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Restoration management of phosphorus pollution on lowland fen peatlands: A data evidence review from the Somerset Levels and Moors

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ABSTRACT

Eutrophication of wetlands caused by urban, industrial and agricultural run-off is an important environmental problem. Eutrophication is characterized by excessive plant and algal growth due to the increased availability of one or more growth "limiting nutrients", in freshwater generally considered to be controlled by the bioavailability of phosphorus (P). The Somerset Levels and Moors (SLMs) catchments are subject to intensive agriculture and wastewater inputs which leads to nutrient contamination of the inflow waters, to the extent that they fail Water Framework Directive Good Status targets for P concentrations. In 2021, Natural England downgraded the status of the SLMs Sites of Special Scientific Interest (SSSIs) to 'Unfavourable Declining', owing to poor water quality, mostly associated with P concentrations and associated duckweed and filamentous algal blooms. Macroplant nutrient concentrations were analysed in ditches, dipwells, soil, sediment and harvested plant biomass across a number of sites to provide an assessment of the overall apportionment of P inputs and reservoirs. Here we present a combined dataset of stores, fluxes and loadings of P. The data show large temporal and spatial changes in the concentrations of P and nitrogen (N) across the peat rich soils. We suggest how an altered hydrological regime and plant biomass harvesting could be used to reduce further eutrophication and how legacy P stored in the peat body could be mobilized by flooding and over time evacuated from the wetland. The findings suggest how paludiculture (wet agricultural crops) and rewetting of the peat body may help to restore the Ramsar wetland. We discuss how complex biogeochemical interactions occur during the rewetting process and how the need to export P via new land management mitigation measures should be balanced against requirements to maximise regulating and provisioning ecosystem services.

1. Introduction

Peatlands occupy around 12% of the UK land area (Evans et al., 2017); provide over a quarter of the UK's drinking water and store a significant amount of carbon making them an important habitat for providing both provisioning and regulating ecosystem services in the UK (Office of National Statistics 2019). Agriculture on lowland peats, in the west of England mainly includes livestock grazing. Farming on peatlands has a negative impact on the peat through drainage, nutrient addition, loss of fenland vegetation and ploughing activities. In the UK, 80% of the land area of peatlands have been drained or damaged by agriculture, peat extraction, and forestry; adding 3.5% to the UK's total annual GHG emissions in 2019 (Office of National Statistics 2019). Peatlands that have been drained for grassland, occupy 8% of the UK's peat area and emit 6.3 million t CO_2e/yr, accounting for 27% of total UK peat GHG emissions, intensively managed and drained lowland grasslands being the primary source (Evans et al., 2017).

Peatlands are important for the ecosystem services they provide such as carbon storage, agriculture, water storage, biodiversity, flood resilience and recreation (Joosten, 2016). Intensively managed and deeply drained agricultural peatlands lose on average 1 cm depth of peat every year (Evans et al., 2017). The Climate Change Committee made recommendation to the UK Government that in order to achieve a Balanced Net Zero Pathway by 2050: 1) 25% of the area of lowland grassland on deep peat should be rewetted by 2035, rising to half by 2050. 2) 75% of lowland cropland on deep peat should be rewetted and 15% of this rewetted land area be switched to paludiculture (farming under wetland conditions using species tolerant to these conditions)

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(BEIS, 2021). Wetlands International and the International Union of the Conservation of Nature (IUCN) have recommended the use of paludiculture to reduce peatland carbon emission, restore biodiversity and wetland function (Cris et al., 2014; Budiman et al., 2020; Wichtmann et al., 2017).

Perennial wetland reeds have been used for millennia as a construction material, especially for thatched roofing with potential for use of *Typha* (cattails) and *Phragmites* (common reed) as alternative wetland agricultural crops for production of sustainable building materials such as fibre boards, energy biomass crops and for use as animal folder (Mulholland et al., 2020; Lahtinen et al., 2022). Concentrations of P in wetland dry plant shoot biomass range from 0.08% to 0.32%, depending on plant species, time of year and location (Geurts et al., 2020; Vroom et al., 2022). Mean concentrations of P in dry shoot biomass of 0.21% have been recorded in paludiculture crops such as cattails (Geurts et al., 2020). Adoption and uptake of paludiculture techniques has the potential to make an important contribution to achieving a favourable status for phosphate in lowland peatlands as well as providing an income for farmers and contributing to the UK's commitment to net zero carbon emissions by 2050.

The Common Standards Monitoring Guidance (JNCC, 2005) for the assessment of ditch SSSIs, states that total phosphorus (TP) should be less than 0.1 mg TP/l to be in "favourable condition". Above this concentration, there is a high risk that the adverse biological effects of nutrient enrichment will occur, leading to excessive growth of plant species such as *Lemna* (duckweed) and filamentous algae that shade or smother other aquatic life respectively.

The potential sources of excess phosphate in the surface waters of the Levels include:

- The river inputs to the Levels, themselves contaminated from Wastewater Treatment Works (WwTW) effluent and diffuse agricultural pollution,
- Fertiliser additions by farmers to improve yield of grass meadows for hay, silage or grazing,
- Manure from in situ grazing during the summer months,
- Guano from overwintering and resident bird populations,
- Runoff from intensive agriculture on the adjacent hillslopes,
- Ditch maintenance (dredging),
- Legacy contamination of soil and sediment from previous agriculture and wastewater discharge.

Peatland restoration can yield significant public benefits with improvements in nature conservation value, carbon sequestration, attenuation of flood water and improvements in water quality. For the SLMs catchments, considerable investment by the local Water Company (Wessex Water) over the past two decades has seen loads from WwTW significantly decrease (Wessex Water, 2018, 2020), leading to agricultural loads probably now dominating (Natural England, 2021).

Fig. 1 shows mean total reactive phosphorus levels as orthophosphate (a conservative measure for TP). Recorded over a five-year period (2015–2021) for West Sedgemoor. In all river catchments phosphate levels exceed the Environmental Quality Standard (EQS) of 0.1 mg-P/L, with mean concentrations of total reactive P in the River Parrett over 10 times the target.

Over the past 5 years, a considerable amount of data have been independently generated across a number of sites for various purposes and it is timely to collate and analyse these data in order to feed into a strategy to improve water quality across the SLMs. Although for a number of studies soluble reactive and total reactive phosphorus was determined, for this data analysis, because the SLM phosphorus target is TP, only this fraction has been assessed and reported in detail here.

Monitoring and research into soil, sediment, ground and surface water quality, sources of pollution, the biogeochemical cycling of phosphate and impacts on biodiversity within these rich ecosystems has been fragmented. The aim of this research has been to collate existing information to provide a thorough data evidence review to inform the current magnitude of contamination and to consider options for future restoration of heavily phosphate polluted water, sediment and soil throughout the SLMs.

2. Methods

The Somerset Levels and Moors (SLMs) occupy an area of approximately 70,000 ha in the county of Somerset, England, with 6388 noncontiguous hectares of this designated in 1997, under the Ramsar Convention (Fig. 2). The inland wetland consists of wet grassland, drained and modified peat bog, fen and reedbed, which provides habitats for rare invertebrates, particularly beetles, and internationally important numbers of wildfowl in winter. National designations include National Nature Reserves (NNR) and Sites of Special Scientific Interest (SSSI) (Fig. 2). Water levels are controlled by the Internal Drainage Board, broadly being lowered in winter for flood capacity and penned in summer to maintain water levels to act as wet fences to keep cattle in fields and to support habitats associated with this largely agricultural landscape. The Ramsar site is fed by five main rivers, the Parrett, King's Sedgemoor drain, Huntspill, Brue and Axe, themselves highly modified canalised waterbodies. These catchments are subject to intensive agriculture which leads to nutrient contamination of the rivers, to the extent that they fail the Water Framework Directive (EU, 2000), good targets for phosphate, as well as a TP target to protect 'Favourable Conditions' of the SSSIs and Ramsar sites (Natural England, 2021). In addition, a 'nutrient-neutrality' approach for new housing development is being implemented across 27 river catchments (equating to 14% of England's land area) to prevent additional phosphate pollution at Protected Sites already exceeding TP targets (Natural England, 2022).

The landscape of the Levels is open, often treeless, with a chequerboard-like pattern of rectilinear fields, rhynes (the local name for field ditches), drains and engineered rivers, and roads. The land is owned by independent farmers, the Royal Society for the Protection of Birds (RSPB) and Natural England (often with tenant farmers). Livestock farming is the economic mainstay, and the primary land use pattern is one of summer cattle grazing (dairy and beef) with hay or silage production and application of manure on the more intensively managed pastures. Cattle are over wintered on increasingly intensified farms on the hillslopes of the Levels.

2.1. Sampling and Analysis

Sampling was focused on two main areas West Sedgemoor and Moorlinch, with some supporting data available for Nailsea Moors and Greylake (an RSPB bird reserve) (Fig. 2). Details of the sampling sites and sampled matrix are provided in Table 1.

2.2. Groundwater phosphorus concentrations

Groundwater controls the mobility and supply of nutrients to both the water courses as well as the overlying vegetation and so is a key metric with which to assess the levels of pollution present. A series of dipwells (approximately 1.5 m deep) were sunk at West Sedgemoor (at 1, 3, and 5 m away from the ditch bank) at two control sites where dredging had not occurred for 1 year (C1) and at least 7 years (C2) and at 3 locations scheduled to be dredged (Fig. 3). Six samples were taken from before dredging then up to 58 days after dredging at each site. A further ten dipwells were sunk at Moorlinch to a depth of 1.5 m, geographically distributed across the study site. Monthly samples were taken for SRP and TP at West Sedgemoor and for SRP as well as for iron speciation (Fe(II), Fe(III), Total Fe) at Moorlinch and Greylake.

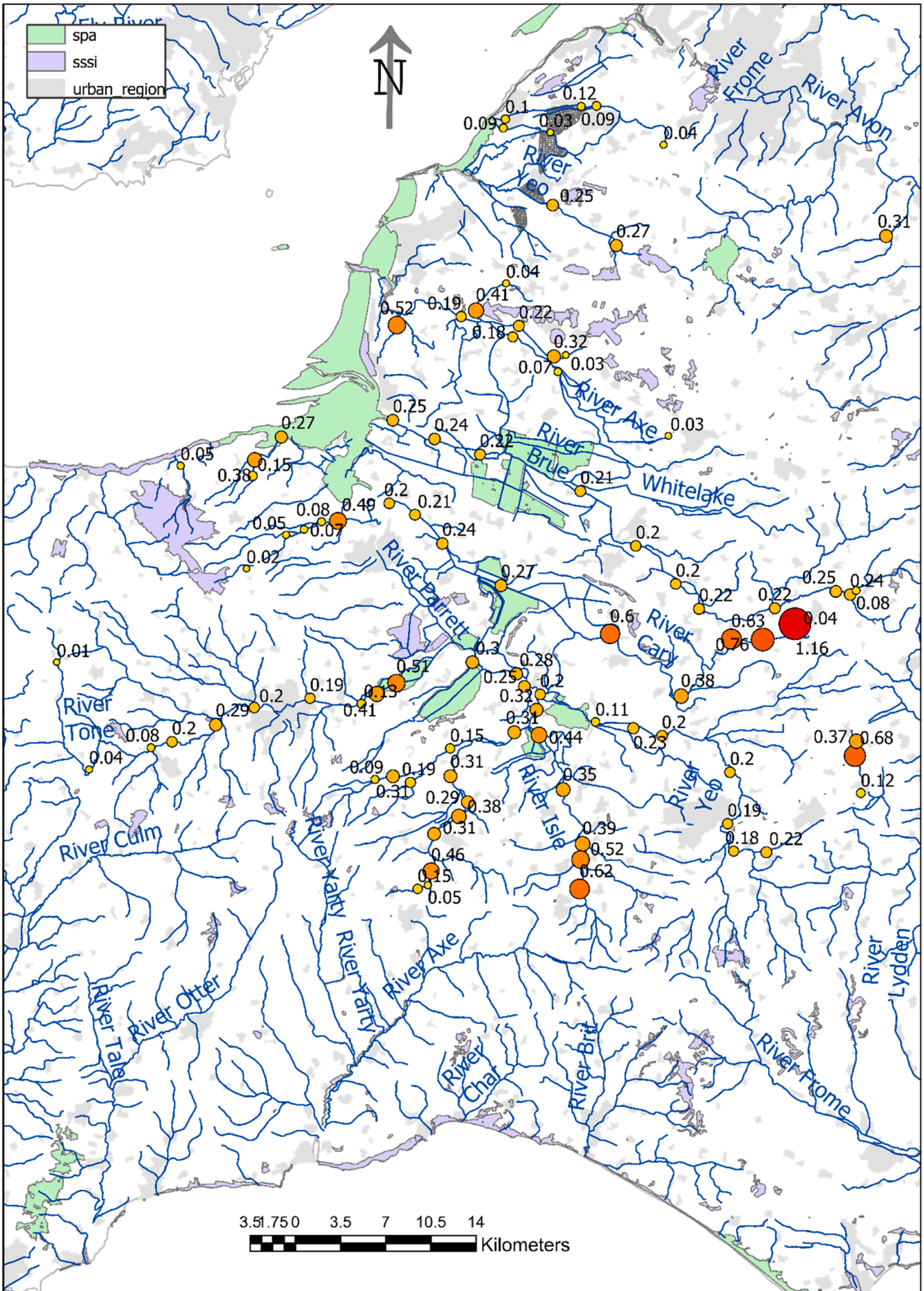

Fig. 1. Mean total reactive phosphorus (mg-P/L) for the main rivers of West Sedgemoor, the Parrett, Tone, Isle, Yeo, Cary, Brue and Axe concentrations (2015–2021). *All data for rivers in the Wessex catchment which supply the SLMs was downloaded from the Environment Agency's data archive (*EA, 2022*). Annual averages were calculated for all sites between 2015 and 2022.* Larger circles denote higher TRP concentrations. Circles coloured red or amber show exceedance of the environmental quality standard (EQS).

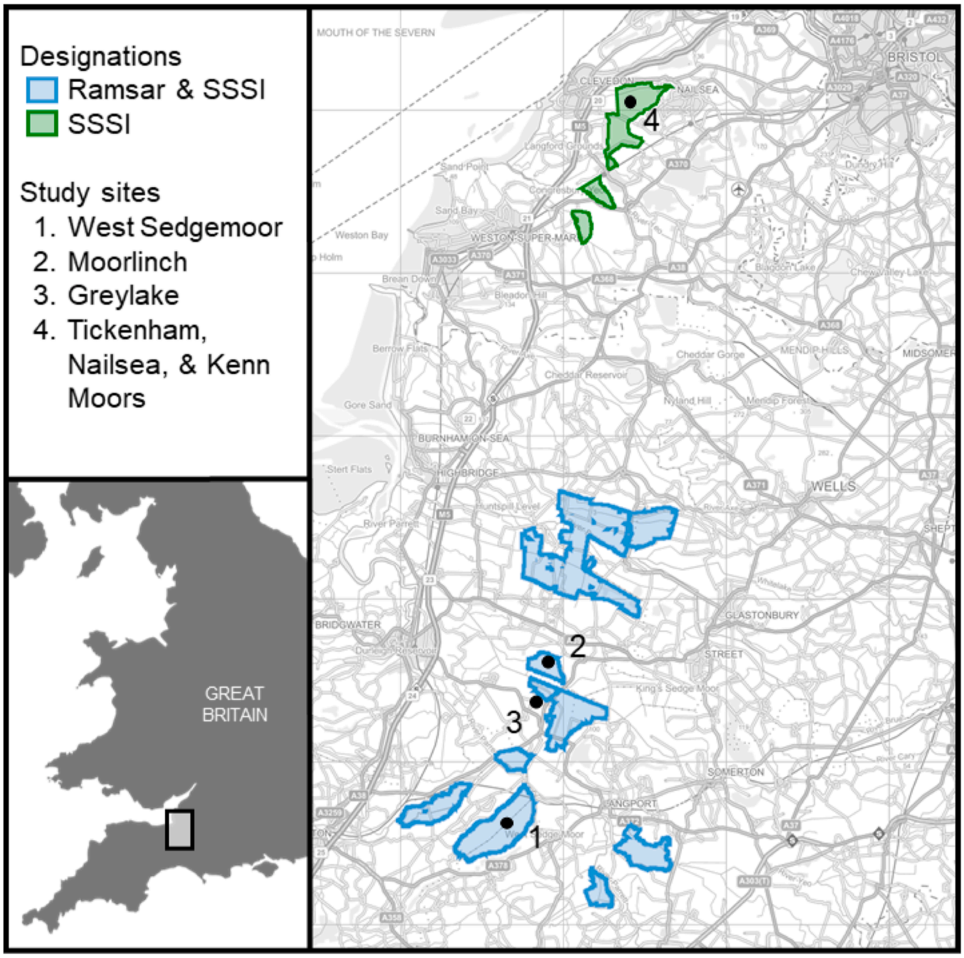

Fig. 2. Ramsar and wetland sites of special scientific interest on the Somerset Levels and Moors.

Table 1
Summary of key sampling site features.

Site	West Sedgemoor	Moorlinch	Greylake	Nailsea Moor
Designated Area (ha)	1016	226	9.3	200
River source	Parrett	King's Sedgemoor Drain	King's Sedgemoor Drain	Land Yeo
Agricultural Land use	• Summer grazing • Hay/silage RSPB Bird reserve	• Summer grazing	• RSPB Bird reserve • Summer grazing • Hay/silage	• Summer grazing • Hay/silage • Arable
Pressures	• Inlet water quality • Legacy nutrients • Farm runoff • Cattle manure • Bird guano	• Inlet water quality • Legacy nutrients • Farm runoff • Cattle manure	• Inlet water quality • Legacy nutrients • Farm runoff • Cattle manure • Bird guano	• Inlet water quality • Legacy nutrients • Farm runoff • Cattle manure
Sampling	• Surface drainage water • Sediment • Groundwater • *Lemna* Emergent vegetation	• Surface drainage water • Groundwater • Peat Terrestrial vegetation	• Surface drainage water • Groundwater	• Surface drainage water
Statutory designations	Ramsar Special Protected Area National Nature Reserve SSSI	Ramsar Special Protected Area National Nature Reserve SSSI	None	SSSI
Support references	1, 4	2,4	2,4	4,5

Key to Table 1 references: [1] Crocker et al. (2021); [2] Morris et al. (2010); [3] Wessex Water (2021) and [4] Natural England (2013).

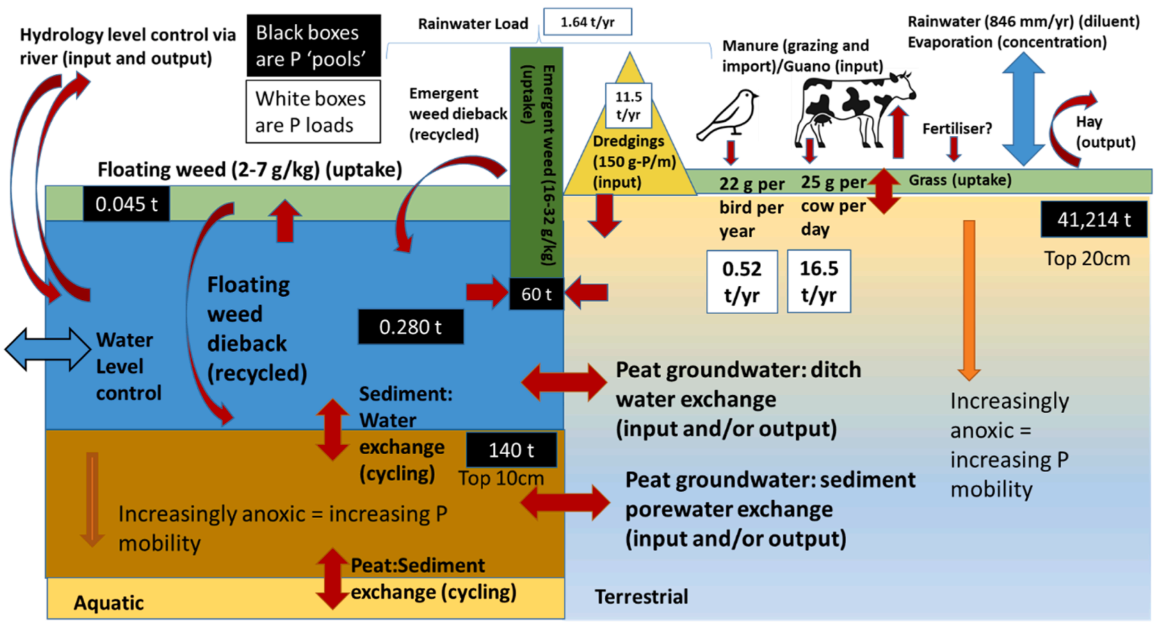

Fig. 3. Overall mass balance of phosphorus inputs and reservoirs estimated to exist within West Sedgemoor. *Black boxes are P pools. White boxes provide estimates of P exchange.*

2.3. Surface sediment and peat

Particulate phosphorus in the sediment of the watercourses and within the peat on the moors act as reservoirs of nutrient pollution and offer an assessment of integrated loads over time from all sources. Surface sediment samples (59) were collected in March 2018 from West Sedgemoor (Crocker et al., 2021). Samples were collected using a Van Veen Grab sampler and transferred into hydrochloric acid (10% - Fisher Scientific Primar Plus) and Ultra high purity water (>18 Mohm.cm) soaked HDPE 500 ml Nalgene bottles and stored frozen at − 18 °C in the dark until further analysis. Five sediment cores were also collected from West Sedgemoor in March 2018 and divided into 2 cm slices down to a maximum of 32 cm.

Once thawed, samples were centrifuged at 4000 rpm for 10 min, and the majority of the pore water was poured off. At this stage samples were individually mixed and had subsamples taken for particle size analysis. Roots and other large plant material were either not present or removed from samples manually. The sediment was then frozen, freeze-dried, disaggregated and sieved to the < 63 μm fraction. Subsamples were then milled and pressed into pellets for analysis of P and other elements using a PANalytical Wavelength Dispersive X-Ray Fluorescence Spectrometer (WD-XRF) (Axios Max) (Crocker et al., 2020).

Peat samples were taken from West Sedgemoor from 5 locations and at 1, 3, and 5 m from the edge of the ditch (Fig. S1 and S2) to determine any impacts of ditch maintenance on soil P concentrations (dredgings are heaped up on the bank adjacent to the ditch based on a typical 5-year cycle). Samples were preserved, prepared and analysed as for the sediment above.

Core soil samples (10–20 cm, 30–50 cm, 100 cm depth) were also collected from Moorlinch at 10 spatially distributed locations then air dried, sieved to < 63 μm and determined for elements based on aqua regia digestion, Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES).

2.4. Bankside and aquatic vegetation

Bankside and aquatic vegetation utilise and cycle the nutrients present where they grow. Their growth and competition with other species will be related to exiting nutrient conditions and under the correct management regime, may be used to remove nutrients held in the water, porewater and sediment as part of a remediation strategy. Bankside aquatic vegetation dredged from the ditches and floating duckweed (*Lemna minor*) was collected from West Sedgemoor to determine P content. Vegetation was aggregated for 3 positions along the ditches, commensurate with the soil sampling sites above. Vegetation was chopped, milled and freeze-dried before acid digestion (67% nitric acid). Phosphorus concentration of 3 sub-sample replicates was determined through ICP-OES analysis.

2.5. Water samples

Surface water phosphorus concentrations are used to assess compliance with CSMG targets (0.1 mg-TP/L). Any assessment of ecological status therefore requires TP in water to be determined. Water samples collected from the selected sites were measured for a range of phosphate forms; namely soluble reactive phosphorus (SRP), total reactive phosphorus (TRP), total soluble phosphorus (TSP) and TP depending on the location. However, for this assessment only TP is reported here to align with the CSMG targets. Further detail regarding P speciation and bioavailability for West Sedgemoor is available in Crocker et al. (2023). Analysis was performed with appropriate certified reference materials and further details are available in S1 of the ESI.

Dissolved iron (II) was determined using a standard 1–10 phenanthroline colorimetric methodology (Caldwell and Adams, 1946; ESI S3).

2.6. Vegetation analysis

Plant biomass and ability to accumulate phosphorus is key to any remediation strategy. The species are frequently occurring and locally dominant wetland plants and the mixed grass sward is the typical existing vegetation of the SLMs. Plants were harvested from low-lying areas of meadow at 11 randomly allocated 0.5 × 0.5 m quadrats at Moorlinch in early October of 2021:

- *Glyceria maxima* (reed sweet-grass)
- *Phalaris arundinacea* (canary-grass)
- *Phragmites australis* (common reed)
- *Sparganium erectum* (branched bur reed)

- Mixed species wetland grass sward

Standing biomass production (kg/m^2/yr) was calculated for each sample. Replicate samples were dried to a constant weight and dry-matter (DM) production calculated for each species and a mixed species grass sward. Percentage carbon content of the DM was used to calculate net primary plant production (t CO_2e/ha/yr) presented in Table S1 of the ESI.

2.7. Phosphorus mass balance

Measured concentrations (as per the methodology above) for samples taken from West Sedgemoor were used for:

- Concentrations of P in floating algae and bankside vegetation
- P in first 10 cm of sediment
- P in dredged plant material
- P in top 20 cm of peat/soil
- P in water column

To determine the significant phosphorus reservoirs and main cycling pathways of P through a peatland – porewater – surface water system a number of parameters need determining and assumptions made to fill in gaps in data/knowledge. Loadings require a combination of concentrations (P mass per unit area or mass) and a volume (litres of surface or pore water; kilograms of soil, sediment or biomass). The mass balance for West Sedgemoor relied on Geographic Information Systems (GIS) analysis using ArcMap Pro to estimate areas of land and water across the moor. The ditches were split into three types large (>3 m width), medium (1.9–3 m width) and small (<1.9 m width), their lengths were calculated using ArcGIS pro, then a total volume of water present was calculated by multiplying an average depth of 2, 1.5 and 1 m for the large, medium and small ditches respectively. The volume was multiplied by a typical mean concentration of Total P in the water of 0.3 mg-P/L for all types of ditches, to derive a load. Sediment loads were assumed to be related to the first 10 cm of sediment and mean concentrations from core data collected in the field derived a concentration of 1311, 1191 and 1223 mg-P/kg dry weight for large, medium and small ditches respectively. A volume was generated assuming a density of 1800 kg/m^3, allowing a P load in the top 10 cm of sediment to be calculated. The soil P reservoir was calculated from measured by subtracting the area of water on West Sedgemoor from the total area and converting to a volume using a density of 1330 kg/m^3, then multiplying by a concentration of 2447 mg-P/kg dry weight (a mean of soil data from 10 cores down to a depth of 20 cm) to calculate a load of P held within the soil. The P load held within floating vegetation was predicted by taking the concentration measured in *Lemna* (5 sites and 3 replicates) of 323, 203 and 328 mg-P/m^2 of *Lemna* coverage, multiplied by a coverage percent estimated from site walk overs of 20%, 40% and 70% for large, medium and small ditches respectively. Phosphorus held within bankside vegetation was predicted from measured data for ditch dredging plant material (mean of 150 g-P/m of bank) by length of banks taken from the GIS analysis. Phosphorus in dredged material heaped onto the bankside was generated from assuming a loading of 150 g-P/m of bank multiplied by length of ditch dredged per year, assuming a 5-year cycle of dredging ditches greater than 1.9 m in width.

Literature data were used to estimate P loading from cattle manure, bird guano and rainwater P concentrations. Bird population on the SLM were taken from the Wetland Bird Survey (WeBS) for West Sedgemoor as a mean of 2015–16, 2016–17 and 2017–18 data. Phosphorus content in guano was abstracted from Hahn et al. (2007). Bird type and numbers could then be combined with P excretion rates to calculate a load. Loads from cattle were set as based on 53 g-P/cow/day being excreted (Natural England, 2009) multiplied by 1700 head of beef cattle grazing the West Sedgemoor for 6 months of the year. Finally, rainwater loads were simply calculated by multiplying together typical rainwater P concentrations (0.0304 mg-P/L, Berthold et al., 2019) by annual rainfall of 846 mm on the area of land and water within West Sedgemoor.

3. Results

3.1. Water quality

Moorlinch, a known nutrient contaminated site from extensive arable cropping in the 1970′s (carrots) shows particularly elevated ditch (annual mean 0.16 mg-P/L, seasonal mean range 0.12–0.19 mg-P/L) and sediment pore water (annual mean 1.39 mg-P/L, seasonal mean range 0.26–0.211 mg-P/L) concentrations of total phosphorus over 10 times the compliance value (Table S3). Nailsea and West Sedgemoor exhibit high levels of non-compliance (76%), with levels (annual mean 0.22 mg-P/L, seasonal mean range 0.09–0.44 mg-P/L) up to 4 times the standard and no improvement between 2015 and 16 and 2019–20 (Table S2). These data, alongside river P data collected by the Environment Agency and Wessex Water, support the Natural England decision to change the condition status for the Somerset Levels and Moors SSSI ditch systems to Unfavourable Declining. A similar downgrading of status is also in progress for the Nailsea site.

3.2. Groundwater quality

At West Sedgemoor concentrations of P varied spatially and temporally with mean SRP in ditches of 0.6 mg-P/L (range 0.05–0.44 mg-P/L), with values almost always greater than the 0.1 mg-P/L limit set for the drainage system (Fig. S3). Groundwater within the peat at West Sedgemoor had P concentrations ranging from 0.95 to 4.2 mg-P/L with a mean of 1.5 mg-P/L (Fig. S6). Therefore, the peat/sediment is contaminated with of P to a greater degree than water in the ditches. There was no clear impact of dredging on concentrations. The variation in concentrations appears to be mainly driven by dilution with rainwater and physico-chemical processes within the largely anoxic peat profile. Data for Moorlinch supported this assumption, with groundwater concentrations of a similar or greater magnitude to those of West Sedgemoor (only 7 out of 102 samples <0.1 mg-P/L). Concentrations appeared to reflect combinations of rainfall (Fig. S4) which leads to dilution of concentrations as well as biogeochemistry associated with controlling factors such as iron speciation, related to high water levels leading to anoxia in the peat, formation of soluble (reduced) iron, which in turn solubilises the P (Table S3).

Mean and median nitrate concentrations in peat body waters ranged from 1.9 to 2.5 mg-N/L (Fig. S5). The highest concentrations of 2.5 mg-N/L occurred in the surface waters with no significant difference ($p \leq 0.05$) between waters. Nitrate readings in river waters of less than 1.0 mg-N/L is considered excellent. Seasonal differences occurred in

Table 2
Mean concentration of orthophosphate for Environment Agency river data, 2016–2021.

River	Replicate Number	Mean (mg-P/L)	SD (mg-P/L)	no. > 0.1 (mg-P/L)	% non-compliance
Kings Sedgemoor Drain	15	0.217	0.0439	15	100%
Yeo	62	0.239	0.1720	52	84%
Parrett	48	0.375	0.1818	40	83%
Cary	43	0.480	0.3188	30	70%
Brue	62	0.193	0.0719	41	66%
Isle	38	0.264	0.1581	24	63%
Tone	62	0.200	0.1804	36	58%
Land Yeo	13	0.087	0.0310	6	46%
Axe	19	0.214	0.0811	8	42%
Lox Yeo	9	0.156	0.1779	3	33%

Source EA (2022)

median nitrate water concentrations; winter (January 2021) available N was significantly higher ($p \leq 0.05$) than levels recorded at the peak of the growing season (June 2021) across all sample sites.

3.3. Inlet water quality

All data for rivers in the Wessex catchment which supply the SLMs was downloaded from the Environment Agency's data archive (EA, 2022). The data shows that there is a general, ongoing improvement in water quality, with often step-changes associated with upgrades of WwTW to reduce P in the effluent. However, the data also shows that most rivers supplying water to the Levels are still significantly contaminated and greater than 0.1 mg-P/L as orthophosphate, the equivalent of total reactive phosphate, a conservative measure for TP. Table 2 shows that compliance is poor, particularly for King's Sedgemoor Drain, the rivers Cary, Yeo and Parrett. Although further reductions in P loads are planned in the next five years (for example, a further 50% reduction of WwTW discharge to the Parrett (Wessex Water, 2018) without reductions in agricultural runoff concentrations are unlikely to fall below 0.1 mg-P/L.

3.4. Cattle manure and bird guano

It has been reported that cows on average excrete 53 g-P/day (Defra, 2006). As an example, for West Sedgemoor, there is an average of 1700 cows grazing on the moor for six months of the year. This equates to a P load from manure of 16,479 kg-P/yr (see Fig. 3). An average (2015–2018 data) of 19,213 birds across 26 species over winter on West Sedgemoor per year (RSPB, pers comms, 2020). Combining bird numbers with data for P excretion (Hahn et al., 2007) provided a load. Where P excretion data were not available for specific bird species, loads were estimated based on the relationship between reported mass of bird (known for all species at West Sedgemoor) versus P excreta known for 10 of the 26 bird species observed at the site (P excreted (g/d) = 0.0579 x mass of bird (g); $R^2 = 0.9439$). Using this approach a total load of P from birds was estimated to be 522 kg-P/yr; significantly less than that from cattle (see Fig. 3). The majority of the P inputs from cattle and birds are likely to have originated from vegetation consumed from within the site's catchment (closed loop). The most significant impacts to water quality will result from redistribution and increases in nutrient bioavailability of phosphorus.

3.5. Atmospheric deposition

Atmospheric concentrations of P are low and deposition is not considered a significant source of P to the UK environment (Comber et al., 2013), however, over a large surface area amounts can be significant and easily calculated (excluding dry deposition) to give 1642 kg-P/yr from this source.

3.6. Internal loadings – sediment and peat

Sediment background concentrations for P are typically 500 mg/kg dry weight (Crocker et al., 2021. However, detailed spatial analysis of West Sedgemoor has shown concentrations are at least twice this level and up to almost 10 times background in places (Crocker et al., 2021) (Fig. S6). Similarly high levels of P have been reported downstream of intensive agriculture and industry discharges such as dairies (Burns et al., 2015). Elevated concentrations were influenced by contaminated river feedwaters (Fig. 2). Sediment core data (Fig. 4) typically showed elevated levels in the upper layers, likely to reflect post war intensification and nutrient use as well as P mobilisation within the sediment. Mean concentrations of total P within the top 10 cm of sediments pore water were calculated (Section 2.7) to be 140 tons (Fig. 3).

Fig. 4 shows that concentrations of P in the soil are not dissimilar to those in the sediment (~1000–3500 mg-P/kg, Fig. S7), with some evidence of a trend towards concentrations decreasing away from the ditch banks (Fig. S7). Reported P concentrations in 20 bulk soil samples collected across three catchments in England and Wales reports a range of 200–2000 mg-P/kg with a mean of 889 mg-P/kg (Adams et al., 2020),

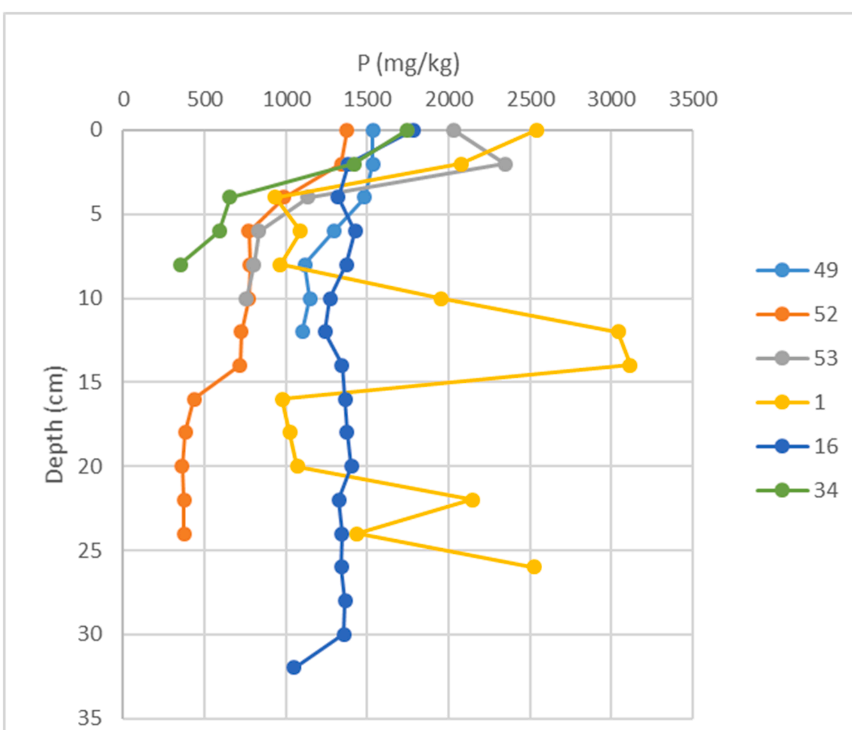

Fig. 4. Sediment core data for total phosphorus concentrations (mg/kg dry weight) from West Sedgemoor. *The numbers in the legend indicate sediment core transect numbers. Values obtained from Wavelength Dispersive X-Ray Fluorescence Spectrometer.*

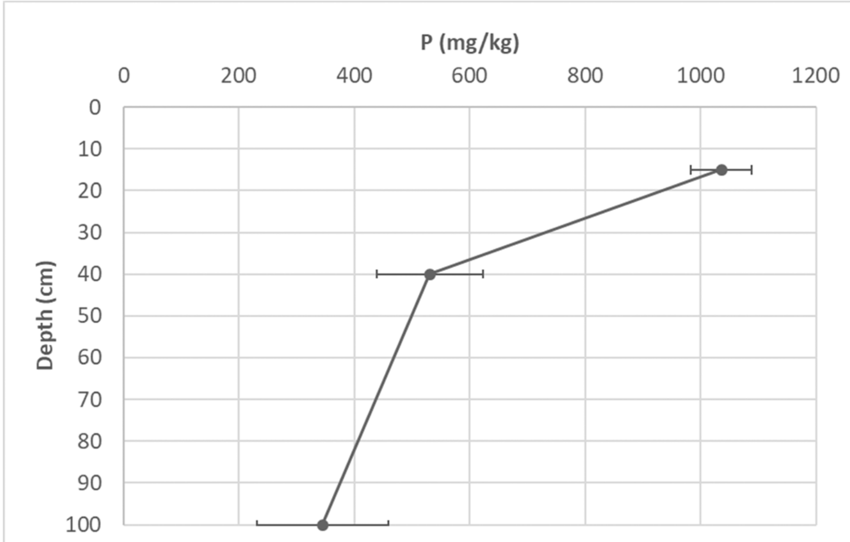

Fig. 5. Depth profile of soil peat total phosphorus concentrations (mg/kg dry weight) at Moorlinch. *Mean of 10 locations with 95% confidence intervals plotted. Values obtained from acid extractable aqua regia digestions.*

which is significantly lower than values for sediments measured at West Sedgemoor (Fig. 4). Peat core samples (Fig. 5) from 10 sites at Moorlinch showed a surface maximum, although levels were lower than observed at West Sedgemoor, which may reflect analytical differences (total XRF for Sedgemoor vs acid extractable – aqua regia digestions at Moorlinch).

3.7. Internal Loadings – Vegetation

Concentrations of P were measured in floating duckweed (*Lemna minor*) on the ditches of West Sedgemoor over the course of a year, giving a mean of 4.4 g/kg dry weight (n = 48, SD = 1.2 g/kg). Furthermore, bankside vegetation dredged from the ditches as part of a maintenance programme was washed and determined for TP. Nine samples were taken from each of three sites (A1, A2, A3 – Fig. S2) giving mean concentrations of 16.6, 18.1 and 32.8 g P/kg dry weight respectively, the variability likely to reflect the different plant species present in the dredgings. Overall, the mean was 22.5 g P/kg (n = 27, SD = 8.4 mg/kg) which was significantly higher than that of the duckweed. Previous reports state the reed *Phragmites australis* can contain between 2 and up to 10 g P/kg (1%) (Kobbing et al., 2013). Lower concentrations have been reported elsewhere (only up to 1 g P/kg) but soil P concentrations were only up to 600 mg/kg (Ge et al., 2017), lower than observed in the samples on the SLMs.

4. Discussion

In SLMS, failure of ditch water quality standards for P are determined by a combination of factors including water sources, inflow rates, residence times, internal nutrient cycling and rates of outflows. It is therefore essential to quantify the loads from the main sources including river supply, manure and guano inputs, sediment adsorption-desorption processes and soil-groundwater-surface water interactions. Calculation of P stocks in soil, sediment, water and vegetation also provides an indication of priorities regarding any remediation involving export of P from the site.

4.1. Options for improving water quality

Given the available data presented above, it is possible to generate a mass balance of P present within the specific environmental compartments for the most studied area: West Sedgemoor (Fig. 3), which indicates considerable P reservoirs in the peat, followed by the sediment then emergent plants. There is also the potential for considerable exchange of P between the different environmental compartments owing to the connectivity between the water, unconsolidated sediment and bankside peaty soil. This suggests that any remediation will require a holistic approach to removing P from the system, thus preventing the cycling currently associated with the minimal exchange of water available across hydrologically inactive and often isolated systems.

The data indicates significant pollution within the SLMs. It is clear that improvements can only be made by a combination of reducing input loadings to the system from contaminated rivers and removal of legacy P from the sites themselves. There are a number of options regarding remediation that are explored in Table 3.

4.2. Improving inflow water quality

Wessex water operate 155 WwTW, 601 sewage pumping stations and 311 storm overflows within catchments such as the Parrett, Tone, Bristol Avon, Brue and Axe, which provide feed water into the SLMs. Ongoing investment has seen significant load reductions of P, 108 tonnes per year between 2015 and 2020, with a further 70 tonnes per year to be removed by 2025. For example, this will half the current load of P coming from Wessex Water WwTW within the Parrett catchment (Wessex Water, 2021). Furthermore, there are agricultural schemes to reduce P loads to catchments such as agri-environment schemes, which are being transitioned to Environmental Land Management Schemes (ELMS, Environment Agency, 2019), nutrient neutrality mitigation methodologies (Natural England, 2022) and Catchment Market approaches, such as EnTrade, employed within the Wessex Catchments (Entrade, 2023). The effectiveness of farm management practices are not as easily measured as those for WwTW discharges and so the improvements proposed by ELMS in combination with Catchment Sensitive Farming (CSF) is unclear. Existing data for CSF and linked agri-environment incentives have only shown to deliver a modest reduction in P loading (5–10%) (Environment Agency, 2019). Use of proportionate regulation alongside incentives for landowners to provide nature-based solutions and innovative trading schemes such as EnTrade, are currently the cornerstones of future reduction of agricultural inputs. Novel schemes to export farmyard slurries and manures (Doody et al., 2020) to locations outside of the SLMs catchments to sites where there is demonstrable crop need may also be required. Paludiculture systems at inlets to Ramsar sites could serve to reduce incoming loads, the P being actively accumulated into plant crop biomass (see Section 4.6).

Table 3
Potential interventions to reduce phosphorus loadings within the Somerset Levels and their impacts and considerations.

Intervention	Likely effects on P concentrations/internal P loading	Ecological considerations/impacts	Additional Pros/Cons
No further addition of nutrients in any form to SLMs designated site	No effect on legacy P but will clearly help prevent further contamination	Likely to be only positive effects as the system is already highly hyper-nutrified	May be a problem for local farmers who need to dispose of slurries and manures, though if further additions were made these are unlikely to be compliant with Diffuse Water Pollution Regulations. Farmers will need support to find alternative disposal options.
Changes in grazing regime	Summer grazing with cattle that do not receive supplementary feed is unlikely to lead to significant increases in the overall P budget of the site, though disposal of manures from winter housings is key and schemes to export manures from the catchment are likely to be required. A shift to cattle breeds that can cope with wetter conditions during the summer is likely to be critical to allow other proposed interventions in this paper.	Livestock grazing is an important component of the nature conservation management of the system and this is likely to be key into the future, though selection of breeds that match with the creation of wetter habitats, for P reduction, and other objectives, is likely to be key.	Shifts in the nature of cattle stocking will obviously affect local farming businesses though if there are the correct incentives for diversification there might be multiple wins. Breeds not currently used for grazing may provide new niche markets (e.g. water buffalo) and even ecotourism interests (e.g. Konik ponies)
Raise water levels and more closely mimic natural hydrological processes	Raising water levels to saturate and protect peatland resources is likely to lead to a change in P chemistry, through redox changes, making more P bioavailable and more mobile. This may be negative initially though through time it may help to export the existing internal P burden. Retaining more direct rainfall to the Ramsar could help dilute P pollution. Reducing lateral flow from peat to ditch by maintaining high water levels may also lessen the translocation of P into the ditch from heavily contaminated porewater.	Further assessment is required to understand likely changes. Whilst evaluating the balance of winners and losers and the significance of this is subjective, a future wetter environment is likely to lead to a more sustainable ecology with more ecosystem-services provided. MG5 grasslands, which are a key SSSI interest feature, are likely to decline if saturated continually. SPA waterfowl may be relatively unaffected if fen habitats remain open and grazed. Peatland habitats are likely to prosper comparatively, and many newly colonising wetland birds (eg. egrets, herons, bittern, storks) may do well in this new environment.	Reduction of CO_2 emissions from drained peat is a clear benefit. It should also be noted that methane (CH_4) emissions are typically higher when water levels are above the peat surface, although CH_4 emissions are more than offset by increased CO_2 sequestration. It may well be more sustainable wetland management in light of climate change and reduced future water availability. Relying less on summer water from the rivers to maintain the wetland is potentially a significant benefit. On the downside the current agricultural regimes will need to change and such transition will need to be supported. Perceptions on increased flood risk will need to be addressed. Uncontrolled flooding events must be avoided in any new management regimes
Raise water levels plus paludiculture and subsequent export of plant material	As above with the added benefit of exporting additional P and N.	As above although the 'crop' grown and the associated level of wetness could have significant effects on biodiversity but could allow the restoration of diverse fen communities in the longer term.	As above though a crop for sustainable building materials or green energy is likely to be a significant carbon sink.
Change in ditch management – frequency and spatial extent of plant removal	Likely to reduce the rate of water conveyance through the system if less cutting is done. This could reduce the loads of P in, if the inflow source is poor quality.	Likely to be beneficial for plant and invertebrate communities so that submerged plant species are not repeatedly removed promoting floating plant dominance. There could be a trade off in terms of the mitigating of effects of flow on reduced oxygen linked to existing pollution burden (e.g. increased risk of fish kills) and the clearance of floating plant overgrowth.	Concerns will be raised about risk of flooding and could be at odds with the current Water Level Management status quo. Flood risk and the effects on water conveyance would need to be carefully considered.
Sediment removal from ditches and export material away from aquatic habitats	Export of P offsite is beneficial in terms of P balance, but its value if it is retained close by ditch watercourses is questionable.	If done in line with best practice cycles and balance of early/mid/late successional ditches (see JNCC ditch CSM) positive for ditch habitats, but may be negative if ditch infilling to restore peat is also an objective. Potentially conflicting objectives need to be reconciled.	Cost and feasibility of exporting sediment off site will be questioned. However, the risings may have a future economic value in terms of P recovery for agriculture where additional fertilizer is required for production.
Removal of heavily P contaminated topsoil	Could be an effective way of reducing P index quickly which will also reduce the contamination of open water habitats.	Likely to be ecologically positive all round given the high nutrient status of the soils which will adversely affect peatland habitat restoration. This could also help with rewetting and the establishment of a high value diverse vegetation community from a biodiversity perspective. Conceivably some bird species which have artificially enhanced population sizes because of increased food productivity driven by nutrients may suffer though more naturally sustainable populations should not be considered a negative shift.	Obvious concerns about moving peat and C emissions linked to this. Also links to concerns above about changes in water level management regime, with the necessary adjustments in the farming systems possible. Possible tension between the need to move material offsite to protect flood storage capacity and gropeat protection objectives.

However, the sites would have to be managed and vegetation removed to export P offsite for use in energy generation or in building materials, otherwise yet further recycling of P will prevail.

4.3. Altering water level management to mobilise and export phosphorus

Existing data suggests that raising water levels to restore peatlands leads to anoxia within the peat as it floods. The chemically reducing conditions lead to solubilisation of manganese compounds and particularly iron species, which in turn release soluble P, bound to these redox-sensitive substances, into the porewater (Zak et al., 2010; Gelbrecht, 2007). Van Diggelen et al. (2014) and Van de Riet et al. (2013) report P mobilization rates from rewetted fertilized peatlands of 10–50 kg/P/ha/y. The soluble P is then available for mobilisation and transport from the wetland system, potentially spreading eutrophication on a wider scale. The increase in available P could also be harnessed to grow a wet crop via paludiculture (Section 4.6). However, there would likely be short-term impacts on ecology, which would have to be traded against longer-term objectives (Table 3).

4.4. Nutrient removal in ditches via the of export of dredged sediment

Dredging of ditches on the SLMs occurs as part of a maintenance regime to keep the waterways open for the purposes of 'wet fences' for cattle segregation and as part of the wider water level and flood risk management. Dredged material (sediment, plant material and water) is placed on the bank within 5 m of the ditch. The dredging stirs up the unconsolidated sediment and significantly increases the suspended solid concentrations in the water column (Schindler and Comber, 2021). Following dredging TP levels significantly exceed the 0.1 mg-P/L level, the disturbance is a temporary effect, lasting around one week before returning to P concentrations typical of the ditch before the perturbation. As already noted, concentrations of P in dredged plant and sediment are high, so if dredgings are exported this may contribute to reducing the legacy P problem in the SLMs. Excessively frequent ditch dredging, however, can have significant negative impacts on aquatic ecology, leading to floating plant-domination (van Zuidam and Peeters, 2013), so a balance must be struck between the rate of P export, the need to mitigate against the harmful effects of eutrophication, and the maintenance of hydroseral succession (Table 3). The costs of removing vegetation from site also have to be taken into account.

4.5. Export of nutrients by topsoil removal

The data presented in Figs. 4 and 5 show higher concentrations of P in the upper peat layers, making topsoil removal advantageous, although problematic in terms of identifying an outlet for the topsoil once removed and the associated financial costs. However, topsoil removal can be used to create isolated, rain fed scrapes with lower levels of N and P (Cabezas et al., 2014) and has been undertaken in peatland restoration especially for former agricultural peatlands with high surface peat nutrient content where rewetting alone can risk excessive nutrient and methane emissions (Harpenslager et al., 2015; Zak et al., 2017). Based on limited data, it has been successful in boreal and temperate regions for nutrient management and remediation (Emsens et al., 2015) but there are obvious implications for ecosystem services (Table 3).

4.6. Biogeochemical restoration, paludiculture and rewetting

Paludiculture is a cost appropriate management solution (Table 3) which has the potential to generate an alternative source of income for farmers and landowners whilst reducing summer concentrations of P (and N) in inflow water to wetland Ramsar sites (Land et al., 2016; Geurts et al., 2020; Vroom et al., 2022). In a review of 93 papers, Land et al. (2016) found median removal rates of TN and TP of 93 and 1.2 $g/m^2/yr$, respectively. Removal efficiencies are correlated with inlet concentrations, loading rate, retention time and annual average air temperature. However, given the practical difficulties of creating and managing Integrated Constructed Wetlands on water feeds to the SLMs Ramsar, such as the lack of gradient and flow, paludiculture may provide a more feasible option.

To remove P and reduce the damaging effects of excessive plant growth only one plant macronutrient needs to be growth rate limiting (Schindler et al., 2008). In mineral soils and freshwater bodies that nutrient is normally P (Tallowin and Jefferson, 1999; Zak et al., 2010), however, in static water bodies over peat, with lower O_2 concentrations and redox potential, N may become plant growth rate limiting (Van Duren and Pegtel, 2000; Vroom et al., 2022). Under anaerobic conditions, denitrification and loss of N is stimulated, as facultative anaerobic bacteria use nitrate (NO_3^-) instead of oxygen (O_2) as the terminal electron acceptor (Vroom et al., 2022). Analysis of summer N concentrations in peatland water bodies and ditches suggest that available N is rapidly assimilated during spring plant growth and therefore could limit P influenced eutrophication.

Paludiculture has the potential to combine peat preservation, carbon sequestration and the removal of legacy nutrients from water and peat bodies to control nutrient effluxes at the landscape scale, whilst producing commercially viable plant biomass (Geurts et al., 2020; Zak, Mcinnes, 2022). *Phragmites australis* has been reported to contain between 2 and up to 10 g P/kg (1%) (Kobbing et al., 2013). However, lower P concentrations have been reported (1 g P/kg) where soil P concentrations were only up to 600 mg/kg (Ge et al., 2017), lower than observed in the samples on the SLMs. *Typha* is reported (Geurts et al., 2020) to have the highest removal rates of P under high N availability, however, based on our 1 g-P/kg peat concentrations, a 1% dry matter P content and a 10 t/ha/yr dry weight crop biomass (as shown by our data) it would take an estimated 100 *Typha* harvests to remove legacy P (~ 1 kg P m^{-2}) from the peat body on the SLMs and several hundred harvests at the lower end growth rates report for *Phragmites* and also *Typha* (Geurts et al., 2020).

Fig. 6 shows a schematic representation of the effects of rewetting on P mobilization in the water column and peat body. Following rewetting the previously oxygenated surface layers of peat become anoxic. The resulting redox conditions increase the mobility and bioavailability of P reducing in-situ peat P concentrations (Schindler and Comber, 2021). The absence of O_2 also results in the denitrification of mineralized N.

Denitrification caused by rewetting combined with plant uptake can result in N becoming a plant growth-limiting nutrient. If N becomes limiting in the water body and, inflow waters can be kept below 1 mg-N/L (Vroom et al., 2022), this can neutralise the damaging effects of excessive plant growth from accumulated P. Given time, N limitation will result in an increase in the diversity of emergent wetland plants irrespective of the availability of P. Removal of available P and N from the water column can be achieved by the placement of paludiculture crops in inflow waters along main drains to act as nutrient buffer zones (Walton et al., 2020) where high nutrient waters drain from adjacent intensively managed agricultural land.

Under rewetted, anoxic conditions, mobilised P could then be exported from the fen peat system to estuarine waters using a sustainable pump system overtime drawing down legacy P that has built up in the peat body over decades of inputs from nutrient rich inflows. It is also possible that the mobilization of P could alter N cycling by stimulating organic N mineralization with resulting flux of ammonium and dissolved organic N (Zak et al., 2010). In water bodies over peat with low conveyance or the absence of an N rich inflow a *Typha* paludiculture crop is likely to become N growth rate limiting within 2–5 harvests (Vroom et al., 2022). As there are several unknowns, this strategy would need to be tested in experimental paludiculture field trials.

More research is required to adequately predict potential impacts from hydrological restoration and paludiculture crops (Sandin et al., 2022). The diversity of emergent vegetation is likely to increase with N

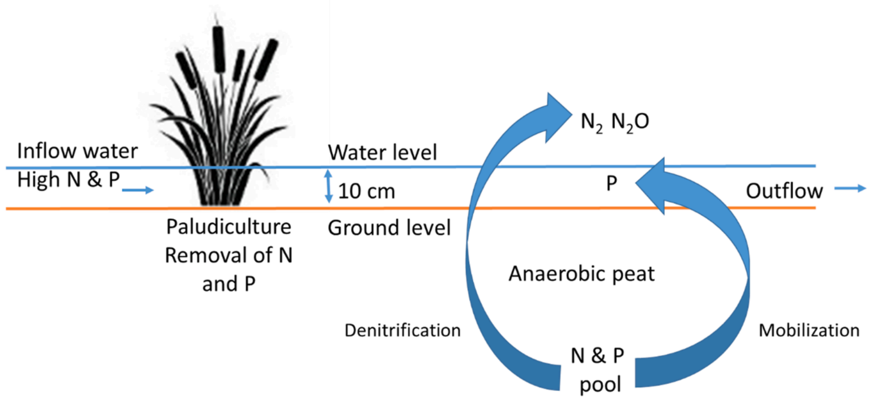

Fig. 6. Schematic representation of phosphorus and nitrogen exchange on rewetted of fen peatland.

limitation and lower competition. However, at the water-air interface, oxygenation of surface layers may result in the excessive growth of floating *Lemna* in unshaded water environments where rewetting has increased the mobilization of P (Peeters et al., 2013). Invasive floating aquatic plants such as *Azolla,* which is a problem species in the SLMs have N fixing capabilities and therefore may not be controlled by N limitation alone.

5. Conclusions

The data presented in this paper clearly indicates P legacy and ongoing P pollution of the Somerset Levels Ramsar site. This can only be remediated via a combination of reducing the input concentrations to below the ditch quality standard (currently 0.1 mg-P/L but this may need to be even lower) and removing the legacy P pollution locked up in the peat and sediment. An increasing body of evidence shows that although significant efforts are being employed by the relevant Water Company over the next 5 years to reduce loads of P to the SLMs, this is unlikely to be sufficient for site restoration given inflow water pollution from agriculture and ongoing water level and flood risk management approaches.

A more sustainable vision for the SLMs would include naturally functioning wetland ecosystems with nutrient buffer zones, lower internal water conveyance and a greater proportion of wetland habitats that are fen or wet woodland. Whilst in the short-term, this could have some negative implications for habitat diversity and specialist wet grassland species (Table 3), in the long-term there would be significant benefits to ecosystem function. Paludiculture could help in the transition to higher summer wet levels and has the potential to reduce legacy P. However, experimental trials of paludiculture crops would be required to fully evaluate the biogeochemical implications of this management option for the SLMs.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests Dr Paul Lunt reports financial support was provided by Natural England Worcester. Natasha Underwood reports financial support was provided by Wessex Water Bath Office. Dr Mark Taylor reports a relationship with Natural England Worcester that includes: employment.

Data availability

I have shared a file containing supporting data at the attached file step.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108419.

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