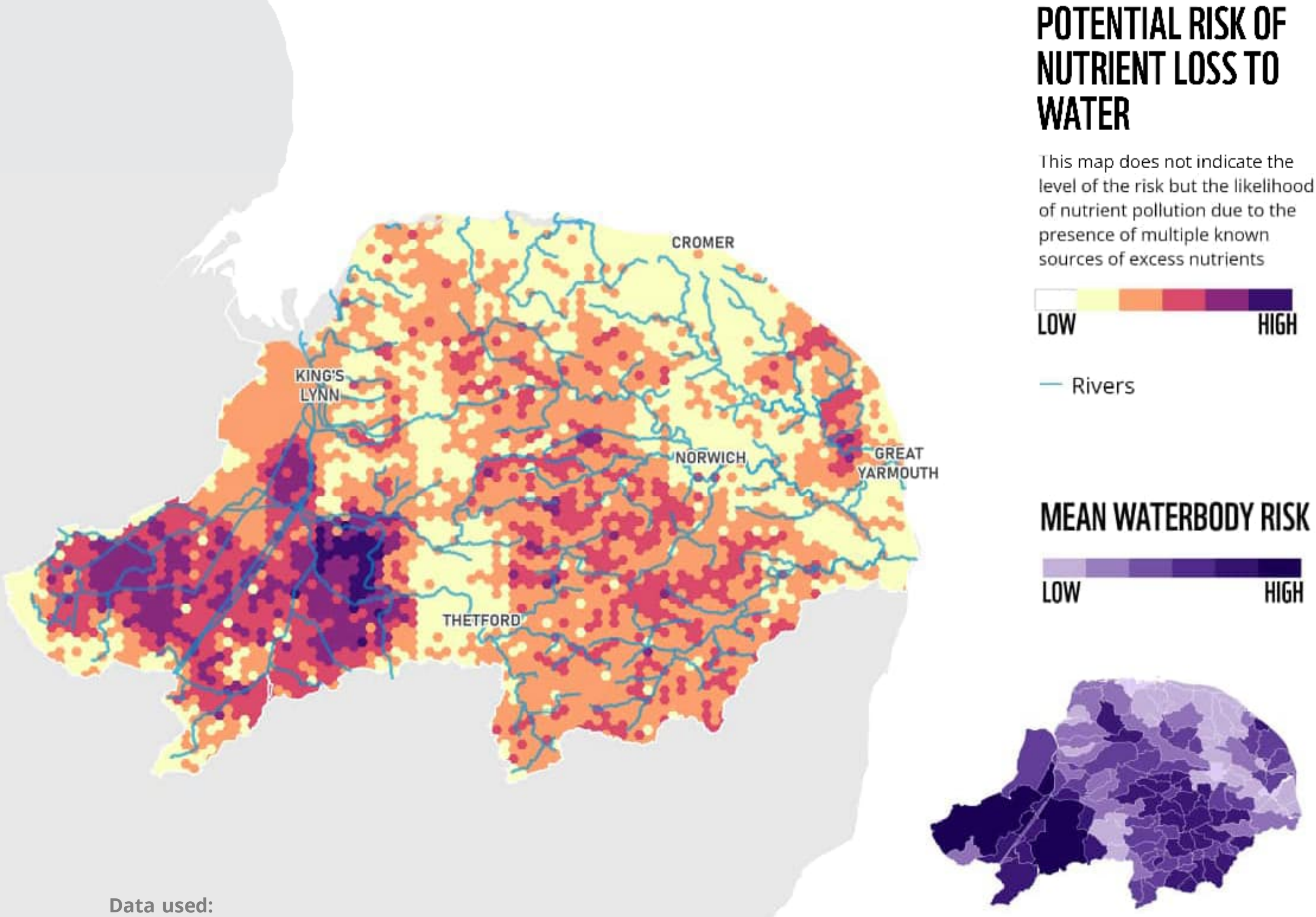
The model shown in Figure 11 combines the following:

- The number of combined sewer overflows, as shown in Figure 6.
- The location of risky crops grown in the focus area, as shown in Figure 7 that are within the surface water network.
- Areas of higher livestock density (relative to the focus area) for poultry, pigs, sheep and cows, as shown in Figure 8.
- The location of peat soils used for crop production, as shown in Figure 9 that are within the surface water network.

Each layer is scored and then those scored are then totaled within each 2km^2 hexagon.

- Sewage discharges are scored based on the number of overflows within a hexagon.
- The risky crops and crops grown on peat are scored based on the area present within each hexagon that intersect with the surface water network.
- The livestock density is scored based on the number of different livestock types present at above average densities (relative to the focus area) within each hexagon.

While the presence of potential nutrient pollution sources are widespread across the focus area there is a greater concentration in the west. This indicates that there may be greater nutrient pollution occurring here and as the rivers in this area reach the sea near Kings Lynn, there may be greater nutrient pollution in the adjacent coastal waters. This correlates with the marine nutrient data presented in Figure 14 that shows higher nutrient concentrations in the west of the marine focus area.



Data used:
Event Duration Monitoring - Storm Overflows (2023), Crop Map of England (CROME) 2021 (2022), WFD River Waterbody Catchments Cycle 2 (2021), WFD River, Canal and Surface Water Transfer Water Bodies Cycle 2 Classification 2019 (2022), Boundary-Line™ (2021), Agcensus (2016), Peaty Soils Location (England) 2022.

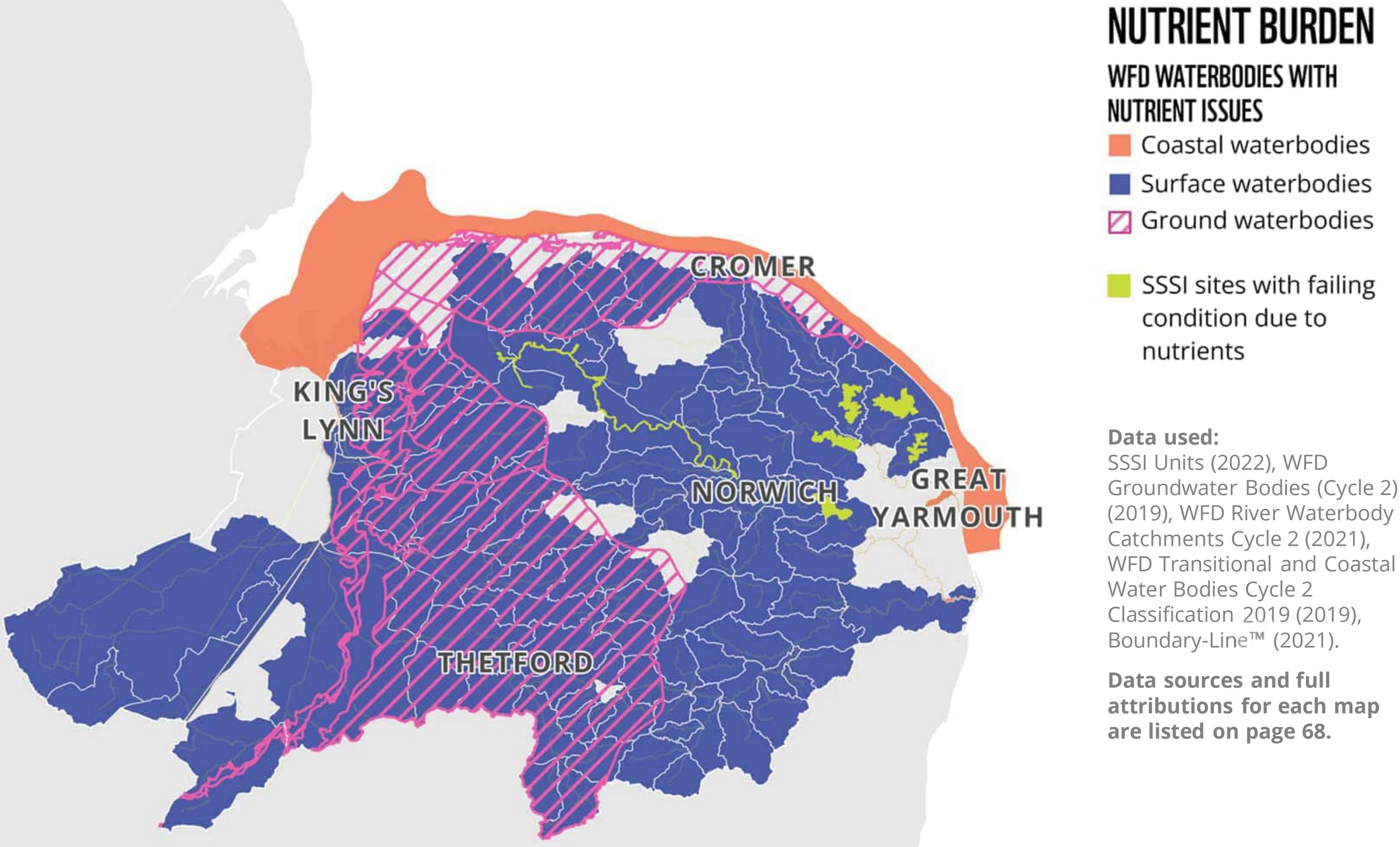
Data sources and full attributions for each map are listed on page 68.

Figure 11. The modelled risk of nutrient pollution across the focus area. The model uses main sources of excess nutrients to indicate the likelihood of nutrient pollution to surface waters (main sources include: combined sewer overflows; risky arable crops and crops grown on peat soils (within the surface water network); arable farming on peat soils; high livestock densities) to indicate the likelihood nutrient pollution to surface waters. The risk is based on the location of sources and is summarised into 2 square kilometre hexagon grid to show the variation across the landscape. The inset map show the average risk score summarised by WFD surface waterbody catchments. Please note the model does not consider the level of nutrient loading, it is based solely on the location of sources and does not quantify any parameters relating to the level of pollution or nutrient lost to surface waters.

CURRENT NUTRIENT SITUATION

EXISTING NUTRIENT BURDEN

Figure 12 shows areas that are known to be impacted by nutrient pollution. The map presents the WFD surface water, groundwater and coastal waterbodies that had nutrients cited as one of the Reasons for Not Achieving Good in the 2019 WFD classification. Also shown are the SSSI sites that are subject to the nutrient neutrality strategy in Norfolk. The figure shows that much of the focus area is currently suffering from excess nutrients.



Data used:
SSSI Units (2022), WFD Groundwater Bodies (Cycle 2) (2019), WFD River Waterbody Catchments Cycle 2 (2021), WFD Transitional and Coastal Water Bodies Cycle 2 Classification 2019 (2019), Boundary-Line™ (2021).

Data sources and full attributions for each map are listed on page 68.

Figure 12. Areas known to have issues related to excess nutrients within the focus area.

NUTRIENT CONCENTRATIONS IN SURFACE WATER

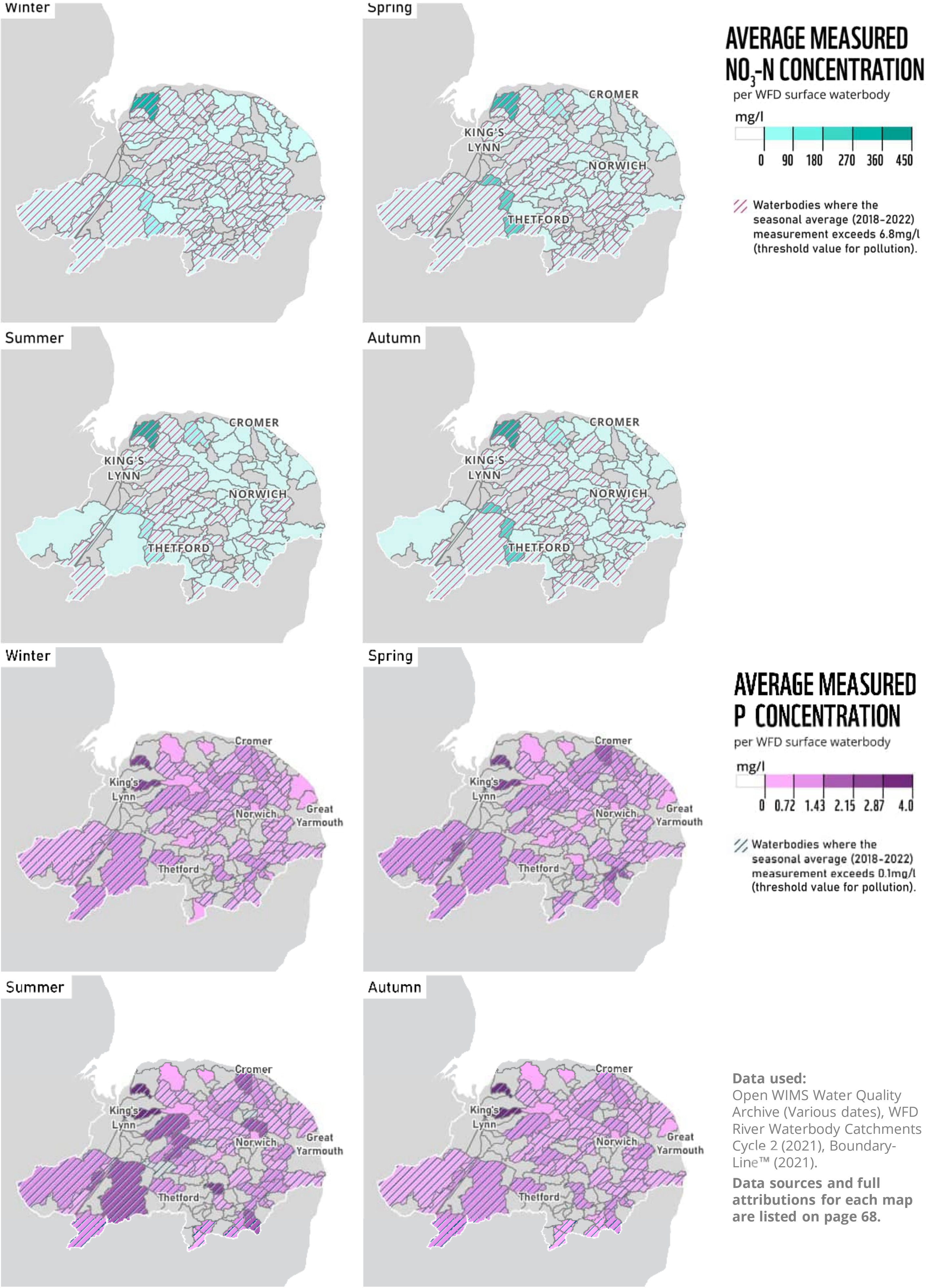
ENVIRONMENT AGENCY WATER QUALITY SAMPLING (MEASURED DATA)

The Environment agency takes water samples from rivers, lakes, ponds, canals, estuaries, coastal water, and groundwater. They are taken for several purposes including compliance assessment against discharge permits, investigation of pollution incidents or environmental monitoring. While the coverage is not comprehensive, this is the best available measured data to represent the level of nutrients within the focus area without further sampling. Figure 13 shows the seasonal average concentration of the surface water samples (mg/l) collected between 2018-2022 for NO_3-N (above) and PO_4-P (below). The sample concentrations have been averaged across their WFD surface waterbody for each season. N and P exist naturally in the environment at different levels. Government guidance recommends that rivers should not exceed annual mean concentrations of 0.1mg PO_4-P l^{-1} and 6.8mg NO_3-N l^{-1} (Defra, 2012). The figure also shows where the waterbody average exceeds these threshold levels within each season. There is no clear trend between these data and the potential risk map in Figure 11.

NUTRIENT CONCENTRATIONS IN COASTAL WATER

ATLANTIC - EUROPEAN NORTH WEST SHELF - OCEAN BIOGEOCHEMISTRY (MODELLED DATA)

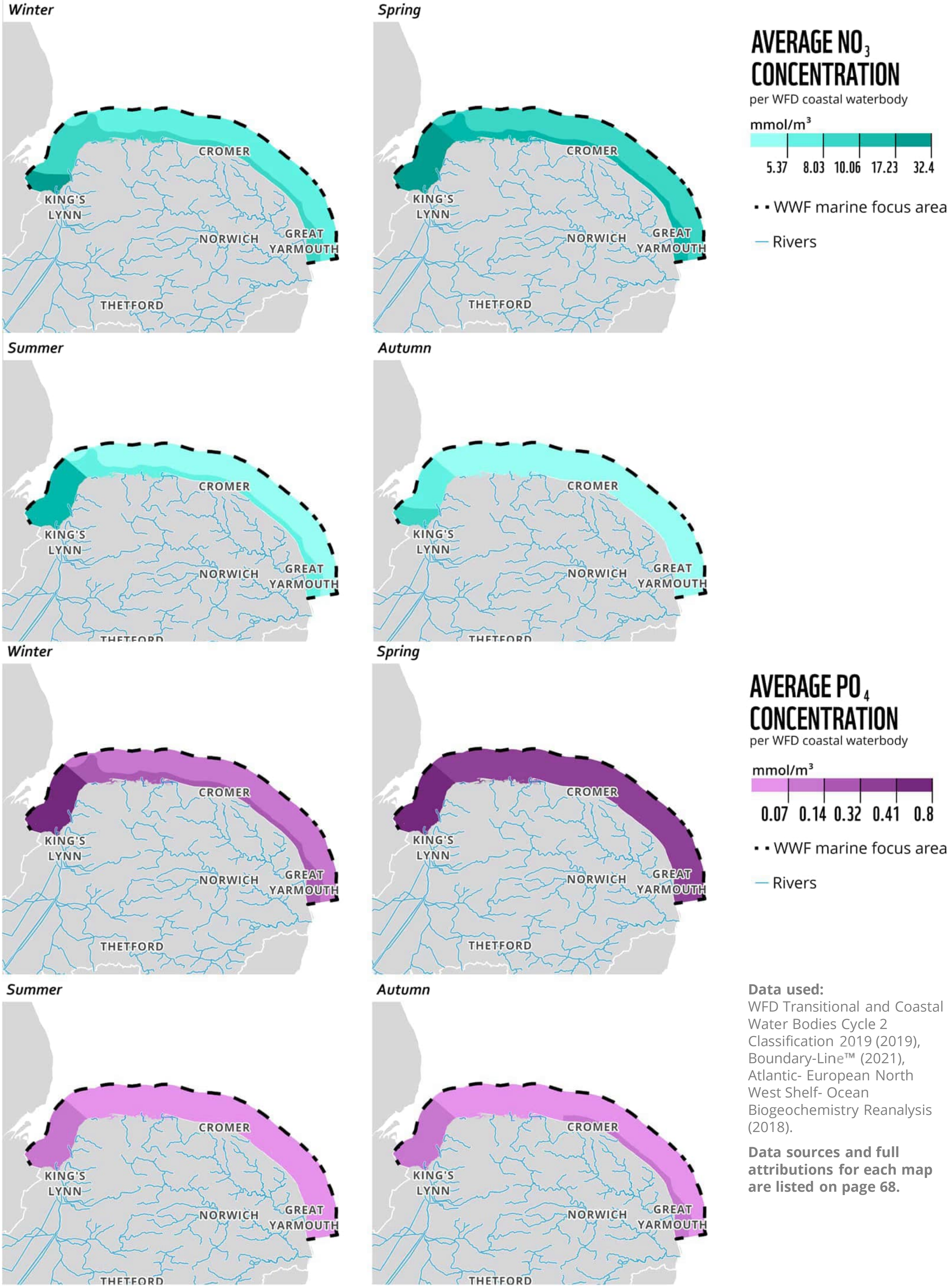
The best data available to compare the concentrations of nutrients across the whole of the marine portion of the focus area is a modelled dataset by the Copernicus Marine Service. The dataset provides monthly average concentrations of NO_3 and PO_4 at various depths. The 3m depth was selected here as it is the most relevant for seaweed production, which is discussed later in this report. Figure 14 shows the average concentrations (mmol m^{-3}) for each season and summarised by the WFD transitional and coastal waterbodies. Transitional waterbodies are estuaries and coastal waterbodies are defined as ‘territorial waters 1 nautical mile from the mean high water coastline’, they are also characterised by their physical regimes such as exposure and sediment type. Some of the coastal water bodies have been extended beyond 1 nautical mile to include the full focus area. The maps show that levels of both NO_3 and PO_4 are higher through the winter and spring. Levels in the Wash near King’s Lynn are consistently higher throughout the year compared to other waterbodies and concentration decreases with distance from land. The coastal waters in these locations would be expected to have higher nutrient levels than other sections of the coast due to the influx from the catchments upstream. This trend is supported by the risk model shown in Figure 11 where the greatest number of potential sources are concentrated in the west throughout each season.



Data used:
Open WIMS Water Quality Archive (Various dates), WFD River Waterbody Catchments Cycle 2 (2021), Boundary-Line™ (2021).

Data sources and full attributions for each map are listed on page 68.

Figure 13. The seasonal average concentration (mg/l) of the surface water samples collected by the Environment Agency between 2018-2022 for N0$_3$-N (above) and P (below). The sample concentrations have been averaged across their WFD surface waterbody for each season.



Data used:
WFD Transitional and Coastal Water Bodies Cycle 2 Classification 2019 (2019), Boundary-Line™ (2021), Atlantic- European North West Shelf- Ocean Biogeochemistry Reanalysis (2018).

Data sources and full attributions for each map are listed on page 68.

Figure 14. The seasonal average concentration (mmol/m³) of NO_3 (above) and PO_4 (below) modelled by Copernicus Marine Service. The concentrations have been summarised by the WFD transitional and coastal waterbodies.

CATCHMENT SCALE NUTRIENT REDUCTION MEASURES

Reducing nutrient inputs at a catchment scale should always be the priority intervention over other remedial measures. There are already several active schemes that aim to achieve this, including:

PLANNING AND DEVELOPMENT

In 2022 Natural England published the Nutrient Neutrality principles to combat the adverse effects of nutrient pollution (Wood et al., 2022). This means that new developments across English planning authorities are required to consider the treatment and mitigation of nutrient-rich wastewater that would be produced, ensuring that development does not add to existing nutrient burdens within catchments. For development in these regions, including Norfolk, to be permitted, mitigation is required to protect vulnerable sites (under the Conservation of Habitats and Species Regulations 2017).

CROSS COMPLIANCE RULES FOR AGRICULTURAL SUBSIDIES

Cross compliance is a set of rules which farmers and land managers must follow on their holding if they are claiming basic payment schemes (BPS) from the Rural Payments Agency (RPA). These will be replaced in England with delinked payments in 2024. The scheme rules will be set out in new regulations which are expected to come into force by the end of 2023, following parliamentary approval.

NITRATE VULNERABLE ZONES

Nitrate Vulnerable Zones (NVZs) are areas of land identified as being at risk from agricultural NO_3 pollution and are designed to protect water quality. These are defined under Nitrates Directive and Nitrate Regulations as polluted if they contain or could contain NO_3 concentrations greater than 50mg/l, are eutrophic, or could become eutrophic if preventative action is not taken. The designation applies to England, Scotland and Wales. Currently 90% of Norfolk is designated as a NVZ. These areas are reviewed every four years and once designated, there are certain additional rules that farmers need to follow. For example, they set out how fertiliser can be applied and how organic manure is stored.

STORING SILAGE, SLURRY AND AGRICULTURAL FUEL OIL REGULATIONS (SSFAO)

These regulations set standards for storing silage, slurries and agricultural fuel oil, to minimise the risk of water pollution. These substances can cause significant pollution, usually due to farms having inadequate storage capacity, or defunct storage infrastructure. They describe the siting and design of infrastructure required to comply. Farms within NVZs must adhere to additional requirements such as creating more storage capacity.

THE REDUCTION AND PREVENTION OF AGRICULTURAL DIFFUSE POLLUTION

Also known as the farming rules for water, the Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018, were introduced to reduce and prevent diffuse water pollution from agricultural sources. The rules build upon the good practice already in operation and relate to managing fertilisers, manures and soils.

ENVIRONMENT ACT 2021

In addition to the regulations described above, the government's Environment Act 2021 sets legally binding targets for the UK to reduce N, P and sediment pollution from agricultural sources into the water environment by at least 40% by 2038, compared to a 2018 baseline. The act also sets a target to reduce P loadings from treated wastewater by 80% by 2038 (against a 2020 baseline).

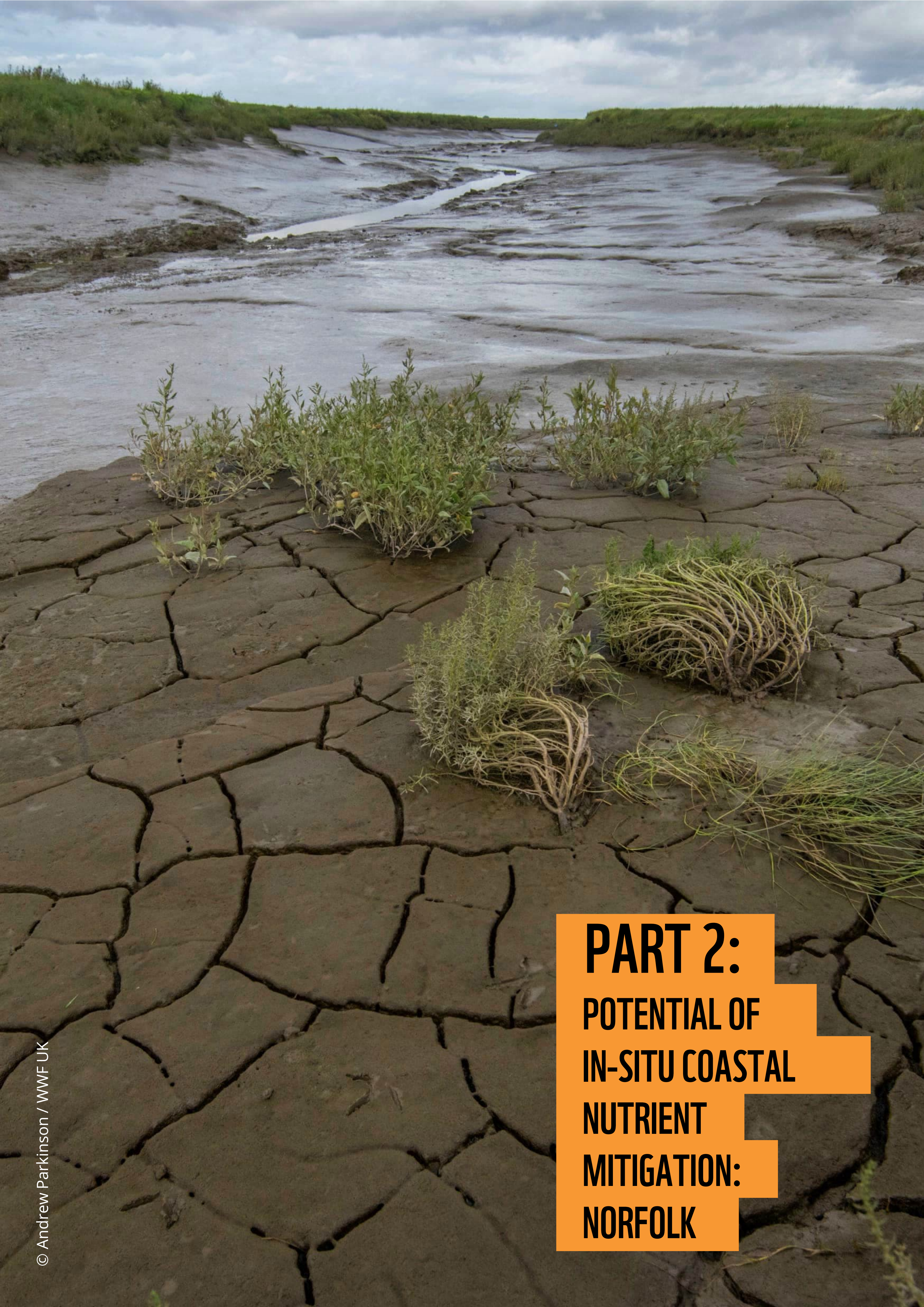
WASTE-WATER TREATMENT REGULATION (WATER COMPANIES AND INDUSTRIAL DISCHARGES)

Water Company and industrial discharges of wastewater to either surface waters or groundwater are regulated by the Environment Agency. Compliance limits are set which require appropriate treatment of wastewater, but these limits are not fixed and are determined by the population equivalent they serve and the designations of receiving areas.

The first and most important step in eliminating nutrient pollution should be to reduce nutrient inputs at source across the catchment. However, there are secondary methods of mitigating *in-situ* water pollution, which are potentially useful in reducing the harmful impacts of nutrients on coastal ecosystems (Part 2). These solutions can harness the natural ecosystem services provided by habitats to deliver water quality improvement benefits.

NUTRIENT SUMMARY

In Part 1 sources of N and P were presented using the best available data at the time of writing and provides an indication of the losses and where the risks of N and P losses to water are highest. The source mapping shows that the sources vary across the county, and as would be expected, the sources linked to urban areas and critical infrastructure are highest around built-up areas. Agricultural sources are the most widespread, with high-risk crops grown throughout the NVZs. The density of livestock are somewhat spatially distinct from one another. When the sources are combined into the risk map in Figure 11 the highest levels of risk are found in the west. In this area the livestock densities are lowest compared to other parts of Norfolk, however, the underlying soil type, combined with higher risk cropping, as well as higher levels of surface water connectivity (Appendix C) could mean that nutrient losses to water are more likely. When the marine nutrient data are compared to the risk map, the areas of highest nutrient levels and risk correspond. This shows that it is likely that the sources, pathways and risks presented in Part 1 are reflecting the current situation in Norfolk. This information could potentially support prioritisation of catchment scale nutrient reduction. The nutrient risk, for now, is only an indication and would need further detailed data available to target specific sources. Caution is needed when interpreting the results.



PART 2:

POTENTIAL OF IN-SITU COASTAL NUTRIENT MITIGATION: NORFOLK

© Andrew Parkinson / WWF UK

IN-SITU MITIGATION FOR EXCESSIVE NUTRIENTS - BIOREMEDIATION

Bioremediation is a process that uses mainly microorganisms, plants, or microbial or plant enzymes to detoxify contaminants and remove pollutants from an ecosystem. Constructed and natural freshwater wetlands are examples of commonly used bioremediation methods. These can be used to treat point and diffuse sources of pollution, such as agricultural run-off or as tertiary treatment for sewage. Bioremediation of excess nutrients in coastal waters could be achieved through restoration of coastal and seascape habitats, such as saltmarsh, seagrass and seaweeds. These are new methods that could be applied to potentially mitigate nutrient pollution in Norfolk. The two methods discussed in this report are the restoration saltmarsh habitat and implementation of seaweed farms. Saltmarsh is a naturally occurring habitat found around the Norfolk coastline, and due to the physical features of the habitat, nutrient removal is one of the ecosystem services that it provides. Significant areas of saltmarsh habitat were lost in this area through historical conversions to farmland, therefore there are opportunities to restore the habitat. There are also opportunities for farming seaweed in the coastal areas of Norfolk, which in addition to the bioremediation potential, has the additional benefit of a harvestable output and depending on how it is used, could also support reductions in overall nutrients inputs.

Saltmarsh habitat and seaweed farms have the potential to act as *in-situ* mitigation measures for nutrient pollution. Although the processes in which they achieve this are different (described on page 39 (saltmarsh) and 48 (seaweed)), they each present opportunities in Norfolk and have the potential to reduce the nutrient load in coastal areas. However, estimation of these ecosystem services has yet to be undertaken for this area, and if their use as mitigation measures is to be recognised and accepted, understanding and quantifying these capabilities in relation to the catchment inputs of N and P (described in Part 1), and how these vary spatially and temporally is critical.

In this part of the report, the process by which saltmarshes and seaweed farms remove nutrients is explored in detail, along with outlines of the processes of nutrient removal, a summary of the factors that can affect the quantity of nutrient removed and, high-level calculations of the nutrient removal potential for both. The latter is presented in several scenarios based on area of potential saltmarsh restored and/or created, and the area of seaweed farming established. These calculations have been derived from spatial data created by the Marine Management Organisation (Saltmarsh Potential (MMO) - Potential habitat creation sites within floodplain (2020); Evidence Project MMO1184 - Identification of areas of aquaculture potential in English waters (2021), full dataset information can be found on page 68).

Lastly the potential use of Norfolk grown seaweed in a circular agriculture system is discussed. This focusses on the potential for biostimulants produced from harvested seaweed biomass to be utilised by the arable agricultural industry

LITERATURE REVIEW METHODOLOGY

To review the available literature, an adapted the Quick Scoping Review (QSR) protocol was used based on Collins et al. (2015). This adapted protocol enabled a search for relevant literature to be undertaken in the time available for this project.

QSR METHOD

With input from the project steering group, the search terms were agreed and can be seen in full in Appendix E.

Topics:

1. Nutrients (N and P)
2. Seaweed
3. Saltmarsh
4. Seaweed nutrient assimilation
5. Native seaweed cultivation
6. Saltmarsh nutrient assimilation
7. Saltmarsh management

Title searches were undertaken in Google Scholar and Scopus. The first 200 results were extracted and saved in Microsoft Excel. The results were saved as a separate tab in Microsoft Excel and when all the searches were carried out, the results were compiled into a single list, a check for duplicates was undertaken and duplicate results were removed. Two phases of sifting took place, the first pass involved reading the title of and deciding if it is relevant, uncertain or not relevant. Those determined as not relevant were filtered out, but for clarity the information is retained in the background.

The first pass focused on retaining papers which meet the following criteria:

- UK based (this has been expanded to northwest Europe where needed)
- For seaweed farming, species were limited to *Alaria esculenta, Saccharina latissima*, *Laminaria digitata*, and *Palmaria palmata*.
- Published from 2000 onwards. The date range set during search should have filtered out but this was checked at this point.
- The text must be available in full
- It must have relevance to at least one of the topics (see list)

During the second pass, the abstract/first paragraph that were classed as relevant were reviewed to determine the relevance of the paper based in the criteria listed above. Those that were uncertain were only reviewed if no other literature could be located on a specific topic in those marked as relevant.

The remaining papers/evidence were reviewed and the key points per topic summarised, which was then used to provide a synthesis of the available evidence.

SALTMARSH NUTRIENT REMOVAL PROCESS

SALTMARSH

Saltmarsh is not a single species, but a community of many species that form a complex and diverse habitat which can occur within the intertidal areas, primarily in bays and sheltered inlets. A key feature of this habitat type is that it receives large amounts of dissolved and particulate organic and inorganic matter from rivers and the sea. Saltmarsh habitat is involved with three key mechanisms of N removal from the water column, which include uptake by plants, burial of organic N and denitrification.

SALTMARSH FORMATION

Saltmarshes are generally formed in relatively low energy inter-tidal areas, where suspended sediments can settle and where the low wave energy and current limit resuspension. This is normally associated with the presence of mudflats which attenuate wave energy. Once the sand/mud has settled out of suspension it accumulates and over time these areas become vegetated and saltmarsh habitat can develop. Saltmarshes generally consist of two main elements, vegetated platforms high in the tidal range, which are flooded by the tide, and a series of generally unconnected networks of tidal creeks that diminish as they progress landward. These creeks transport sediment into the saltmarsh interior and drain tidal water when the tide retreats.

SALTMARSH MANAGEMENT, RESTORATION AND CREATION

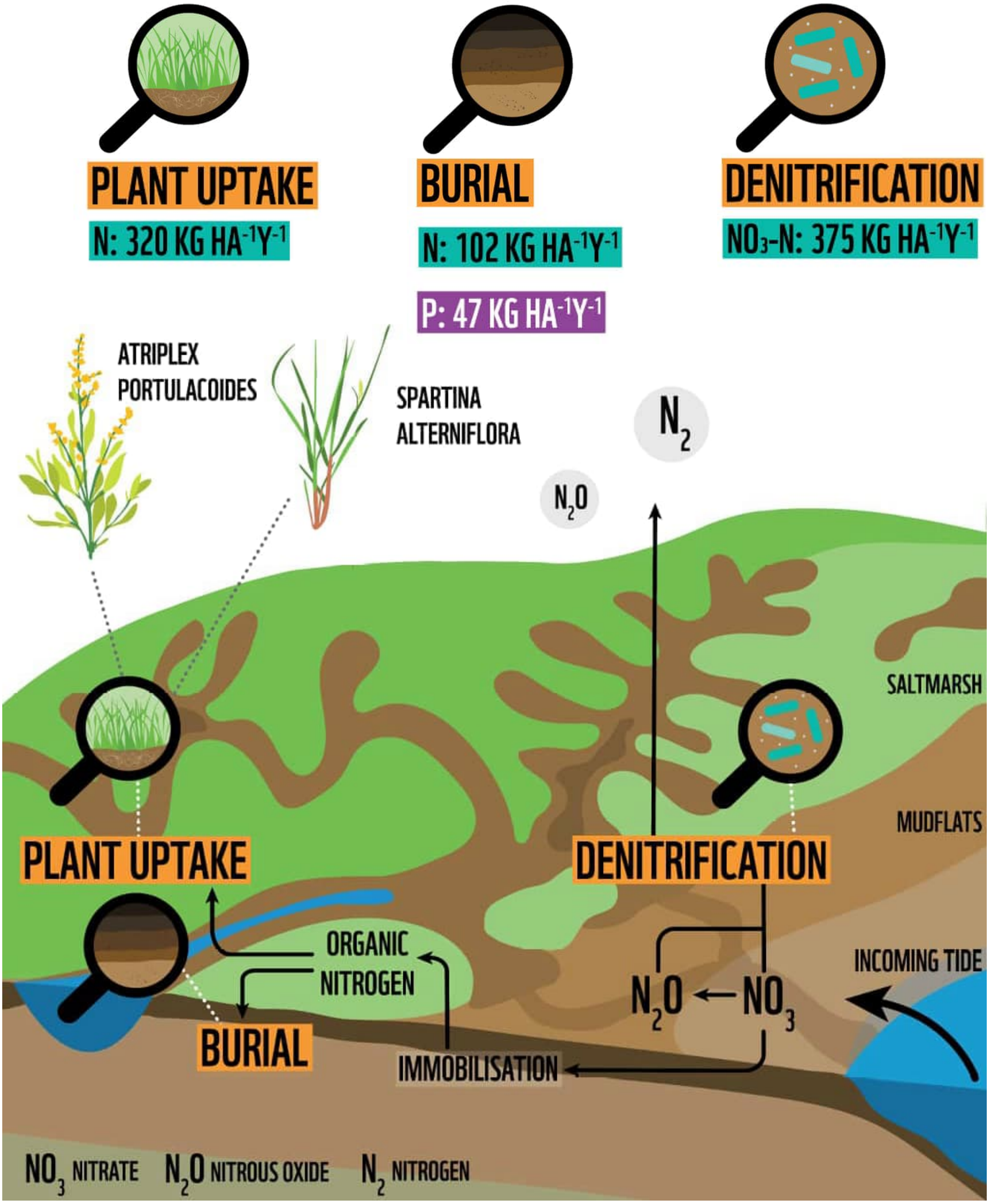
In England there has been an overall increase in saltmarsh habitat of around 7% when compared to baseline data collated between 2006-2009 (Environment Agency, 2022). In the East Anglian area, there has been an increase of around a 5%, some of this as a result of managed realignment (Environment Agency, 2022). When the physical processes that sustain saltmarsh are not present then management/restoration/creation will normally be needed in some form to ensure the longevity of the habitat (Adnitt et al., 2007). The primary form of management located within the literature was related to grazing and mowing. Managed realignment is a saltmarsh creation technique, which involves breaching sea defenses to allow tidal inundation, resulting in the development of intertidal habitats, such as saltmarsh (Adnitt et al., 2007).

NITROGEN REMOVAL PROCESS

N can be found in many different oxygenation states and chemical forms (Francis et al., 2007), which makes the N cycle highly complex, and an integrated part of ecosystem function. Saltmarsh ecosystems are involved with three key mechanisms of N removal from the water column, including uptake by plants, burial and denitrification (Velinsky et al., 2017; Cai, 2018), shown in Figure 15. Denitrification is the only process that will permanently remove N from the water column. Plant uptake and burial result in the storage of N, but there is potential that at some point in the future it may be remobilised. The rate of remobilisation can vary spatially and temporally, in the short-term storm events, tidal surges and changes to management could cause erosion and remobilisation. While in the longer-term changes in tidal currents, sediment accretion rates and/or sea-level rise could be key factors in the remobilisation process.

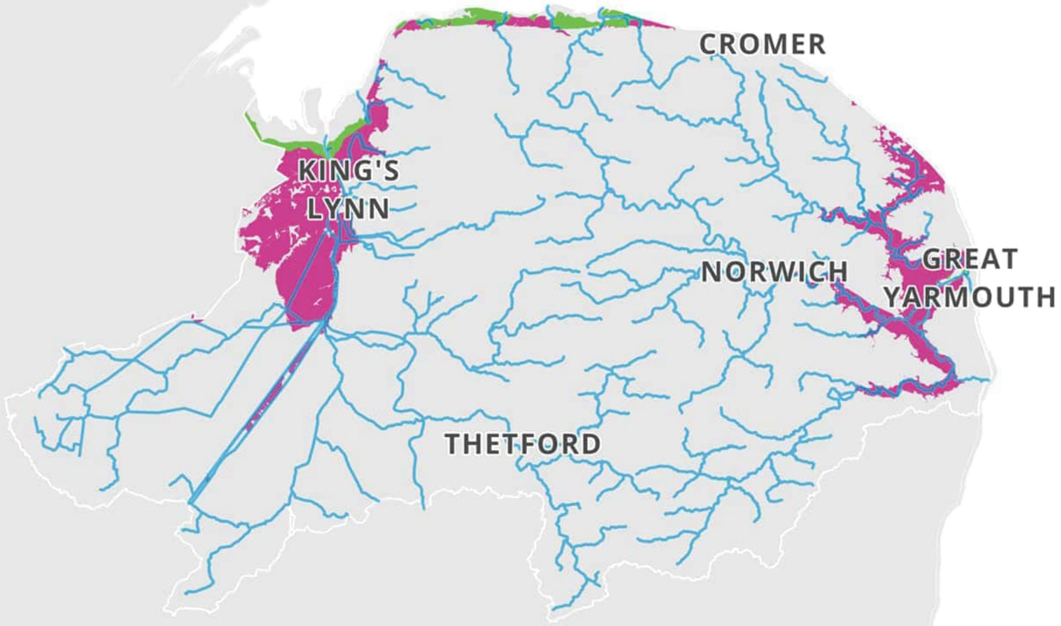
Not all N that enters saltmarshes is removed/stored, some will be recycled or re-mineralised and will re-enter the water column. It is important to note here that the amount of N removed or recycled by saltmarsh will vary depending on the different processes and season (Velinsky et al., 2017; Cai, 2018).

Figure 15. Graphical depiction of the nitrogen removal processes in saltmarsh habitat. The three removal processes include burial, denitrification and plant uptake. Denitrification is the only process that will permanently remove nitrogen from the water column**.**



POTENTIAL SALTMARSH HABITAT IN NORFOLK

The MMO developed spatial data which delineates potential areas for saltmarsh habitat that are currently areas of floodplain defended from sea water. These areas could be suitable for managed realignment or regulated tidal exchange to create saltmarsh habitats. These data should only be viewed as a high-level indication where these measures may be feasible. Sites are not ranked according to their suitability, nor does the layer indicate whether land is available for intertidal habitat creation. It does however provide the theoretical potential scale at which saltmarsh could be created. Some of the potential saltmarsh area will include restoration of historic habitat. Figure 16 shows the existing extent of saltmarsh habitat, mapped from aerial photography between 2016 and 2019, alongside the potential areas modelled by MMO.



SALTMARSH

🟩 Existing saltmarsh habitat

🟥 Potential saltmarsh habitat

— Rivers

Figure 16. Locations of existing saltmarsh habitat and locations that could be suitable for saltmarsh restoration in the Norfolk area.

HABITAT	AREA
Existing saltmarsh	4,500 ha
Potential saltmarsh	55,000 ha

Data used: WFD River, Canal and Surface Water Transfer Water Bodies Cycle 2 Classification 2019 (2022), Boundary-Line™ (2021), Saltmarsh Potential (MMO) - Potential habitat creation sites within floodplain (2020), Saltmarsh Extent & Zonation (2023).

Data sources and full attributions for each map are listed on page 68.

The map above shows there is around 4,500ha of saltmarsh habitat present around the Norfolk coastline, which is primarily located in the North Norfolk area. There is potential for around 55,000ha of saltmarsh across Norfolk, and if it was allowed to form in the entire area of potential there would be over a 1000% increase in area compared to the current extent. While this is somewhat unrealistic, quantifying the nutrient removal benefits of the whole area will help to assess the amount of saltmarsh restoration needed to have a positive impact on the nutrient issues described in Part 1 of this report.

REVIEW OF SALTMARSH

A review of the available literature was undertaken to establish the key considerations relating to the quantification of nutrient mitigation by saltmarsh, including: the suitable parameters for quantification, the estimates relating to these and any associated limitations. The literature on the estimation of nutrient removal in the UK was limited, however, the factors that would impact removal rates are outlined below:

BURIAL

The settlement of suspended sediments, which can hold bound nutrients, is an essential feature of saltmarshes. Understanding the rate that this occurs is essential when estimating the N and P removal potential. Bartholdy (2012) noted that sedimentation can occur either through channel flow close to the tidal creeks, the flow of water over vegetated saltmarsh surfaces (Möller, 2006; in Bakker et al., 2016) or at the exposed saltmarsh edges. Over time sedimentation leads to surface elevation change (SEC). In England a long-term estimate for this accrual was 5.4 mm yr^{-1} (Adams et al., 2012).

Nutrient burial rates are dependent partly on the rate of SEC (Adams et al., 2012), a higher SEC means there is greater potential for nutrient burial. The SEC can change depending on the age of the saltmarsh. Younger saltmarsh habitat created using managed realignment can have temporarily higher SEC which will level out as the habitat establishes. The amount of nutrients buried will also depend on the inputs/availability to the saltmarsh, and the decomposition rate of organic matter stored within the sediments.

DENITRIFICATION

Denitrification describes several microbial processes that reduce N in multiple forms to gasses, either N_2O or N_2 (Knowles, 1982). Denitrification occurs when oxygen is limited, and anaerobic bacteria can use reduced nitrogen oxides as electron acceptors in the absence of oxygen. In saltmarsh habitats conditions can mean there are regular changes in oxygen availability allowing denitrification to occur (Blackwell et al., 2010). The soil density and structure can affect the flow of water into and out of saltmarsh soils, so the structure of these soils will impact the rates of denitrification. Soil microbes would have greater access to nutrients in floodwaters in soils with a good structure (i.e., good aggregate formation and pore space) (Perret et al., 2000 in Blackwell et al., 2010). Blackwell et al. (2010), found that in established saltmarsh soils NO_3 was limited, and N_2O was more likely to be reduced to N_2. When NO_3 is available, denitrifiers will favor it over N_2O, in this scenario complete denitrification and the permanent removal to N_2 is unlikely. However, Andrews et al. (2006) noted around 2% of the estimated denitrification will be N_2O production, which needs to be considered when reviewing the N removal calculations on page 45.

Denitrification is a complex process involving multiple pathways whereby different forms of N maybe produced/reduced (Blackwell et al., 2010). The theoretical quantification approach taken in this report assumes full denitrification has occurred, therefore any estimation will be based on NO_3 being fully reduced to N_2.

PLANT UPTAKE

N and P are essential for growth in all plant species, meaning these nutrients are taken up, assimilated and stored in the plant cells and tissues. Nutrient uptake rates in plants are variable and can depend on several factors, including; species, plant elevation, and water column N availability, rhizome oxygenation, chemical form of N, salinity and the presence of toxins (Bradley and Morris, 1990; Bradley and Morris, 1992; Cott et al., 2018; Hill et al., 2018). When plants die, the stored nutrients can be broken down by microbial activity and be remineralised or the organic plant material can be stored in the saltmarsh sediments. To accurately estimate the uptake and assimilation rates by the vegetated areas of saltmarsh, location specific information, including species composition and individual uptake efficiencies would be required.

The proportion of a saltmarsh that is unvegetated can vary widely depending on several factors, such as tidal currents, sediment deposition and erosion, the types of plant species present, and human activities. Saltmarshes are characterized by a mosaic of vegetated areas and unvegetated or bare areas, including mudflats, tidal channels, and open water pools. The percentage of unvegetated areas within a saltmarsh can range from a few percent to a substantial portion of the marsh, depending on the local geomorphology and ecological dynamics. Some saltmarshes may have a higher proportion of bare areas, especially in regions with a more dynamic tidal range and sedimentation patterns. In contrast, saltmarshes in more sheltered areas with less tidal action may have a higher proportion of vegetation cover. Furthermore, the proportion of unvegetated areas in saltmarshes can change over time due to natural processes, human interventions, and climate-related factors such as sea-level rise.

NUTRIENT REMOVAL SUMMARY

The literature review process identified a small number of papers that related to N burial and denitrification in saltmarshes. Of the literature identified not all the N removal rates could be extracted and utilised for bioremediation estimates in this report. For example, using modelled data, Shepherd et al. (2007) estimated that 82.7 t y^{-1} of N would be removed by denitrification for the Blackwater estuary based on around 10,000ha of managed realignment, but this estimate did not separate mudflats from saltmarsh, therefore it could not be used to estimate denitrification in this report. Estimates of N and P burial, which contained spatial units were located within a single paper (Adams et al., 2012), here sediment core samples were analysed to establish bulk density, and in turn N and P storage. These limited results suggest that there are limited data to draw conclusions on the nutrient storage potential of saltmarsh in the UK, and the number found here corresponds to those presented in a summary by Watson et al. (2020). Understanding the reasons for this limited data was not possible within the scope of the report, but could related to funding limitations or, methodological restrictions, which would be useful to address in future work.

The factors mentioned above relating to plant uptake are difficult to account for without location specific information, such as species composition/plant communities, which would require localised surveys to be undertaken, and individual species uptake rates to be available. Hill et al. (2018), provided an estimate for N uptake in Spartina alterniflora (smooth cordgrass) by sampling vegetated saltmarsh cores, supplying the sediment with tracible form of N (^{15}N) and measuring the uptake into above and below ground biomass, as well as the denitrification potential of the sediments. As no alternative N uptake estimates were located during the literature review that specifically related to an area measurement, the above and below ground N uptake rates presented in Hill et al. (2018) were used as a proxy for all plant uptake to provide a broad indication of the plant uptake rates across the saltmarsh habitat in the Norfolk area.

CALCULATING MITIGATION POTENTIAL OF SALTMARSH

Where a range of values were included in the literature the maximum reported value was extracted (Appendix F). The estimation of denitrification was based on an hourly rate, it was converted to an annual estimation using 8736 hours in a year. For the calculations shown in Table 3 on the following page the values for natural saltmarsh were used, which included 10.2 g N m^{-2} yr^{-1} and 4.72 g P m^{-2} yr^{-1} for burial (Adams et al., 2012) and 4.29 mg N_2O-N m^{-2} h^{-1} for denitrification (Blackwell et al., 2010) or 37.5 g N_2O-N m^{-2} y^{-1} based on 8736 hours in a year. The estimate for N uptake by plants was derived from Hill et al. (2018). The above and below ground uptake rates were summed (39.6 and 49.2 mg N m^{-2} d^{-1}) to give an overall figure 88.8 mg N m^{-2} d^{-1}, or 32.32 g N m^{-2} y^{-1} (8736 hours in a year).

Please note, information on the extent of vegetated and unvegetated saltmarsh habitat within the focus region was not available at the time of this report. The estimated plant uptake rates in Table 3 have therefore been calculated under the assumption that 100% of the restored habitat has plant coverage. This rate should be interpreted with caution as it would not apply uniformly across all areas defined as a saltmarsh, including across vegetative gradients from low to high marsh and in unvegetated areas such as tidal creeks and mudflats. Where available, estimates for natural saltmarsh were used rather than managed realignment as these provide longer-term view to the bioremediation potential of saltmarsh.

The estimates shown in Table 3 are annual rates of removal potential. It outlines the mitigation potential of the saltmarsh habitat that is already found in the Norfolk area (green), and a number of scenarios of mitigation were saltmarsh habitat restored, these are derived from percentages of the total area identified by the MMO (pink).

Table 3. Estimated bioremediation potential of saltmarsh habitat in Norfolk. Green represents existing habitat, and the scales of pink represents potential restoration scenarios. Burial rates: 10.2 g N m^{-2} y^{-1} and 4.72 g P m^{-2} y^{-1} (Adams et al., 2012). Denitrification: 37.5 g N_2O-N m^{-2} y^{-1} (Blackwell et al., 2010). Plant uptake: 32.32 g N m^{-2} y^{-1}. The estimation of denitrification and plant uptake were converted to an annual estimation using 8736 hours in a year. Plant uptake is calculated under the assumption that 100% of the restored habitat has plant coverage. This rate should be interpreted with caution as it would not apply uniformly across all areas defined as a saltmarsh, including across vegetative gradients from low to high marsh and in unvegetated areas such as tidal creeks and mudflats.

SCENARIO (ha)	N BURIAL (t N y^{-1})	DENITRIFICATION (t N_2O-N y^{-1})	PLANT UPTAKE (t N y^{-1})	P BURIAL (t P y^{-1})
Existing saltmarsh (4458)	455	1672	1441	210
Potential Saltmarsh 100% (55142)	5624	20678	17824	2592
Potential Saltmarsh 50% (27571)	2812	10339	8912	1296
Potential Saltmarsh 25% (13786)	1406	5170	4456	648
Potential Saltmarsh 10% (5514)	562	2068	1782	259
Potential Saltmarsh 5% (2757)	281	1034	891	130
Saltmarsh Summary (1ha)	0.10	0.38	0.32	0.05

OPPORTUNITIES AND DATA LIMITATIONS

These high-level calculation show that there are opportunities for saltmarsh restoration and conservation to improve and maintain nutrient bioremediation offered by these habitats locally. Particularly in areas where land suitable for saltmarsh managed realignment coincides high nutrient concentrations. Table 3 indicates that denitrification would provide the greatest impact in terms of N removal. This estimate assumes that this rate is constant over a year which is unlikely. Denitrification is a complex process that can be impacted by several factors (i.e., oxygen availability, nutrient availability, soil density), it is likely to fluctuate spatially and temporally. This should be taken into consideration when reviewing these findings. Please note that the values in Table 3 are estimates, they provide an indication of the bioremediation potential of saltmarsh, they should not be used as the actual values, or to imply an economic benefit related to bioremediation.

SALTMARSH MANAGEMENT

The sustainability of saltmarshes depends on the ability of sediment to build vertically at a rate that is in line with sea level rise, (Reed et al., 1999). As of 2020 the global estimate of sea level rise was around 3.3 mm yr^{-1} (Ramsayer, 2020). One long-term estimate for sediment accretion in England is 5.4 mm yr^{-1} (Adams et al., 2012). The deposition of sediments is a vital element of N and P sequestration; therefore, this needs to be considered when planning managed realignments. Reed et al. (1999) found that proximity to tidal creeks was an important factor, with the majority of sediments being deposited within 20m of the tidal creek, and on high tides, resuspension and transportation to the marsh surface is more likely.

Sediment erosion/loss through resuspension would impact the overall N and P sequestration potential of saltmarsh habitat. Management measures that minimise resuspension would help the long-term storage of N and P. One such measure included the use of dredged sediment to prevent failure of an eroding bank, that lead to the natural accretion 630m^3 of sediment (Leggett et al., 2020). Which could have positively impacted the local bioremediation potential of the saltmarsh. Much of the literature identified during the review were related to grazing, which is a common management measure for saltmarsh habitats and appropriate grazing regimes can be a vital tool for maintaining diversity and preventing of erosion. The impacts of grazing on saltmarsh vegetation and soil structure, and how these could impact nutrient assimilation are outlined below.

VEGETATION

In terms of benefits for biodiversity, implementing a grazing/mowing regime on saltmarsh can help to maintain plant diversity, and can be used to minimise successional processes that may lead to dominance of a single species (Wolters, Garbutt and Bakker, 2005). The presence of vegetation is an essential factor in the sedimentation process in saltmarsh (Bartholdy, 2012), and can help to manage erosion risk, either flow-induced or gravity-induced through bankside sediment stabilisation (Chen et al., 2019). Chen et al. (2019) found that the root of *Atriplex portulacoides* (sea purslane) was more effective at stabilising creek banks in the Beaulieu Estuary (UK), providing better resistance to flow-induced erosion, while the root system of *Juncus maritimus* (sea rush) provided better resistance to gravity-induced erosion.

SOIL STRUCTURE

Marin-Diaz et al. (2021) found that in the Netherlands, lateral erosion resistance increased with several different grazing regimes, including larger grazers (cattle) that compacted the soils, and grazing by geese and hares (small grazers) which promoted high root density vegetation. However, they also found that compaction by larger grazers can lead to thinner fine-grained layers to form, as well as lowering elevation. The combined effect of these factors can lead to greater inundation, which can reduce resistance to erosion.

Although grazing can help to improve plant diversity and, in some circumstances help to prevent erosion, Li et al. (2022), found that short-term and long-term exclusion of cattle improved denitrification rates in saltmarshes in China. The denitrification potential of saltmarsh significantly increased the longer grazing was prohibited and was attributed to improved soil moisture; restricting cattle grazing improved soil structure, whereby bulk density decreased, and porosity increased (Li et al., 2022). Furthermore, grazing can cause soil salinity increase and SEC to decrease (Van Duin et al., 2003 in Wolters, Garbutt and Bakker, 2005), which could impact the rate of denitrification (Marks et al., 2016) and burial.

SUMMARY

The literature discussed above indicates that presence of grazers can have positive effects in terms of preventing erosion by soil compaction, which can support the long-term burial of sediments and organic forms of N and P. However, it has been shown that compaction can negatively impact soil structure and denitrification potential. When the potential for N burial and denitrification are compared (Table 3), denitrification is estimated to remove around 3.5 times more N than burial (respectively). Therefore, in terms of saltmarsh management, the measures that support denitrification could be prioritised where nutrient mitigation is a priority. Further research is needed in the UK to understand local dynamics and develop management plans appropriately (e.g., balancing nutrient assimilation with other needs).

SEAWEED NUTRIENT REMOVAL PROCESS

SEAWEED

Seaweed refers to a group of large marine algae which has three main groups, green, red and brown. The key difference between these groups is the pigments that capture sunlight as part of photosynthesis (e.g., green seaweeds contain higher levels of chlorophyll). Many seaweed species are cultivated around the world, and certain groups such as kelps are particularly well suited to growing on ropes due to the way they grow by anchoring on to surfaces.

SEAWEED FARMING

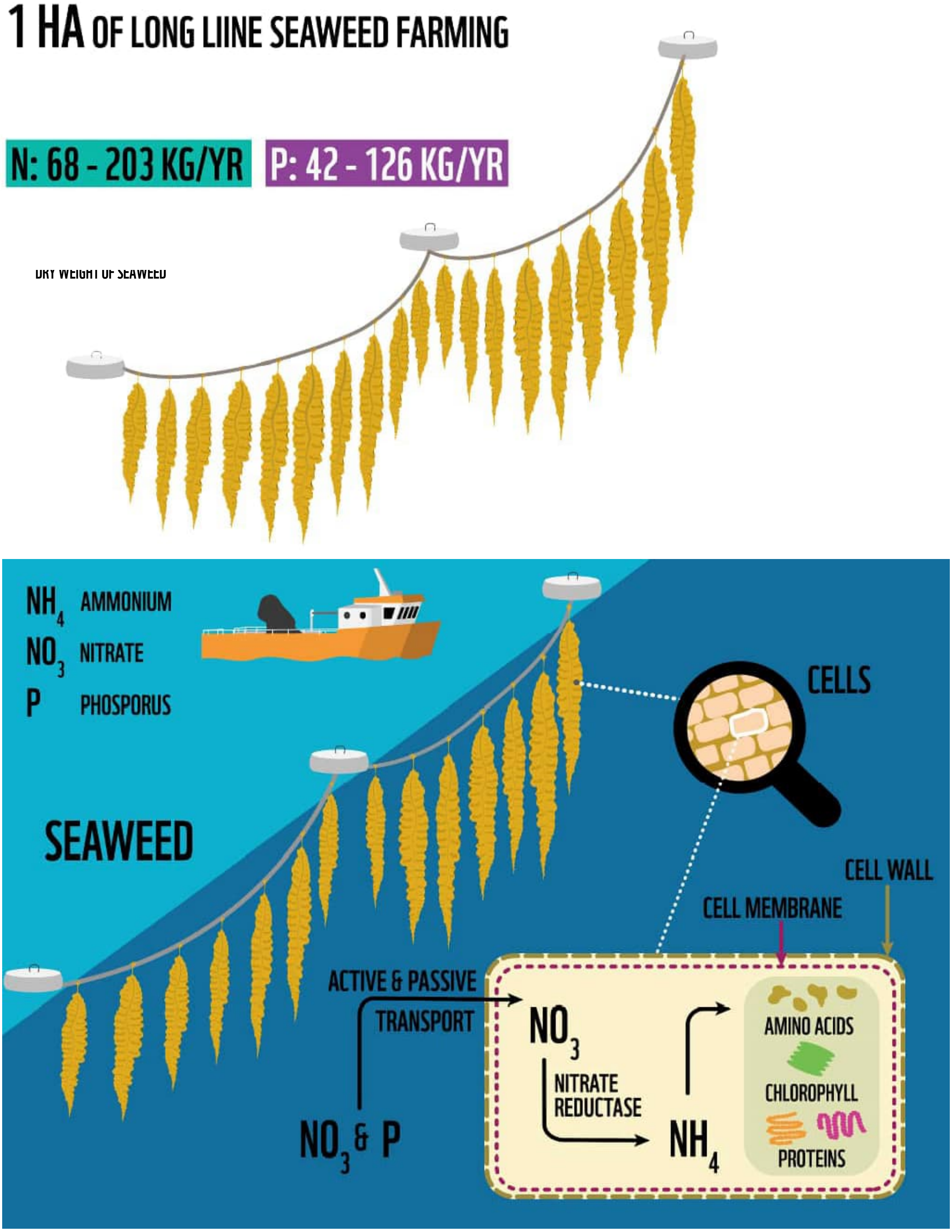
Seaweed farming is a relatively new form of aquaculture in UK waters and has potential to leave nature in a better state after it has taken place. Unlike many other cultivated crops, it doesn't require fertiliser, pesticides, freshwater or land, and it grows rapidly. It removes N and P from the water column, and it could support the transition to a more sustainable and lower carbon UK food industry through its potential use as animal feed, bioplastic, and biostimulants. With its potential use as biostimulant and animal feed, it can also reduce the environmental impact of agriculture, and support healthier land and fresh waters across the UK.

In the UK the growing season for seaweed is from late autumn to early summer. N and P becomes incorporated into algal tissue and is committed to storage while the seaweed is in the water. Unlike saltmarsh which is a community of species, seaweed farming tends to focus on a single species, though mixed species farming and natural settlement of wild seaweed on lines is also common. Seaweeds are highly effective at taking up nitrogen and phosphorous from seawater, assimilating them into organic compounds and storing them within their cells. These stored nutrients can be physically removed with the biomass, which can then be used in a variety of marketable products. The use of seaweed as biostimulant could help to reduce dependency on manufactured fertilisers. This will be discussed in more detail on pages 56-57.

NUTRIENT REMOVAL PROCESS

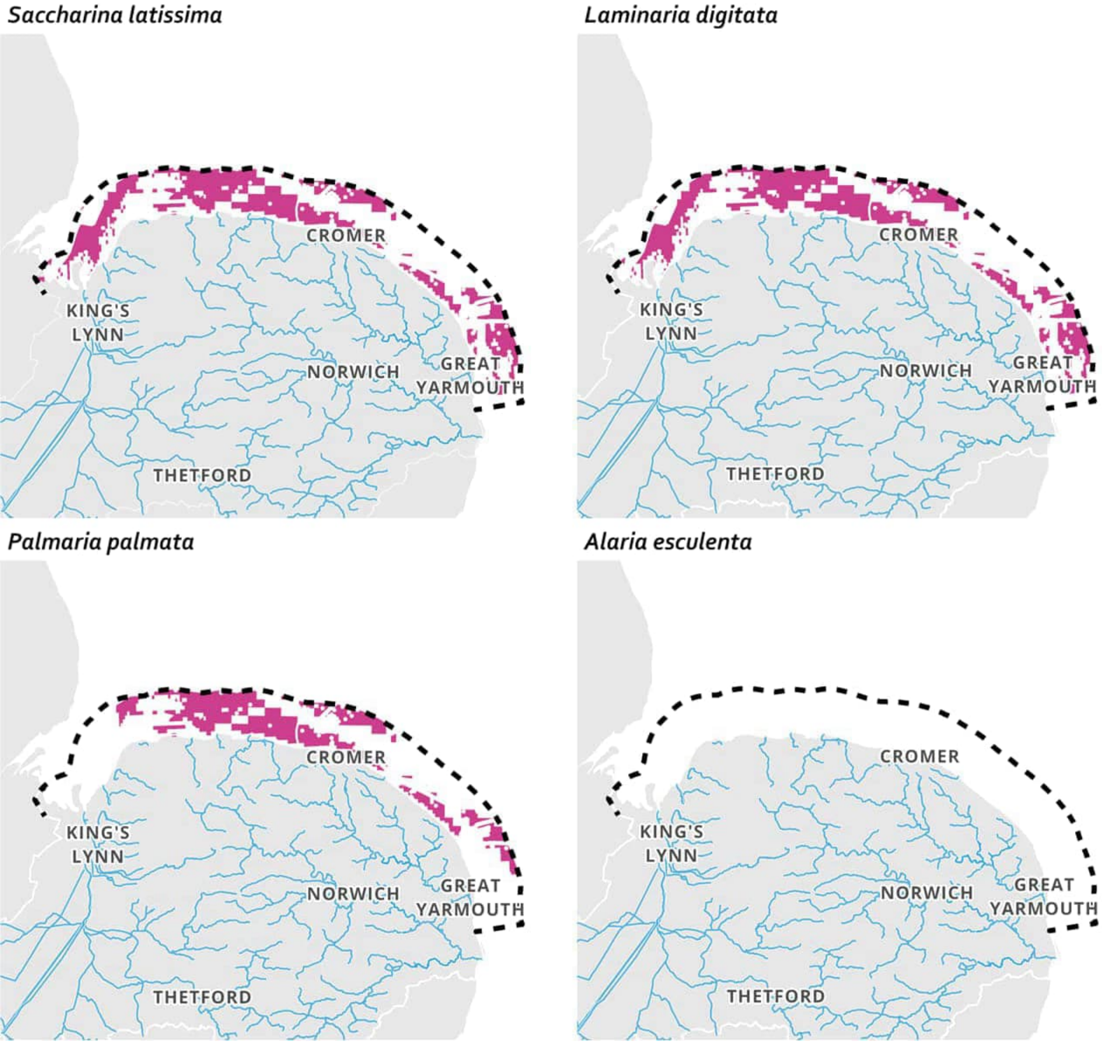
Although seaweeds are not plants, there are some similarities in that they contain chlorophyll, have vacuoles and cell walls, however, they don't have a vascular system, which means they don't have roots and stems, instead, N (NH_4 and NO_3) and P (PO_4) uptake occurs through transport across cell membranes (Harrison and Hurd, 2001; Douglas et al., 2014). Depending on the saturation level and molecule, this may be through passive or active transport (Harrison and Hurd, 2001). When NO_3 is taken up across cell walls, it can be stored in the vacuole or cytoplasm, or reduced by nitrate reductase to ammonium (NH_4) (McGlathery et al., 1996; Harrison and Hurd, 2001). Ammonium is then assimilated into organic compounds (amino acids and amino compounds) and incorporated into proteins and chlorophyll (McGlathery et al., 1996). See Figure 17 for a graphical representation of the uptake and assimilation process for NH_4 and NO_3. Harrison and Hurd (2001) note that compared to N storage, little is known about P storage in macroalgae.

Figure 17. Graphical depiction of nutrient removal processes with focus on nitrogen, as information on phosphorous storage is limited. Seaweeds do not have vascular system, instead nutrients are transported across the cell membrane and then assimilated into organic compounds.



POTENTIAL SEAWEED FARMING IN NORFOLK

The MMO has developed spatial dataset that delineates areas of potential for aquaculture development of key species (Identification of areas of aquaculture potential in English waters, 2022). These data were created using environmental variables including sea surface temperature, salinity, light, climate, total oxidized N, dissolved oxygen, and chlorophyll concentration to provide a suitability scoring. The MMO also identified and removed technical constraints on infrastructure required for an aquaculture operation. Figure 18 shows the potential suitable area for four commonly farmed species in the UK, *Saccharina latissima, Laminaria digitata, Alaria esculenta,* and *Palmaria palmata.* As Figure 18 shows, there is suitability for three of the four species, but not for *A. esculenta,* as it is limited to more northerly locations due to summer seas surface temperatures (MMO, 2019).



SEAWEED

AQUACULTURE SUITABILITY

- ■ Maximum possible extent
- ▪▪ Marine focus area
- — Rivers

SPECIES	OPTIMAL
S. latissima	60,000 ha
L. digitata	60,000 ha
P. palmata	44,000 ha
A. esculenta	0 ha

Data used: WFD River, Canal and Surface Water Transfer Water Bodies Cycle 2 Classification 2019 (2022), Boundary-Line™ (2021), Evidence Project MMO1184 - Identification of areas of aquaculture potential in English waters (2021).

Data sources and full attributions for each map are listed on page 68.

Figure 18. Locations of optimum suitability for four seaweed species, as identified by the MMO.

In the area within the 11km coastal buffer, just under 40% was found to be optimal for *S. latissima* and *L. digitata*, and just under 30% for *P. palmata.* As there was no potential for *A. esculenta* in the Norfolk area, this species will not be discussed further. Information on *P. palmata* cultivation using a long-line system was also limited, therefore this species will also not be discussed any further. With *P. palmata* and *A. esulenta* not being considered, the remaining two species are *S. latissima* and *L. digitata.*

Using the area of optimal habitat within the 11km coastal buffer, the outputs in biomass yield and N and P bioremediation potential for *S. latissima* and *L. digitata* were estimated (page 55). These calculations could help to understand the potential for biomass production and nutrient removal by the farming of these species in the coastal area of Norfolk. The process for undertaking these calculations are discussed on pages 53-54.

REVIEW OF SEAWEED

Available literature was reviewed to establish key parameters for estimating seaweed yield. This included a review of existing estimates and any associated limitations of these estimates. The literature review highlighted that estimating the biomass yield as an indicator of productivity is an essential element of bioremediation potential. However, there are many variables that can influence growth and therefore yield, these are discussed below along with optimum ranges for each of the factors where available.

LIGHT AVAILABILITY

Sufficient availability of light is needed for photosynthesis to occur. The depth to which light can penetrate the water column is dependent on the level of suspended sediments (turbidity) and/or increased algal biomass linked to eutrophication. Van Der Molen et al. (2018) noted that the optimum photic depth for *S. latissima* was >2m and <1 was considered unsuitable. No information relating to *L. digitata* was located.

TEMPERATURE

The metabolic rate of seaweeds is affected by sea temperature (Kerrison et al., 2015), which can impact their growth potential. The optimum temperatures for *S. latissima* and *L. digitata* is between 5ºC and 15ºC (Kerrison et al., 2015) which means the growing season for both species can commence in late winter when sea temperatures are coldest (White and Marshall, 2007; Hill, 2008).

SALINITY

The optimum salinity ranges varies slightly between *S. latissima* and *L. digitata* (24-35 PSS and 20-35 PSS respectively), with *S. latissima* likely to be more sensitive (Kerrison et al., 2015). A drop in salinity, particularly for a sustained period (around 5 days or more) can cause stress and in some cases kills seaweed.

WATER VELOCITY AND MOTION

Sufficient water velocity and motion is important for sustained growth of seaweed species as this reduces the thickness of the diffuse boundary layer and prevents settlement of epiphytes, grazers and sediment (Kerrison et al., 2015). The optimum is > 25 cm s^{-1} (Kerrison et al., 2015), where water flow is too low and settlement occurs, photosynthesis and nutrient uptake could be inhibited, impacting growth and biomass yield. Conversely, flow rates too high can cause plants to become dislodged.

WATER NUTRIENT AVAILABILITY

The optimum availability of N for both *S. latissima* and *L. digitata* is between 10 and 40 µM NO_3 $l^{-1,}$ and PO_4 was reported to be >0.3 µM l^{-1} (Kerrison et al., 2015). However, each of the factors mentioned above that can limit growth can also impact nutrient uptake rates from the surrounding seawater, as can the nutrient history of the plant, desiccation and the chemical form of the nutrients (Harrison and Hurd, 2001).

SEASONALITY

All the factors mentioned above will lead to seasonal variability in the growth and nutrient content of *S. latissima* and *L. digitata* tissues. Schiener et al. (2015) found that the stored N varied depending on season, with the highest levels recorded in March.

CULTIVATION METHOD

The review of the biomass yield presented in Appendix I highlights variability in cultivation methods used, this is likely to explain the large differences in yield reported. The density of seeded lines affects yield in a unit of area, and there is a trade-off between density of line and accessibility by boat, tangling of lines, and other operational constraints. However, if lines are too dispersed this can also lead to operational inefficiencies and sub-optimal yield. Based on a site in Denmark, Bolderskov et at. (2023) confirmed that high line density in the upper water column can increase yield, but also found that yield from the same cultivation system and site can vary four-fold from one year to the next. This reinforces the high variability in yield from year to year, and even across the same season, due to all of the complex and interacting factors mentioned in this section.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CALCULATING MITIGATION POTENTIAL OF SEAWEED FARMING

BIOMASS CALCULATIONS

During the literature review biomass yield estimates were collated for three of the four MMO identified species (Appendix I), however, accounting for all the variables outlined on page 51 and 52 was challenging, and may provide estimates that do not fully reflect the conditions in the coastal area of Norfolk, particularly as data on biomass yield was limited for the individual species. This was especially the case for *L. digitata* (Appendix I). Rather than using an estimate taken from the literature that may not be geographically relevant to Norfolk, and after discussion with UK stakeholders, the potential yield of 15 kg ww m^{-1} y^{-1} using longline cultivation method was selected for the basis of all biomass yield calculations. This figure is similar to what was reported by Pechsiri et al. (2016) (details in Appendix I). To estimate the biomass yield per ha the density of growing lines is also needed. While some of the literature reviewed did include the length of growing structure per ha, the results were varied, so the line densities reported by UK stakeholders were also used when calculating biomass yield. These were represented by low density growing lines (667m ha^{-1} or a 15m line separation) and high density growing lines (2000m ha^{-1} or a 5m line separation) and the results are presented in ranges which relate to these line densities.

BIOREMEDIATION CALCULATION

The bioremediation rates for *S. latissima* and *L. digitata* were taken from the literature and were divided into two distinct parts, uptake rates, which are characterised by surface area and/or unit of time (Appendix G and H), and nutrient removal potential (Appendix J and K), which is directly or indirectly related to the biomass yield weight (Appendix I). The removal potential is classed as the nutrient content (N or P or derivative of these) of the respective seaweed species. Please note, while this does not represent the rate that these nutrients are assimilated into organic compounds, this does provide an estimation of the amount of N or P (or their derivatives) that could be removed from the available pool within the coastal waters of Norfolk.

The best estimates for N was 3.5% (April harvest) (Adams et al., 2011) and 4.5% (April harvest) (Bruhn et al., 2016) of the dry weight for *L. digitata* and *S. latissima* respectively (Appendix J). The estimation for P was 0.28% of dry weight for *L. digitata* (August harvest) and *S. latissimi* (April harvest) (Bruhn et al., 2016; Ohlsson et al., 2020) (Appendix K). These are the maximum figures found in the literature and could be less if the seaweed was harvested at later in the year (Schiener et al., 2015). The criteria/justification for using these values are outlined in Table 4 below, and the calculations of nutrient removal are presented on the following page. The conversion rate from wet weight biomass to dry weight was 15% as per Seghetta et al. (2016).

UPTAKE CALCULATION

While the estimates of N and P uptake are useful data to summarise (Appendix G and H), all the values which were identified within the literature were derived from cultivation in lab conditions, and therefore figures are unlikely to be directly transferable to cultivation *in-situ*. Furthermore, a characteristic of uptake estimates is that they are limited to surface area units and/or unit of time. When trying to apply these spatially to understand the potential uptake across the MMO identified areas, it becomes challenging, as the surface areas in a wild situation cannot be easily determined. Therefore, these data were not utilised for calculations, instead the nutrient removal potential estimations were used, where weight of nutrient can be reported as a proportion of biomass yield.

Table 4. Criteria used to identify the best estimates from the range of values presented in Appendix J and K.

TOPIC	CRITERIA
Geographical scope	Studies based in the NE Atlantic were selected over those outside of this area, unless no alternative was available.
Unit	Kjeldahl-N was excluded due to complexities of measurement. Units that included a unit of time, but no spatial element were not selected due to complexity in estimating spatially. For N and P, % of biomass was selected as this provided the simplest method for standardising estimates.
Cultivation	*In-situ* cultivation was selected over lab cultivation. Modelled data were not used as estimates
Literature access	Estimates from literature that was accessed in full was preferred instead of those taken from abstracts as these lacked context relating to methods and results.
Max. value	In all cases the maximum reported valued was selected.

BIOREMEDIATION POTENTIAL OF SEAWEED FARMING

The following table describes the biomass yield, in wet and dry weights, as well as the associated nutrient removal potential (N = turquoise, P = purple). As it is somewhat unrealistic and undesirable that seaweed farming would be implemented across the entire area of optimum suitability identified by the MMO, a number of different scenarios have been outlined. Table 5 indicates that the outputs in terms of biomass and nutrient removal are very similar for both species, the only measurable differences is that *S. latissima* may remove more N than *L. digitata*. These calculations are based on one harvest per year, but it is possible that more than one could be achieved.

Table 5. Estimation of total biomass yield and bioremediation potential for *S. latissima* and *L. digitata*. Lower end of range relates to estimates where lines are spaced 15m apart, and higher end with lines spaced 5m apart. 60,000ha = 100% of optimal suitability as reported in the MMO study, based on one harvest per year.

SPECIES	AREA OF OPTIMAL SUITABILITY (%)	WW (t) y^{-1}	DW (t) y^{-1}	N (t) y^{-1}	P (t) y^{-1}
L. digitata	100	600,300 1,800,000	90,045 270,000	3,152 9,450	252 756
	50	300,150 – 900,000	45,023 – 135,000	1,576 – 4,725	126 - 378
	25	150,075 – 450,000	22,511 – 67,500	788 – 2,363	63 - 189
S. latissima	100	600,300 1,800,000	90,045 270,000	4,052 12,150	252 756
	50	300,150 – 900,000	45,023 – 135,000	2,026 – 6,075	126 - 378
	25	150,075 – 450,000	22,511 – 67,500	1,013 – 3,038	63 - 189

Table 6. Estimation of total biomass yield and bioremediation potential for *S. latissima* and *L. digitata* at different farm scales, based on one harvest per year. Lower end of range relates to estimates where lines are spaced 15m apart, and higher end with lines spaced 5m apart. Literature suggests that the nitrogen content across *S. latissima and L. digitata* varies and therefore species specific values are presented.

AREA POTENTIAL FARM (ha)	WW (t) y^{-1}	DW (t) y^{-1}	N (t) y^{-1}	P (t) y^{-1}
100	1001-3000	150-450	*L. Digitata:* 5.25-15.75 *S. Latissima:* 6.75-20.25	0.42-1.26
50	500-1500	75-225	*L. Digitata:* 2.63-7.88 *S. Latissima:* 3.38-10.13	0.21-0.63
10	100-300	15-45	*L. Digitata*: 0.53-1.58 *S. Latissima:* 0.68-2.03	0.04-0.13
5	50-150	8-23	*L. Digitata:* 0.26-0.79 *S. Latissima:* 0.34-1.01	0.02-0.06

DATA LIMITATIONS

There are a number of limitations to be aware of when reviewing data presented in Tables 5 and 6. The calculations are based on data from locations where the growing conditions might best reflect those of the North Norfolk, taken from a limited pool of data relating to North East Atlantic, but as described earlier there are many variables that will affect growth and nutrient uptake, as well as season and when they deployed and harvested, so these figures provide an indication output potential not actual figures or estimates of economic benefits.

CIRCULAR AGRICULTRAL SYSTEM: RECYCLING SEAWEED

Worldwide, seaweed aquaculture was projected to have provided bioremediation services to the value of $1.1 and $3.4 billion USD for N and $52 million USD for P based on the cost of recovering N and P at wastewater treatment plants (Chopin and Tacon, 2021).

Using seaweed on the land to benefit crop production is not a new concept, and in the UK there is a long history of collecting and using wild seaweed for this as it is locally available, nutrient rich, and inexpensive. If managed correctly, seaweed harvesting and farming could be sustainable. What is a newer concept is using farmed species of seaweed, both as a bioremediation mechanism and as a biostimulant to aid reductions in overall synthetic fertiliser use. If scaled, this could support a more circular agricultural system with reduced overall fertiliser inputs.

SEAWEED BIOSTIMULANTS IN AGRICULTURE

Ali et al. (2021), noted that seaweed extracts were biostimulants rather than fertilisers as they do not contain fertiliser compounds at the levels needed to qualify as a fertiliser. du Jardin (2015) defined a biostimulant as *“any substance or microorganism applied to plants with the aim to enhance nutrition efficiency, abiotic stress tolerance and/or crop quality traits, regardless of its nutrients content”.*

There is growing evidence that seaweed is an effective biostimulant and can be a source of a variety of compounds, including lipids, proteins, carbohydrates, phytohormones, amino acids, osmoprotectants, antimicrobial compounds, and minerals, which can have biostimulating effects (Parađiković et al., 2019). The positive impacts reported include, but are not limited to, promoting seed germination, improved root length and feeder root density (Mattner et al., 2018), improved nutrient uptake and use efficiency (Mattner et al., 2018; El Boukhari et al., 2020), increased crop nutritional value, improved soil structure, and increased yield (El Boukhari et al., 2020; Figure 3 Ali et al., 2021).

There are multiple negative impacts of using chemical fertilisers, especially overuse, including degradation of soil health, water quality, and the carbon emissions from their production. A recent study noted that one-third of the carbon emissions from chemical fertilisers derived from their production, with two-thirds attributed to their use/application (Gao & Serrenho, 2023). There is an opportunity to utilise the biostimulant benefits of seaweed, particularly, the improved nutrient uptake and use efficiently to reduce the overall amount of N and P applied to the land locally, in turn reducing the associated carbon emissions. Trials are needed to demonstrate the scale and effect of seaweed based biostimulants on crops grown in the region, alongside engagement and awareness raising activities with the farming community.


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MANUFACTURING AND APPLICATION

To produce a seaweed biostimulant, the seaweed biomass needs to undergo some form of processing, either physical (heat, pressure, microwaves) or chemical (solvents, acid, alkali) (Ali et al., 2021). An important factor in the creation of seaweed biostimulant is being able to guarantee the integrity of the compounds that are responsible for the biostimulant effects, and where defined, that the concentration of contaminants does not exceed limits. Different extraction methods may be selected based on the intended use of the biostimulant, including crop type and mode of application (El Boukhari et al., 2020). Seaweed biostimulant is normally applied in liquid form, either to the roots, via soil or other growing media, or to the leaves as a spray.

COMMERCIAL SEAWEED BIOSTIMULANT

Many commercial biostimulant products already contain seaweed (Ali & Ramsubhag, 2021). The chemical composition of seaweed can vary spatially and temporally and guaranteeing biological integrity and consistency of any biostimulant product is vital. Other elements contained in the seaweed extract could be too high for application, such as heavy metals. Further research is required to understand seasonal, geographical, and other influences on the chemical composition of seaweeds to optimise harvesting and processing requirements for the production of seaweed based biostimulants.

To reach a level of scale that could make a measurable difference to nutrient pollution issues, the technical, social, and environmental barriers to seaweed farming and biostimulant uptake should be carefully considered. This includes regulatory and legal requirements, and currently in the UK any seaweed farming or wild foraging activities require a license under the Marine and Coastal Access Act (2009), and additional permissions from statutory authorities. Regulations around biostimulant use may be also applicable. Additionally, the logistical infrastructure required to ensure seaweed is distributed efficiently as a commercial product needs careful consideration and feasibility assessment, including processing and the possible storage requirements of the end product.

LONG-TERM SUSTAINABILITY OF A CIRCULAR AGRCULTRAL SYSTEM IN NORFOLK

NUTRIENT AVALABILITY

Whilst seaweed farming can offer nutrient remediation, the ambition is to reduce overall nutrient inputs into the system and various catchment schemes are underway to this end. Therefore, in this report seaweed production under a scenario of 50% reduction of nutrient input was considered to understand the extent to which this could impact yields given that growth relies on N and P availability. The current situation for transitional and coastal waterbodies in the 11km buffer is presented using modelled data in Figure 14. To allow comparison between nutrient removal rates reported as N and P and nutrient availability, these data were converted from NO_3 and PO_4 mmol m^{-3} to NO_3-N and PO_4-P g m^{-3} respectively, and the average monthly availability was calculated and is shown in Figure 19 below. The modelled data indicate that P is expected to become limited during the summer months, and with a 50% reduction this would be further limited, however these data indicate that it wouldn't drop below the optimum for either species of seaweed (orange line below). N availability does not drop as steeply compared to P, and it is also not expected to fall below optimal levels.

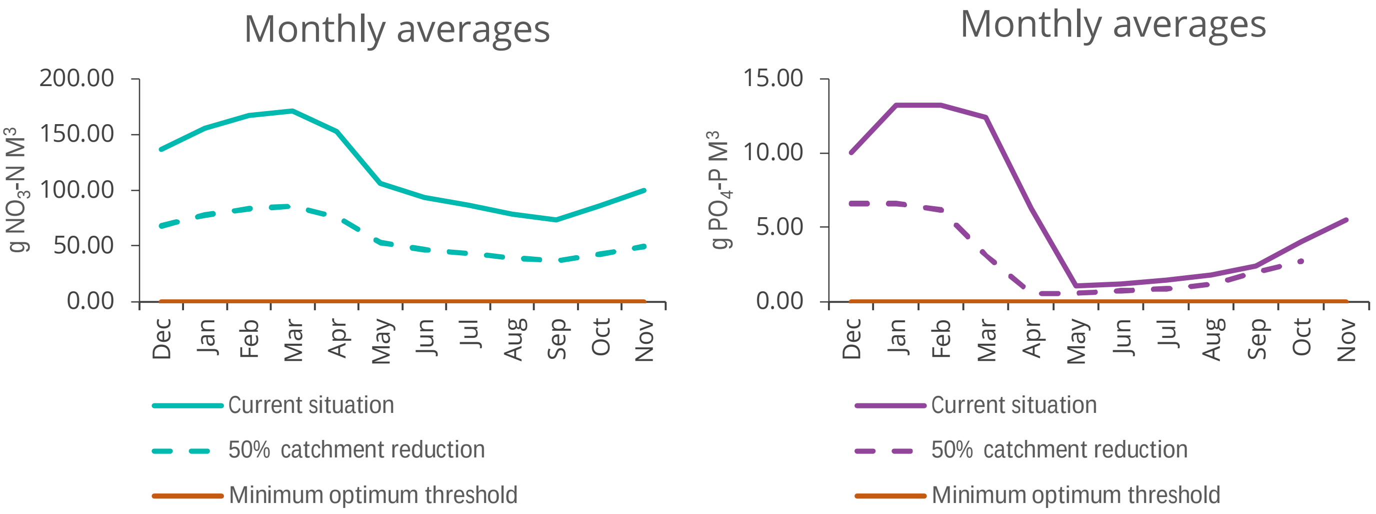

Figure 19. The average weight of N (left) and P (right) m^{-3} per month in 2021 (solid line). Minimum optimum threshold for seaweed growth represented (orange line), along with the potential availability of nutrients if there was a 50% reduction in availability (dotted line). Generated using E.U. Copernicus Marine Service Information; NWSHELF_MULTIYEAR_BGC_004_011.

NUTRIENT UPTAKE

Seaweed species will take up and store nutrients over the winter and spring when availability is highest. To assess the availability of N and P ha^{-1} for a growing structure assumed to be 5m line spacing with a 2m depth, the potential nutrient removal rates for the winter and spring were calculated (Table 7 below) and compared to estimated availability.

The daily N and P rates for *S. latissima* were calculated by taking the maximum biomass yield ha^{-1} (4.5t dw (5m line separation)), calculating the N and P weight as per page 53, then dividing by 150 days. This estimate assumes that there is 150 days from deployment of lines to harvest, so the daily estimation can change depending on deployment days. This can only provide a superficial indication of seaweed farm productivity and bioremediation potential if catchment inputs reduced by 50%. However, these figures suggest that even with a 50% reduction in nutrient input, seaweed farming in Norfolk would not be affected by limitations in N or P availability. Please note, the estimated daily uptakes included below assumes that the uptake is consistent spatially and temporally, however, constant rates are unlikely between the seasons. Therefore, these estimations should not be used as actual figures, or be used to calculate any potential economic benefits of seaweed farming, but they do provide a superficial indication of productivity and bioremediation potential at different nutrient input scenarios.

Table 7. Estimation of the daily uptake rates and the potential nutrient availability based on the current situation and if catchment inputs were reduced by 50%. This estimate assumes that there is 150 days from deployment of lines to harvest, so the daily estimation can change depending on deployment days. This can only provide a superficial indication of seaweed farm productivity and bioremediation potential if catchment inputs reduced by 50%.

NUTRIENT INPUT SCENARIOS	ESTIMATED DAILY UPTAKE (t N ha^{-1})	MIN t NO_3-N ha^{-1} AVAILABLE (DAILY AVERAGE WINTER/SPRING) (t)	ESTIMATED DAILY UPTAKE (t P ha^{-1})	MIN t PO_4-P ha^{-1} AVAILABLE (DAILY AVERAGE WINTER/SPRING) (t)
CURRENT SITUATION	0.001	1.5	0.00008	0.011
50% REDUCTION IN INPUTS		0.7		0.005

COMBINED BIOREMEDIATION POTENTIAL

Assuming that chemically manufactured N and P is applied at the rate of 175 kg N ha^{-1} y^{-1} and 22 kg P ha^{-1} y^{-1} (Ohlsson et al., 2020), the arable land in Norfolk could be receiving approximately 56,000t of N and 7,000t of P each year.

We estimate that if 25% of the possible extent indicated by the MMO to be suitable for seaweed farming is utilised, then the annual nutrient removal potential by *S. latissima* could be around 3000t of N, and 190t of P. This assumes a single harvest from a dense farm with a 5m line separation, across a total extent of 15,000ha (25% of MMO estimated suitable area). If this was combined with N and P removal potential of saltmarsh, which was estimated to be 4412t N y^{-1} and 259t P y^{-1}, (based on around 5500ha of saltmarsh restoration (10% of the area identified by the MMO, which is just over double the current area)) the total estimated removal would be around 7500t of N and 450t of P. This could equate to around 13% of the N and 6% of the P applied as fertiliser across the county. Please note, not all fertiliser applied to arable land will be lost to the waterways, nor will the rate of application be the same across Norfolk, however, these estimates provide a broad indication of the combined potential for saltmarsh restoration and seaweed farming to reduce nutrient pollution across Norfolk. To accurately estimate the impact of saltmarsh restoration and seaweed farming on future nutrient flows and water quality, detailed modelling would need to be undertaken. Without this type of information, there are limitations to conclusions that can be drawn.

REPORT SUMMARY

Part 1 shows that nutrient pollution is a significant issue affecting the majority of Norfolk. Nutrients entering the water network are primarily associated with sewage, agriculture, industrial processes and transport. Without a decrease in these inputs, which is the primary management option for nutrient pollution, no tangible water quality improvements will be realised. This will keep the county in a 'no change' situation at best, where the nutrient supply exceeds the bioremediation potential of seaweed farming and saltmarsh restoration, which is an example of a secondary management option for nutrient pollution.

The ideal future nutrient scenario would be a reduction in the sources of N and P across the county sufficient to meet the planetary boundaries identified by WWF and 3Keel (Jennings et al., 2021). In this scenario, nutrient reduction combined with a bioremediation strategy could not only help to reduce nutrient pollution and improve water quality but could also deliver co-benefits such as improved soil health, biodiversity and carbon capture, potentially strengthening the resilience of the agricultural sector and Norfolk's natural capital provision.

The data drawn upon for this work indicates that it is likely the current level of nutrient inputs are causing nutrient enrichment issues in the coastal waters of Norfolk. The evidence presented in Part 1, outlining sources, pathways and risks, and supported by modelled marine nutrient data, shows that the amount of NO_3 ranges between 4.62 (summer) and 34 (winter) mmol m^{-3}. When converted from mmol m^{-3} to mg/l this indicates that the winter NO_3 levels (2.1mg/l) would equate to a moderate-poor WFD categorisation (1.67-2.51mg/l) (UK TAG, 2008).

The bioremediation estimates presented in Part 2 of the report illustrate that there is great potential for saltmarsh restoration/creation and seaweed farming to have a positive impact locally. Norfolk could therefore be a good candidate for testing and demonstrating these measures further, which is a positive step towards managing nutrient issues in coastal waters. It is important to remember that bioremediation should always be secondary to the primary measure of reducing nutrient inputs across the catchments. The benefits of reducing catchment sources are far reaching and will have a positive impact on the coastal waters as well as freshwater and other sensitive habitats found in Norfolk. These would be enhanced further by a bioremediation strategy which is inherently linked to the creation and restoration of habitats. When the area of natural habitat increases the delivery of associated ecosystem service provision also increases.

It is clear from the detail presented in this report that there is potential for bioremediation to act as a secondary management option for the nutrient pollution issues in Norfolk, but there are key areas where further work is required before the true potential of saltmarsh and seaweed farming can be fully appreciated. The recommendations for further work are outlined on the following pages.

FUTURE ACTION: RESEARCH

Ecosystem service assessment

Depending on the scale at which saltmarshes are restored and seaweed is farmed, the co-benefits and provision of other ecosystem services by these mitigation options could prove valuable at a landscape scale. Estimating these wider ecosystem services, such as flood protection, biodiversity and cultural services for example, was not part of this report, however, it would be useful to understand the additional benefits these bioremediation measures could provide.

Saltmarsh

Data informing the bioremediation potential of UK saltmarshes identified in this report was limited. Indeed, the drivers and factors that influence this function were not fully accounted for, and are complicated by the complex processes associated with saltmarsh habitats (e.g., tidal inundation, sediment accretion, erosion patterns, etc.). It is therefore important that further research explores this in more detail, which will allow for this ecosystem service to be considered in the design of managed realignment projects in the future, potentially increasing its ability to remediate nutrient pollution.

Seaweed farming

At the time of writing, the data available on seaweed cultivated and harvested in UK waters was limited, therefore, much of the information was taken from studies undertaken in the North East Atlantic. Nutrient pollution levels are seasonally higher in winter and spring. The life cycle of many cultivated algae, including kelp, involves rapid growth over this same period, offering potential to bioremediate nutrients at the same time at which they enter the marine environment. Achieving multiple harvests per year, as well as supporting financial viability of a seaweed farm, could extend the bioremediation potential offered as biomass growth is sustained over a longer period of time into early summer months. Yield is a critical determiner of the bioremediation potential of seaweed. There was very limited data on potential yields of different algae species in UK waters, and as a result this study used a set of assumptions and looked at a limited number of algal species. Further work looking at possible UK yields is strongly recommended and would improve calculations around bioremediation potential, especially understanding the extent to which this measure could be carried out at a commercial scale.

Seaweed biostimulant

There is much interest in using cultivated seaweed within local circular economies, especially in the context of reapplying seaweed, and any remediated nutrients within it, back to land to support arable farming. As discussed in earlier sections, seaweed is lower in N and P than traditional synthetic fertiliser, but does contain low quantities of N and P along with a suite of other useful compounds for plant and soil health, and can therefore be used as biostimulant. Trials using seaweed biostimulant to date have tended to use *Ascophyllum nodosum* (Shukla et al., 2019). Comparatively, the species suitable for farming in Norfolk are less studied for use as biostimulant, and it is likely that the same species grown in different waters will contain different concentrations of compounds due to variation in abiotic conditions, therefore geography specific studies are required. Future trials should look to determine (a) the chemical composition of biostimulants made from local farmed species, including how this might vary over time and how this variation could be dealt with to produce a consistent product, (b) impacts of locally produced biostimulant on yield, crop quality, and requirement for synthetic fertiliser, (c) impacts of introducing seaweed biostimulant to local freshwater ecology, and finally (d) the potential reduction in synthetic fertiliser that could be achieved at a local and regional scale, and the concurrent impact this could have on farm economics, including cost of inputs.

While seaweed is not currently considered a fertiliser (Ali et al., 2021), some literature suggests that seaweed does have potential to be used in this way, in addition to being used as a biostimulant (Alobwede et al., 2019). Exploring this possibility further would be beneficial as there may be potential to replace a higher proportion of chemical fertilisers compared to when used as a biostimulant.

FUTURE ACTION: FEASIBILITY AND FUNDING

A feasibility assessment should be undertaken which explores possible financing schemes, such as nutrient trading and offsetting, government funding, water company funding, as well as other investment opportunities from local industry.

Saltmarsh

When the source data from Part 1 are compared with the opportunity data in Part 2, the area of greatest risk and highest modelled marine nutrient levels corresponds to a substantial area of potential for saltmarsh restoration identified by the MMO. It is unlikely that the entire opportunity area will be restored to saltmarsh, but when assessing the need and opportunities across the county, west Norfolk could prove a suitable starting point to assess feasibility of restoration.

Seaweed farming

If carried out responsibly and at an appropriate scale, seaweed farming could be one of the few farming activities that provides useful biomass with little to no input, and could leave nature in a better state than it finds it. Therefore, with additional supporting evidence on the feasibility, bioremediation potential, and biostimulant properties of seaweed farming at a local scale, it is possible that subsidies for these activities could be incorporated into future iterations of farm subsidies, such as the Environmental Land Management Scheme (ELMS), and other payment for ecosystem services schemes.

FUTURE ACTION: LAND MANAGEMENT

Saltmarsh

There is potential for different management methods as well as the restoration process and design of saltmarsh restoration to be optimised. This could maximise bioremediation potential, the provision of other ecosystem services and improve resilience to the effects of sea level rises caused by climate change. It is evident that there are multiple research gaps in relation to saltmarsh management and bioremediation, and research in this area would allow land managers to consider bioremediation during design phases of saltmarsh restoration and creation.

Biostimulant application

The source mapping in Part 1 indicates losses to water are not uniform across the county. Therefore, an effective strategy for targeting application of seaweed biostimulant could be devised if significant evidence is found supporting the potential benefits of biostimulant use. An example of a targeted strategy could be to utilise biostimulant on the areas identified as ‘risky’ for nutrient losses to waterways. In the short-term, this approach could improve nutrient uptake efficiency, which may reduce chemical fertiliser application. In the long-term, soil structure could be improved, over time this would help to minimise nutrient losses to waterways as the water retention and infiltration potential is improved. More research, on both the efficacy of seaweed based biostimulants and potential downstream effects of their use, is needed to inform any such strategy.

CLOSING REMARKS

Nutrient pollution is one of the key challenges facing the UK, and future policy and remediation efforts will need to be underpinned by robust evidence. This report provides a case study exploration of nutrient sources and flows in Norfolk. It also highlights future areas of research required to maximise the potential to use bioremediation measures, such as saltmarsh restoration and seaweed farming, to mitigate such nutrient issues. With more knowledge, these methods could deliver tangible water quality and ecosystem benefits, both in Norfolk and more widely across the UK. Meanwhile, reducing input at catchment level continues to be the first priority.

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DATA ATTRIBUTIONS

Publisher	Dataset	Data attribution statement	Page
British Geological Survey	BGS Geology 625K	Contains British Geological Survey materials © UKRI 2021.	13
	Hydrogeology 625K	Contains British Geological Survey materials © UKRI 2023	66
Copernicus Marine Service	Atlantic- European North West Shelf- Ocean Biogeochemistry Reanalysis	Generated using E.U. Copernicus Marine Service Information; https://doi.org/10.48670/moi-00058	32
EDiNA	Agcensus	© 2021 The University of Edinburgh. All rights reserved.	20, 28
Environment Agency	Event Duration Monitoring - Storm Overflows - 2023 (England and Wales)	Produced by The Rivers Trust. © Environment Agency copyright and/or database right 2024. All rights reserved. © Dŵr Cymru/Welsh Water. © Hafren Dyfrdwy.	16, 28
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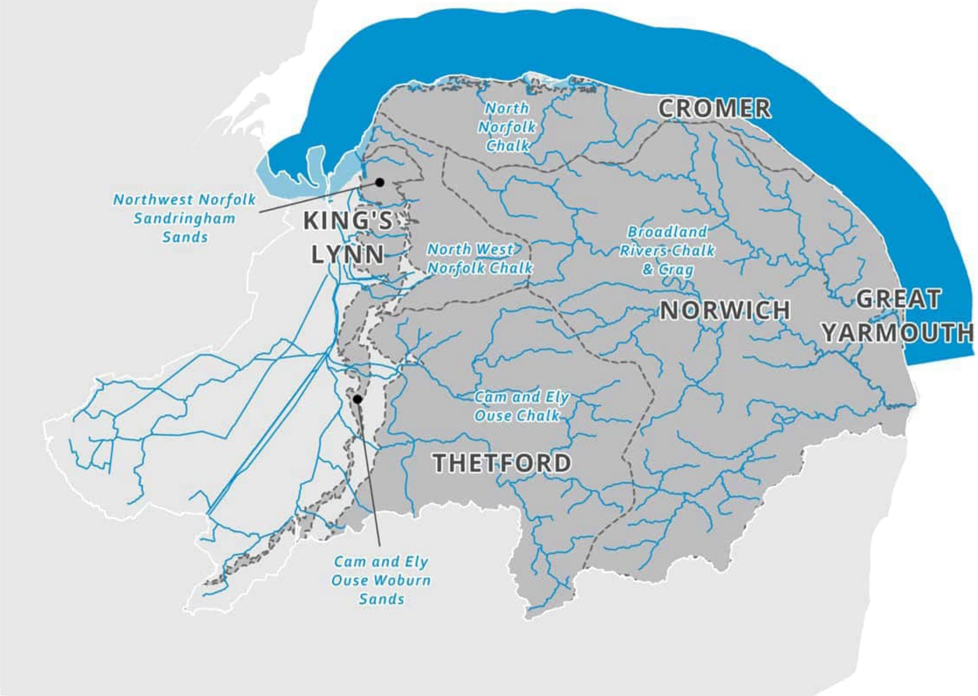
APPENDICIES

Appendix A. Groundwater bodies classified under the Water Framework Directive. Each waterbody if hydraulically distinct, meaning water does not flow between them. They provide management units in which the directive can be delivered and monitored. This map shows the connect between the rivers on the surface and the groundwater bodies below them.



GROUNDWATER PATHWAYS

▨ Water framework directive groundwater bodies

🟦 Tidal water

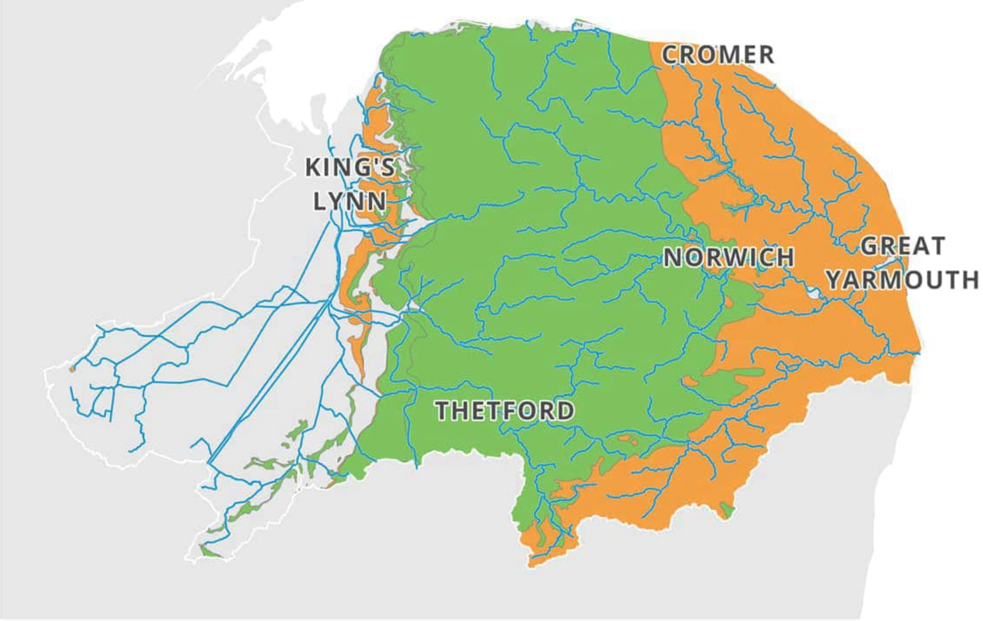
🟦 North Sea

— Rivers

Data used:
WFD Groundwater Bodies (Cycle 2) (2019), WFD River, Canal and Surface Water Transfer Water Bodies Cycle 2 Classification 2019 (2022), Boundary-Line™ (2021).

Data sources and full attributions for each map are listed on page 68.

Appendix B: Designated aquifers and their level of productivity within the focus area. These are the potential sinks of nutrients lost to water that flow through the groundwater network pathway. In areas of permeable soils and geology water carrying high levels of nutrients can travel down into the underground aquifers. It may take a long time for water to reach these underground reserves from the surface so there is usually a lag between the surface pollution and its affect in these sinks.



GROUNDWATER SINKS

AQUIFERS

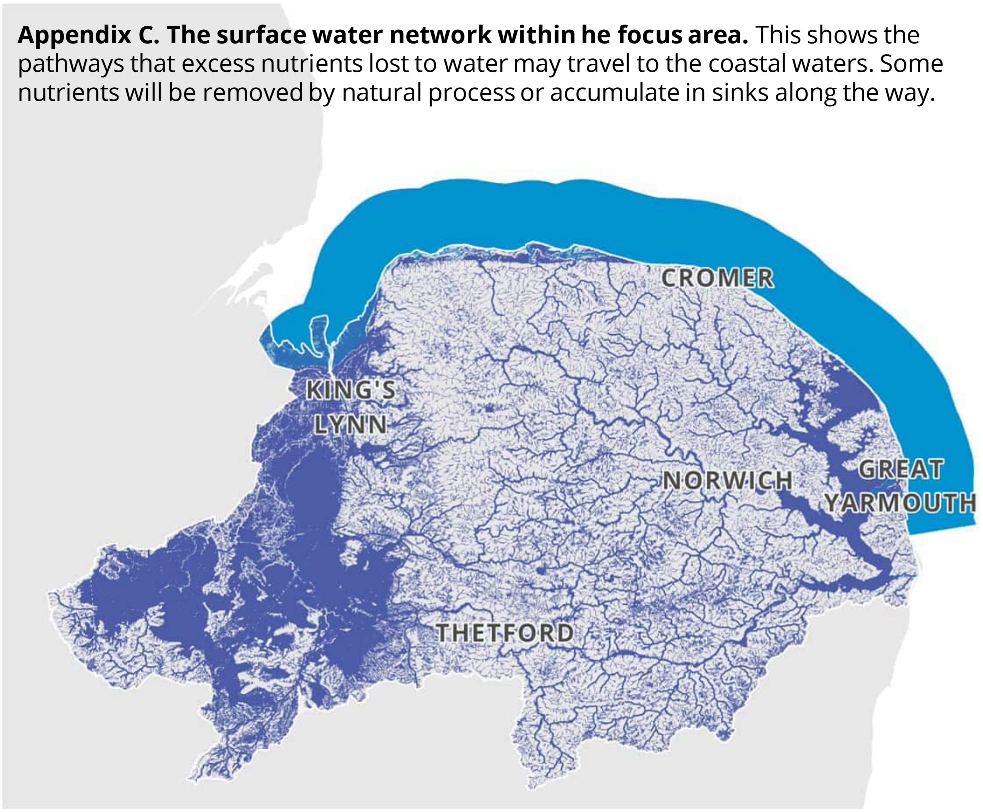
🟩 Highly productive

🟧 Moderately productive

— Rivers

Data used:
WFD River, Canal and Surface Water Transfer Water Bodies Cycle 2 Classification 2019 (2022), Hydrogeology 625K, Boundary-Line™ (2021).

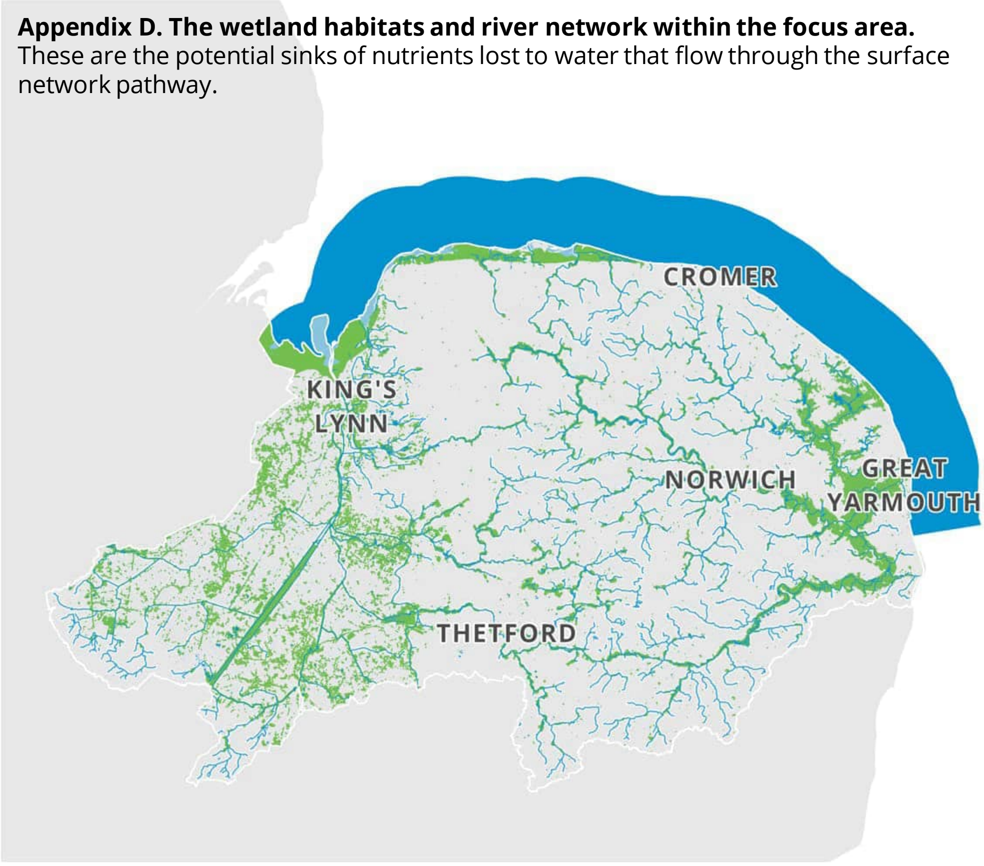
Data sources and full attributions for each map are listed on page 68.



Appendix C. The surface water network within he focus area. This shows the pathways that excess nutrients lost to water may travel to the coastal waters. Some nutrients will be removed by natural process or accumulate in sinks along the way.

Data used:
OS Open Rivers (2020), Priority Habitat Inventory (2020), Boundary-Line™ (2021), Living England Habitat Map (Phase 4) (2023), Saltmarsh Extent & Zonation (2023).

Data sources and full attributions for each map are listed on page 68.



Appendix D. The wetland habitats and river network within the focus area. These are the potential sinks of nutrients lost to water that flow through the surface network pathway.

Data used:
LiDAR based Digital Terrain Model (DTM) data for South West England (2022), OS Open Rivers (2020), OS VectorMap District (2020), Boundary-Line™ (2021).

Data sources and full attributions for each map are listed on page 68.

Appendix E. List of search terms undertaken on in Google Scholar and Scopus - agreed by the project steering group.

"Alaria esculenta" OR "Saccharina latissima" OR "Laminaria digitata" OR "Palmaria palmata" "Nutrient assimilation"

seaweed "nutrient assimilation" "United Kingdom"

"Alaria esculenta" OR "Saccharina latissima" OR "Laminaria digitata" OR "Palmaria palmata" "Nutrient Uptake"

Seaweed "Nutrient Uptake" "United Kingdom"

"Alaria esculenta" OR "Saccharina latissima" OR "Laminaria digitata" OR "Palmaria palmata" "Nitrogen assimilation"

Seaweed "Nitrogen assimilation" "United Kingdom"

"Alaria esculenta" OR "Saccharina latissima" OR "Laminaria digitata" OR "Palmaria palmata" "Nitrogen uptake"

Seaweed "Nitrogen uptake" "United Kingdom"

"Alaria esculenta" OR "Saccharina latissima" OR "Laminaria digitata" OR "Palmaria palmata" "Phosphorus uptake"

"Alaria esculenta" OR "Saccharina latissima" OR "Laminaria digitata" OR "Palmaria palmata" "Phosphorus assimilation"

"Alaria esculenta" OR "Saccharina latissima" OR "Laminaria digitata" OR "Palmaria palmata" farming

"Alaria esculenta" OR "Saccharina latissima" OR "Laminaria digitata" OR "Palmaria palmata" cultivation

"Alaria esculenta" OR "Saccharina latissima" OR "Laminaria digitata" OR "Palmaria palmata" "growth rate"

"Alaria esculenta" OR "Saccharina latissima" OR "Laminaria digitata" OR "Palmaria palmata" "farm suitability"

"Alaria esculenta" OR "Saccharina latissima" OR "Laminaria digitata" OR "Palmaria palmata" "growing conditions"

"Alaria esculenta" OR "Saccharina latissima" OR "Laminaria digitata" OR "Palmaria palmata" "abiotic conditions"

Saltmarsh "nutrient sequestration "Great Britain"

Saltmarsh "nutrient sequestration "United Kingdom"

Saltmarsh "nutrient burial rates" "Great Britain"

Saltmarsh "nutrient burial rates" "United Kingdom"

Saltmarsh "nitrogen sequestration" "Great Britain"

Saltmarsh "nitrogen sequestration" "United Kingdom"

Saltmarsh "phosphorus sequestration" "Great Britain"

Saltmarsh "phosphorus sequestration" "United Kingdom"

Saltmarsh "nitrogen burial" "Great Britain"

Saltmarsh "nitrogen burial" "United Kingdom"

Saltmarsh "phosphorus burial" "Great Britain"

Saltmarsh "phosphorus burial" "United Kingdom"

Saltmarsh "nutrient assimilation" "Great Britain"

Saltmarsh "nutrient assimilation" "United Kingdom"

Saltmarsh "Nutrient Uptake" "Great Britain"

Saltmarsh "Nutrient Uptake" "United Kingdom"

"saltmarsh management" "Great Britain"

"saltmarsh management" "United Kingdom"

Saltmarsh management "burial rates" "Great Britain"

Saltmarsh management "burial rates" "United Kingdom"

Saltmarsh management" "nutrient sequestration" "Great Britain"

"Saltmarsh management" "nutrient sequestration rates" "United Kingdom"

Appendix F. Values for saltmarsh nitrogen burial, plant uptake and dentification located within the literature. *Please note these values were extracted from Table 3 in Adams et al. (2012), here the table headers appear to be misaligned, the values presented in the P ρ gcm−3 column correspond to those reported for N burial within the text, therefore, values presented here are taken from the column headed Pρ g cm−3. **Calculation based on 8736 hours in a year. +Calculated based on 7494ha of intertidal habitat created (Andrews et al., 2006).

SALTMARSH CONDITION	ORIGINAL VALUE (MAX REPORTED)	UNIT		COUNTRY	REFERENCE
N Burial			**t N ha^{-1} yr^{-1} (extrapolated)**		
Natural saltmarsh	10.2*	g N m^{-2} yr^{-1}	0.102	England	(Adams et al., 2012)
Managed realignment – High-saltmarsh	16.2*	g N m^{-2} yr^{-1}	0.162	England	(Adams et al., 2012)
Managed realignment – Mid-saltmarsh	6.1*	g N m^{-2} yr^{-1}	0.061	England	(Adams et al., 2012)
Denitrification			**t N_2O ha^{-1} yr^{-1} (extrapolated)**		
Saltmarsh	4.29	mg N_2O-N m^{-2} h^{-1}	0.375**	England	(Blackwell et al., 2010)
Managed realignment	3.50	mg N_2O-N m^{-2} h^{-1}	0.306**	England	(Blackwell et al., 2010)
N_{org}			**t N_{org} ha^{-1} yr^{-1}(extrapolated)**		
EDG=Extended Deep Green Scenario.	180	t a^{-1}	0.024^{+}	England	(Andrews et al., 2006)
Plant uptake			**t N ha^{-1} yr^{-1}(extrapolated)**		
Spartina Alterniflora	88.8	mg N m^{-2} d^{-1}	32.32	USA	(Hill et al., 2018),
P Burial			**t N ha^{-1} yr^{-1} (extrapolated)**		
Natural saltmarsh	4.72	g N m^{-2} yr^{-1}	0.047	England	(Adams et al., 2012)

Appendix G. Summary of the N uptake rates for three of the four seaweed species.
IMTA = Integrated Multi-trophic Aquaculture. VM = metabolic uptake rates. ISC=Internal storage capacity.

Species	Sampling/cultivation method	Compound(s)	Original value (max reported value)	Unit	Reference
L. digitata	Cultivated in lab conditions from sporophytes collected the Netherlands	Dissolved inorganic nitrogen V_M	1.8	μmol cm^{-2} d^{-1}	(Lubsch and Timmermans, 2019)
	Cultivated in lab conditions from sporophytes collected from the Netherlands	Dissolved inorganic nitrogen ISC	80	μmol · cm^{-2}	(Lubsch and Timmermans, 2019)
P. palmata	Cultivated in lab conditions from blades collected in Canada	Nitrate	0.65	mg N gDW^{-1} day^{-1}	(Tremblay-Gratton et al., 2018) (Tremblay-Gratton et al., 2018) ***inconsistency when referring to nitrate and N.
	Cultivated in lab conditions from sporophytes collected in Ireland	Dissolved inorganic nitrate V_M	5.6	μmol cm^{-2} d^{-1}	(Lubsch and Timmermans, 2020)
	Cultivated in lab conditions from sporophytes collected in Ireland	Dissolved inorganic nitrate ISC	222	μmol cm^{-2}	(Lubsch and Timmermans, 2020)
S. latissima	Cultivated in lab conditions from sporophytes collected the Netherlands	Dissolved inorganic nitrogen V_M	3.94	μmol cm^{-2} d^{-1}	(Lubsch and Timmermans, 2019)
	Cultivated in lab conditions from sporophytes collected the Netherlands	Dissolved inorganic nitrogen ISC	160	μmol · cm^{-2}	(Lubsch and Timmermans, 2019)

Appendix H. Summary of the P uptake rates for all four seaweed species.
VM = metabolic uptake rates. ISC=Internal storage capacity.

Species	Sampling/cultivation method	Compound(s)	Original value (max reported value)	Unit	Reference
L. digitata	Cultivated in lab conditions from sporophytes collected the Netherlands	Dissolved inorganic phosphorus V_M	0.22	μmol cm^{-2} d^{-1}	(Lubsch and Timmermans, 2019)
	Cultivated in lab conditions from sporophytes collected the Netherlands	Dissolved inorganic phosphorus ISC	10	μmol cm^{-2}	(Lubsch and Timmermans, 2019)
P. palmata	Cultivated in lab conditions from blades collected in Canada	Phosphate	0.14	mg P gDW^{-1} day^{-1}	(Tremblay-Gratton et al., 2018)
	Cultivated in lab conditions from sporophytes collected in Ireland	Dissolved inorganic phosphate V_M	0.57	μmol cm^{-2} d^{-1}	(Lubsch and Timmermans, 2020)
	Cultivated in lab conditions from sporophytes collected in Ireland	Dissolved inorganic phosphate ISC	22	μmol cm^{-2}	(Lubsch and Timmermans, 2020)
S. latissima	Cultivated in lab conditions from sporophytes collected the Netherlands	Dissolved inorganic phosphorus V_M	0.3	μmol cm^{-2} d^{-1}	(Lubsch and Timmermans, 2019)
	Cultivated in lab conditions from sporophytes collected the Netherlands	Dissolved inorganic phosphorus ISC	27	μmol · cm^{-2}	(Lubsch and Timmermans, 2019)

Appendix I. Estimates of biomass yield for *A. esculenta, P. palmata* and *S. latissima* identified in the literature review.

DW = dry weight, WW = wet weight, FW = fresh weight. WW and FW are assumed to the same. Only data from studies with seaweed/kelp grown *in-situ* were included. * Values taken from the abstract as full text was not available. +extrapolated from original value.

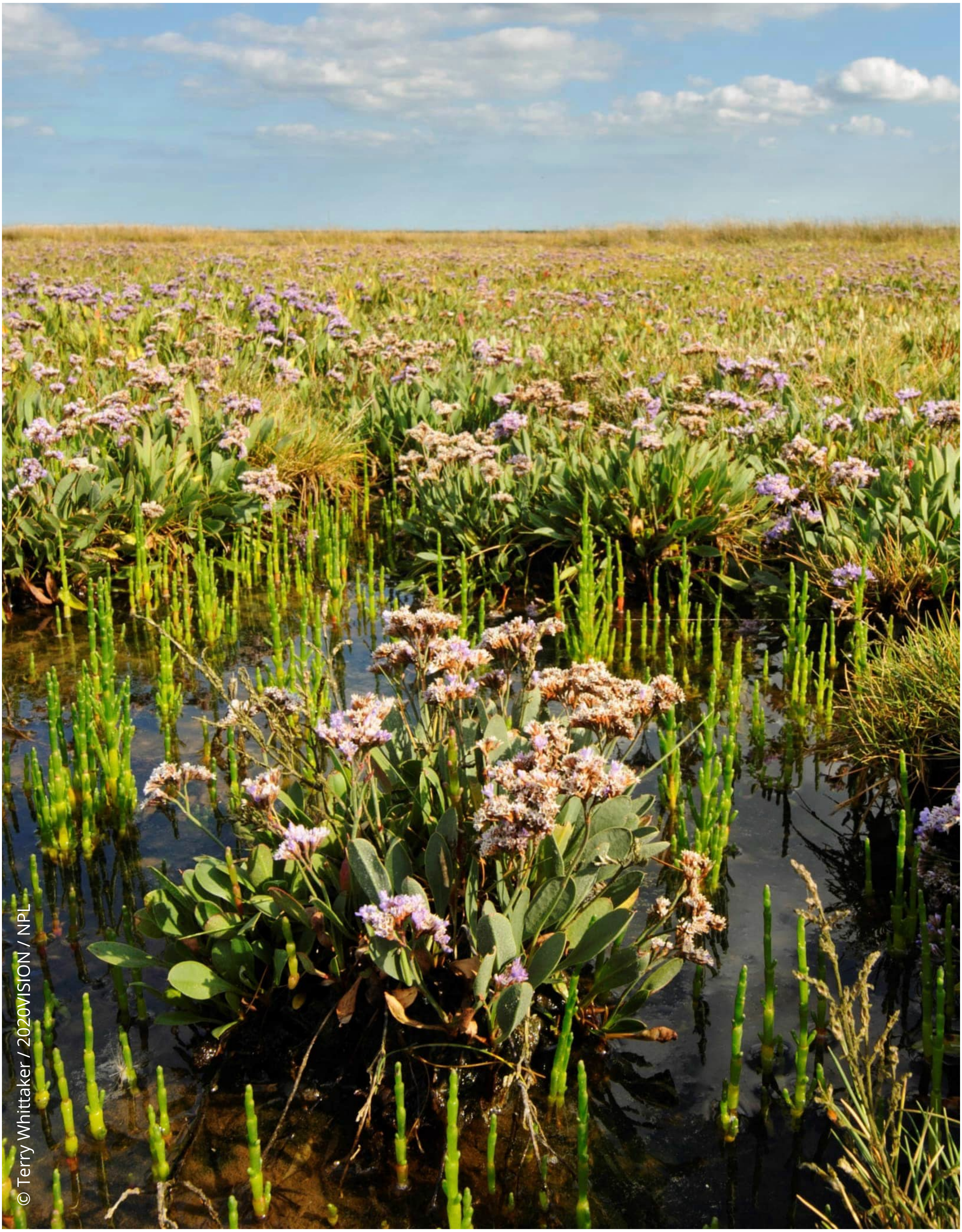
Species	Original value (max reported value)	Unit	Yield (t ha yr^{-1})	Method	Country	Month of harvest	Length of cultivation structure (m ha^{-1})	Reference
A. esculenta	3.5	kg fw m^{-1}		Twine-seeded longline	Scotland	August		(Kerrison et al., 2020) Estimate taken from fig 2 in paper as results not fully described.
	13.75	kg ww m^{-1}	34.4^{+}	Rope	Ireland (Irish/Icelandic cross)	April		(Kraan and Guiry, 2001)
Laminaria hyperborean (L. digitata)	12.5	kg ww m^{-2} y^{-1}	125	Frames	Norway	Can not determine		(Pedersen et al., 2012) in (Ohlsson et al., 2020)
P. palmata	180	t fw ha^{-1}	180	Longlines and frames	Scotland	June	4000	(Sanderson et al., 2012)
S. latissima	230	t ww ha^{-1} yr^{-1}	230	Modelled	Norway	n/a	na	(Broch et al., 2019)
	*38.3	kg ww m^{-2}		Cultivated	Norway	June		(Sharma et al., 2018)
	13.75	kg ww m^{-1}	27.5^{+}	Longlines	Sweden	Early summer	2000	(Pechsiri et al., 2016)
	510	g fw m^{-1}		Seeded lines	Denmark	April		(Bruhn et al., 2016)
	200	t ww ha^{-1} yr^{-1}	200	Cannot access to confirm	Norway			(Matsson et al., 2015) in (Broch et al., 2019)
	220	t fw ha^{-1}	220	Longlines and frames	Scotland	June	4000	(Sanderson et al., 2012)
	91.3	t fw ha^{-1}	91.3	Nets	Denmark	June	1000	(Boderskov et al., 2023)
	21.4	t fw ha^{-1}	21.4	Horizontal 5-line System	Denmark	April	1000	(Boderskov et al., 2023)
	7.4	t fw ha^{-1}	7.4	Vertical line system	Denmark	June	1000	(Boderskov et al., 2023)
	6.7	kg fw m^{-1}		AlgaeRibbon	Scotland	August		(Kerrison et al., 2020) Estimate taken from fig 2.
	*1.51	Kg fw m^{-1}		Cannot access to confirm	Denmark			(Marinho et al., 2015a)
	9.9	kg m^{-1}		Seeded ropes	Faroe	August		(Mols-Mortensen et al., 2017)
	14	kg m^{-1}		Vertical ropes	Norway	Can not determine		(Forbord et al., 2020)

Appendix J. Summary of the nNremoval potential for all four seaweed species.
***** Values taken from abstract. ******Estimation based on growth rate of *Laminaria hyperborean*, none were found specifically *for Laminaria digitata*. IMTA = Integrated Multi-trophic Aquaculture. Where a range of values are reported the maximum has been included here. Best estimate for each species is highlighted in **TEAL**.

A. esculenta	Random Sampling of cultivated (IMTA)	Canada	Nitrogen	33.04	mg gdw^{-1}	May		(Reid et al., 2019)
	Wild	Scotland	Nitrogen	2.1	% biomass	March		(Schiener et al., 2015)
L. digitata	Wild	Scotland	Nitrogen	2.5	% biomass	March		(Schiener et al., 2015)
	Wild	Sweden	Nitrogen	2.34	% of dw	October		(Dahl, 2018)
	Wild	Sweden	Kjeldahl-N	**363	kg Kjeldahl-N ha^{-1} y^{-1}	August	**363	(Ohlsson et al., 2020) (Appendix A)
	Wild	Sweden	Ammonium Nitrogen (NH$_4$$^{-N}$)	340	Mg NH$_4$$^{-N}$ kg^{-1} wet weight	August		(Ohlsson et al., 2020)
	Wild	Wales	Nitrogen	3.5	% by weight DW	April		(Adams et al., 2011)
P. palmata	Cultivated in lab conditions from blades collected in Canada	Canada	Nitrogen tissue content	5.87	% DW	n/a		(Tremblay-Gratton et al., 2018)
	Cultivated in lab conditions from blades collected in Canada	Canada	Nitrogen removal	0.42	mg gDW^{-1} d^{-1}	n/a		(Tremblay-Gratton et al., 2018) ***inconsistency when referring to nitrate and N.
	Cultivated	Scotland	Nitrogen	4.6%	% of dwt N	June		(Sanderson et al., 2012)
S. latissima	Wild	Scotland	Nitrogen	2.2	% biomass	March		(Schiener et al., 2015)
	Cultivated	Scotland	Nitrogen	1.9	% of dwt N	June		(Sanderson et al., 2012)
	Cultivated	Denmark	Nitrogen	4.5	% of DM	April		(Bruhn et al., 2016)
	Cultivated IMTA	Denmark	Nitrogen	*7.02	g N m^{-1}	August		(Marinho et al., 2015a)
	Cultivated	Denmark	Nitrogen	*6.9	g N m^{-1}	September		(Marinho et al., 2015b)
	Cultivated	Sweden	Nitrogen	21.3	kg N dw/t^{-1}			(Pechsiri et al., 2016)
	Cultivated	Denmark	Nitrogen	110.5	kg N ha^{-1}	March	110.5	(Boderskov et al., 2023) Net system
	Cultivated	Denmark	Nitrogen	34.8	kg N ha^{-1}	March	34.8	(Boderskov et al., 2023) Horizontal 5-line.
	Cultivated	Denmark	Nitrogen	16.13	kg N ha^{-1}	June	16.13	(Boderskov et al., 2023) Vertical line
	Random Sampling - Cultivated IMTA	Canada	Nitrogen	24.47	mg gdw^{-1}	May		(Reid et al., 2019)
	Cultivated	Norway	I-DIN	0.7	Mg NO$_3$$^{-}$g^{-1} DW	Undefined		(Forbord et al., 2020)
	Cultivated	Norway	Nitrogen	38	mg N g DW^{-1}	April		(Wang et al., 2014)

Appendix K. Summary of the P removal potential rates for all four seaweed species. *** Inconsistency when referring to phosphate and P. IMTA = Integrated Multi-trophic Aquaculture. Best estimate for each species is highlighted in PINK.

A. esculenta								
L. digitata								
P. palmata	Cultivated in lab conditions from blades collected in Canada	Canada	Phosphorus	0.03	mg P gDW^{-1} day^{-1}	n/a		(Tremblay-Gratton et al., 2018) ***.
	Cultivated in lab conditions from blades collected in Canada	Canada	Phosphorus	0.75	% DW			(Tremblay-Gratton et al., 2018) ***.
S. latissima	Cultivated (IMTA)	Denmark	Phosphorus	1.23	P m^{-1}	August		(Marinho et al., 2015a)
	Cultivated	Denmark	Phosphorus	0.28	% of DM	April		(Bruhn et al., 2016)
	Cultivated	Sweden	Phosphorus	7.9	kg P dwt/t^{-1}	Could not determine		(Pechsiri et al., 2016)
	Cultivated	Denmark	Phosphorus	1.54	kg P ha^{-1}	June	1.54	(Boderskov et al., 2023) Vertical line
	Cultivated	Denmark	Phosphorus	13.1	kg P ha^{-1}	March	13.1	(Boderskov et al., 2023) Net system
	Cultivated	Denmark	Phosphorus	3.3	kg P ha^{-1}	March	3.3	(Boderskov et al., 2023) Horizontal 5-line.
	Random sampling of cultivated IMTA	Canada	Phosphorus	3.09	mg · g DW^{-1}	May		(Reid et al., 2019)



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