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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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11 Abstract

Eutrophication of wetlands caused by urban, industrial and agricultural run-off is an important 12 environmental problem. Eutrophication is characterized by excessive plant and algal growth 13 due to the increased availability of one or more growth "limiting nutrients", in freshwater 14 15 generally considered to be controlled by the bioavailability of phosphorus (P). The Somerset 16 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 17 Water Framework Directive Good Status targets for P concentrations. In 2021, Natural 18 England downgraded the status of the SLMs Sites of Special Scientific Interest (SSSIs) to 19 'Unfavourable Declining', owing to poor water quality, mostly associated with P 20 concentrations and associated duckweed and filamentous algal blooms. Macro-plant nutrient 21 22 concentrations were analysed in ditches, dipwells, soil, sediment and harvested plant biomass 23 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 24 25 data show large temporal and spatial changes in the concentrations of P and nitrogen (N) 26 across the peat rich soils. We suggest how an altered hydrological regime and plant biomass 27 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 28 29 findings suggest how paludiculture (wet agricultural crops) and rewetting of the peat body 30 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 31

management mitigation measures should be balanced against requirements to maximise
 regulating and provisioning ecosystem services.

Keywords: Ramsar; fen peatland; phosphate; Somerset Levels and Moors; pollution; wet agriculture

36

37 **1.** Introduction

38 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 39 habitat for providing both provisioning and regulating ecosystem services in the UK (ONS 40 41 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, 42 loss of fenland vegetation and ploughing activities. In the UK, 80% of the land area of 43 peatlands have been drained or damaged by agriculture, peat extraction, and forestry; adding 44 3.5% to the UK's total annual GHG emissions in 2019 (ONS 2019). Peatlands that have been 45 drained for grassland, occupy 8% of the UK's peat area and emit 6.3 million t CO_2e/yr , 46 accounting for 27% of total UK peat GHG emissions, intensively managed and drained lowland 47 48 grasslands being the primary source (Evans et al., 2017).

49

Peatlands are important for the ecosystem services they provide such as carbon storage, 50 agriculture, water storage, biodiversity, flood resilience and recreation (Joosten, 2016). 51 Intensively managed and deeply drained agricultural peatlands lose on average 1 cm depth 52 53 of peat every year (Evans et al., 2017). The Climate Change Committee made 54 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, 55 rising to half by 2050. 2) 75% of lowland cropland on deep peat should be rewetted and 15% 56 of this rewetted land area be switched to paludiculture (farming under wetland conditions 57 using species tolerant to these conditions) (BEIS, 2021). Wetlands International and the 58 International Union of the Conservation of Nature (IUCN) have recommended the use of 59 paludiculture to reduce peatland carbon emission, restore biodiversity and wetland function 60 61 (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 62 for thatched roofing with potential for use of *Typha* (cattails) and *Phragmites* (common reed) 63 64 as alternative wetland agricultural crops for production of sustainable building materials such 65 as fibre boards, energy biomass crops and for use as animal folder (Mulholland et al., 2020; 66 Lahtinen et al., 2022). Concentrations of P in wetland dry plant shoot biomass range from 67 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 68 recorded in paludiculture crops such as cattails (Geurts et al., 2020). Adoption and uptake of 69 70 paludiculture techniques has the potential to make an important contribution to achieving a 71 favourable status for phosphate in lowland peatlands as well as providing an income for 72 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/I 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.

78 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).

95 Figure 1 shows mean total reactive phosphorus levels as orthophosphate (a conservative 96 measure for TP). Recorded over a five-year period (2015-2021) for West Sedgemoor. In all 97 river catchments phosphate levels exceed the Environmental Quality Standard (EQS) of 98 0.1mg-P/L, with mean concentrations of total reactive P in the River Parrett over 10 times the 99 target.



100

101 Figure 1 Mean total reactive phosphorus (mg-P/L) for the main rivers of West Sedgemoor,

102the Parrett, Tone, Isle, Yeo, Cary, Brue and Axe concentrations (2015-2021). All data103for rivers in the Wessex catchment which supply the SLMs was downloaded from the104Environment Agency's data archive (EA, 2022). Annual averages were calculated for105all sites between 2015-2022. Larger circles denote higher TRP concentrations. Circles106coloured red or amber show exceedance of the environmental quality standard (EQS).

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.

113 Monitoring and research into soil, sediment, ground and surface water quality, sources of 114 pollution, the biogeochemical cycling of phosphate and impacts on biodiversity within these 115 rich ecosystems has been fragmented. The aim of this research has been to collate existing 116 information to provide a thorough data evidence review to inform the current magnitude of 117 contamination and to consider options for future restoration of heavily phosphate polluted 118 water, sediment and soil throughout the SLMs.

119 **2.** Methods

120 The Somerset Levels and Moors (SLMs) occupy an area of approximately 70,000 ha in the 121 county of Somerset, England, with 6,388 non-contiguous hectares of this designated in 1997, 122 under the Ramsar Convention (Figure 2). The inland wetland consists of wet grassland, drained and modified peat bog, fen and reedbed, which provides habitats for rare 123 124 invertebrates, particularly beetles, and internationally important numbers of wildfowl in 125 winter. National designations include National Nature Reserves (NNR) and Sites of Special 126 Scientific Interest (SSSI) (Figure 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 127 128 levels to act as wet fences to keep cattle in fields and to support habitats associated with this 129 largely agricultural landscape. The Ramsar site is fed by five main rivers, the Parrett, King's 130 Sedgemoor drain, Huntspill, Brue and Axe, themselves highly modified canalised waterbodies. These catchments are subject to intensive agriculture which leads to nutrient contamination 131 of the rivers, to the extent that they fail the Water Framework Directive (EU, 2000), good 132 targets for phosphate, as well as a TP target to protect 'Favourable Conditions' of the SSSIs 133 and Ramsar sites (Natural England, 2021). In addition, a 'nutrient-neutrality' approach for 134 135 new housing development is being implemented across 27 river catchments (equating to 14% 136 of England's land area) to prevent additional phosphate pollution at Protected Sites already exceeding TP targets (Natural England 2022). 137

138



139

140Figure 2Ramsar and wetland sites of special scientific interest on the Somerset Levels141and Moors

The landscape of the Levels is open, often treeless, with a chequer-board-like pattern of 142 rectilinear fields, rhynes (the local name for field ditches), drains and engineered rivers, and 143 144 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 145 mainstay, and the primary land use pattern is one of summer cattle grazing (dairy and beef) 146 with hay or silage production and application of manure on the more intensively managed 147 148 pastures. Cattle are over wintered on increasingly intensified farms on the hillslopes of the Levels. 149

150 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) (Figure 2).
Details of the sampling sites and sampled matrix are provided in Table 1.

154Table 1Summary of key sampling site features

Site	West	Moorlinch	Greylake	Nailsea Moor
	Sedgemoor			
Designated	1016	226	9.3	200
Area (ha)				
River source	Parrett	King's	King's	Land Yeo
		Sedgemoor	Sedgemoor	
		Drain	Drain	
Agricultural	 Summer 	• Summer	 RSPB Bird 	 Summer
Land use	grazing	grazing	reserve	grazing
	 Hay/silage 		 Summer 	 Hay/silage
	RSPB Bird		grazing	Arable
	reserve		 Hay/silage 	
Pressures	 Inlet water 			
	quality	quality	quality	quality
	 Legacy 	 Legacy 	 Legacy 	 Legacy
	nutrients	nutrients	nutrients	nutrients
	 Farm runoff 			
	Cattle manure	Cattle manure	Cattle manure	Cattle manure
	 Bird guano 		Bird guano	
Sampling	 Surface 	 Surface 	 Surface 	 Surface
	drainage	drainage	drainage	drainage
	water	water	water	water
	 Sediment 	 Groundwater 	 Groundwater 	
	 Groundwater 	• Peat		
	• Lemna	Terrestrial		
	Emergent	vegetation		
	vegetation			
Statutory	Ramsar	Ramsar	None	SSSI
designations	Special	Special		
	Protected Area	Protected Area		
	National Nature	National Nature		
	Reserve	Reserve		
	SSSI	SSSI		
Support	1, 5	2,3,5	3,5	4,5
references				

155 Key to Table 1 references: ¹ Crocker et al., (2021); ² Royal Haskoning (2009); ³ Morris et al.,

156 (2010); ⁴ Wessex Water (2021) and ⁵ Natural England (2013).

157 **2.2 Groundwater phosphorus concentrations**

158 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 (Figure 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 1.5m, 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.

167 **2.3 Surface sediment and Peat**

Particulate phosphorus in the sediment of the watercourses and within the peat on the moors 168 169 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 170 Sedgemoor (Crocker et al., 2021). Samples were collected using a Van Veen Grab sampler and 171 transferred into hydrochloric acid (10% - Fisher Scientific Primar Plus) and Ultra high purity 172 173 water (>18 Mohm.cm) soaked HDPE 500 ml Nalgene bottles and stored frozen at -18°C in the 174 dark until further analysis. Five sediment cores were also collected from West Sedgemoor in 175 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 minutes, 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 (Figure 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.

188 Core soil samples (10-20 cm, 30-50 cm, 100 cm depth) were also collected from Moorlinch at 189 10 spatially distributed locations then air dried, sieved to <63 μ m and determined for

elements based on aqua regia digestion, Inductively Coupled Plasma-Optical EmissionSpectrometry (ICP-OES).

192 **2.4 Bankside and aquatic vegetation**

193 Bankside and aquatic vegetation utilise and cycle the nutrients present where they grow. 194 Their growth and competition with other species will be related to exiting nutrient conditions 195 and under the correct management regime, may be used to remove nutrients held in the 196 water, porewater and sediment as part of a remediation strategy. Bankside aquatic 197 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 198 199 along the ditches, commensurate with the soil sampling sites above. Vegetation was chopped, 200 milled and freeze-dried before acid digestion (67% nitric acid). Phosphorus concentration of 201 3 sub-sample replicates was determined through ICP-OES analysis.

202 2.5 Water samples

203 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 204 205 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), 206 207 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 208 209 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 210 211 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).

214 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 0.5x0.5 m quadrats at Moorlinch in early October
- 219 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/m²/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 CO₂e/ha/yr) presented in Table S1 of the ESI.

229 2.7 Phosphorus mass balance

230 Measured concentrations (as per the methodology above) for samples taken from West 231 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

237 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 238 239 and assumptions made to fill in gaps in data/knowledge. Loadings require a combination of 240 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 241 242 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), 243 244 medium (1.9 to 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 245 depth of 2, 1.5 and 1 m for the large, medium and small ditches respectively. The volume was 246 multiplied by a typical mean concentration of Total P in the water of 0.3 mg-P/L for all types 247 of ditches, to derive a load. Sediment loads were assumed to be related to the first 10 cm of 248

sediment and mean concentrations from core data collected in the field derived a 249 concentration of 1311, 1191 and 1223 mg-P/kg dry weight for large, medium and small 250 ditches respectively. A volume was generated assuming a density of 1800 kg/m³, allowing a P 251 252 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 253 converting to a volume using a density of 1330 kg/m³, then multiplying by a concentration of 254 2447 mg-P/kg dry weight (a mean of soil data from 10 cores down to a depth of 20 cm) to 255 calculate a load of P held within the soil. The P load held within floating vegetation was 256 257 predicted by taking the concentration measured in Lemna (5 sites and 3 replicates) of 323, 258 203 and 328 mg-P/m² of *Lemna* coverage, multiplied by a coverage percent estimated from 259 site walk overs of 20%, 40% and 70% for large, medium and small ditches respectively. 260 Phosphorus held within bankside vegetation was predicted from measured data for ditch 261 dredging plant material (mean of 150 g-P/m of bank) by length of banks taken from the GIS 262 analysis. Phosphorus in dredged material heaped onto the bankside was generated from 263 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. 264

Literature data were used to estimate P loading from cattle manure, bird guano and rainwater 265 266 P concentrations. Bird population on the SLM were taken from the Wetland Bird Survey 267 (WeBS) for West Sedgemoor as a mean of 2015-16, 2016-17 and 2017-18 data. Phosphorus 268 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 269 on 53 g-P/cow/day being excreted (Natural England, 2009) multiplied by 1700 head of beef 270 cattle grazing the West Sedgemoor for 6 months of the year. Finally, rainwater loads were 271 272 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 273 274 Sedgemoor.

275 **3. Results**

276 **3.1 Water quality**

277 Moorlinch, a known nutrient contaminated site from extensive arable cropping in the 1970's 278 (carrots) shows particularly elevated ditch (annual mean 0.16 mg-P/L, seasonal mean range

279 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 280 (Table S3). Nailsea and West Sedgemoor exhibit high levels of non-compliance (76%), with 281 282 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 2015-16 and 2019-20 (Table S2). These data, 283 284 alongside river P data collected by the Environment Agency and Wessex Water, support the 285 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 286 287 progress for the Nailsea site.

288 **3.2 Groundwater quality**

At West Sedgemoor concentrations of P varied spatially and temporally with mean SRP in 289 290 ditches of 0.6 mg-P/L (range 0.05-0.44 mg-P/L), with values almost always greater than the 291 0.1 mg-P/L limit set for the drainage system (Figure S3). Groundwater within the peat at West 292 Sedgemoor had P concentrations ranging from 0.95 – 4.2 mg-P/L with a mean of 1.5 mg-P/L 293 (Figure S6). Therefore, the peat/sediment is contaminated with of P to a greater degree than 294 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-295 296 chemical processes within the largely anoxic peat profile. Data for Moorlinch supported this 297 assumption, with groundwater concentrations of a similar or greater magnitude to those of 298 West Sedgemoor (only 7 out of 102 samples <0.1 mg-P/L). Concentrations appeared to reflect combinations of rainfall (Figure S4) which leads to dilution of concentrations as well as 299 300 biogeochemistry associated with controlling factors such as iron speciation, related to high 301 water levels leading to anoxia in the peat, formation of soluble (reduced) iron, which in turn 302 solubilises the P (Table S3).

Mean and median nitrate concentrations in peat body waters ranged from 1.9 - 2.5 mg-N/L (Figure S5). The highest concentrations of 2.5 mg-N/L occurred in the surface waters with no significant difference ($p \le 0.05$) between waters. Nitrate readings in river waters of less than 1.0 mg-N/L is considered excellent. Seasonal differences occurred in median nitrate water concentrations; winter (January 2021) available N was significantly higher ($p \le 0.05$) than levels recorded at the peak of the growing season (June 2021) across all sample sites.

309 **3.3** Inlet water quality

All data for rivers in the Wessex catchment which supply the SLMs was downloaded from the 310 Environment Agency's data archive (EA, 2022). The data shows that there is a general, 311 ongoing improvement in water quality, with often step-changes associated with upgrades of 312 WwTW to reduce P in the effluent. However, the data also shows that most rivers supplying 313 314 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. 315 Table 2 shows that compliance is poor, particularly for King's Sedgemoor Drain, the rivers 316 Cary, Yeo and Parrett. Although further reductions in P loads are planned in the next five years 317 (for example, a further 50% reduction of WwTW discharge to the Parrett (Wessex Water, 318 319 2018) without reductions in agricultural runoff concentrations are unlikely to fall below 0.1 mg-P/L. 320

321	Table 2	Mean concentration of orthophosphate for Environment Agency river data,
322		2016-2021

	Replicat			no. >0.1	% non-
	е	Mean	SD	(mg-	complianc
River	Number	(mg-P/L)	(mg-P/L)	P/L)	е
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%

323

Source EA (2022)

324 **3.4 Cattle manure and bird guano**

325 It has been reported that cows on average excrete 53g-P/day (Defra, 2006). As an example, 326 for West Sedgemoor, there is an average of 1,700 cows grazing on the moor for six months of 327 the year. This equates to a P load from manure of 16,479 kg-P/yr (see Figure 3). An average 328 (2015-2018 data) of 19,213 birds across 26 species over winter on West Sedgemoor per year 329 (RSPB, pers comms, 2020). Combining bird numbers with data for P excretion (Hahn et al., 330 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 331 all species at West Sedgemoor) versus P excreta known for 10 of the 26 bird species observed 332 at the site (P excreted (g/d) = 0.0579 x mass of bird (g); $R^2 = 0.9439$). Using this approach a 333 334 total load of P from birds was estimated to be 522 kg-P/yr; significantly less than that from cattle (see Figure 3). The majority of the P inputs from cattle and birds are likely to have 335 336 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 337 nutrient bioavailability of phosphorus. 338



339

340 Figure 3 Overall mass balance of phosphorus inputs and reservoirs estimated to exist

341 within West Sedgemoor. Black boxes are P pools. White boxes provide estimates of P

342 exchange.

343

344 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., 2012), 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.

349 3.6 Internal Loadings – Sediment and Peat

350 Sediment background concentrations for P are typically 500 mg/kg dry weight (Crocker et al., 351 2021. However, detailed spatial analysis of West Sedgemoor has shown concentrations are 352 at least twice this level and up to almost 10 times background in places (Crocker et al., 2021) 353 (Figure 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 354 influenced by contaminated river feedwaters (Figure 2). Sediment core data (Figure 4) 355 typically showed elevated levels in the upper layers, likely to reflect post war intensification 356 and nutrient use as well as P mobilisation within the sediment. Mean concentrations of total 357 358 P within the top 10 cm of sediments pore water were calculated (Section 2.7) to be 140 tons 359 (Figure 3).



360

361 Figure 4 Sediment core data for total phosphorus concentrations (mg/kg dry weight) from

362 **West Sedgemoor.** The numbers in the legend indicate sediment core transect 363 numbers. Values obtained from Wavelength Dispersive X-Ray Fluorescence 364 Spectrometer.

Figure 4 shows that concentrations of P in the soil are not dissimilar to those in the sediment 365 (~1000-3500 mg-P/kg, Figure S7), with some evidence of a trend towards concentrations 366 367 decreasing away from the ditch banks (Figure S7). Reported P concentrations in 20 bulk soil 368 samples collected across three catchments in England and Wales reports a range of 200 to 2000 mg-P/kg with a mean of 889 mg-P/kg (Adams et al., 2020), which is significantly lower 369 than values for sediments measured at West Sedgemoor (Figure 4). Peat core samples (Figure 370 5) from 10 sites at Moorlinch showed a surface maximum, although levels were lower than 371 observed at West Sedgemoor, which may reflect analytical differences (total XRF for 372 373 Sedgemoor vs acid extractable – aqua regia digestions at Moorlinch).





375

376 Figure 5 Depth profile of soil peat total phosphorus concentrations (mg/kg dry weight) at

380

381 3.7 Internal Loadings – Vegetation

382 Concentrations of P were measured in floating duckweed (Lemna minor) on the ditches of

383 West Sedgemoor over the course of a year, giving a mean of 4.4 g/kg dry weight (n=48, SD =

 ³⁷⁷ Moorlinch. Mean of 10 locations with 95% confidence intervals plotted. Values
 378 obtained

³⁷⁹ from acid extractable aqua regia digestions

1.2 g/kg). Furthermore, bankside vegetation dredged from the ditches as part of a 384 maintenance programme was washed and determined for TP. Nine samples were taken from 385 each of three sites (A1, A2, A3 – Figure S2) giving mean concentrations of 16.6, 18.1 and 32.8 386 387 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 388 389 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 390 concentrations have been reported elsewhere (only up to 1 g P/kg) but soil P concentrations 391 392 were only up to 600 mg/kg (Ge et al., 2017), lower than observed in the samples on the SLMs.

393

394 **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.

402 **4.1 Options for improving water quality**

Given the available data presented above, it is possible to generate a mass balance of P 403 present within the specific environmental compartments for the most studied area: West 404 405 Sedgemoor (Figure 3), which indicates considerable P reservoirs in the peat, followed by the 406 sediment then emergent plants. There is also the potential for considerable exchange of P 407 between the different environmental compartments owing to the connectivity between the 408 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 409 currently associated with the minimal exchange of water available across hydrologically 410 411 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 regardingremediation that are explored in Table 3.

416 **4.2** Improving inflow water quality

Wessex water operate 155 WwTW, 601 sewage pumping stations and 311 storm overflows 417 within catchments such as the Parrett, Tone, Bristol Avon, Brue and Axe, which provide feed 418 419 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. 420 421 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 422 423 reduce P loads to catchments such as agri-environment schemes, which are being transitioned to Environmental Land Management Schemes (ELMS, Environment Agency, 424 425 2019), nutrient neutrality mitigation methodologies (Natural England 2022) and Catchment Market approaches, such as EnTrade, employed within the Wessex Catchments (Entrade, 426 427 2023). The effectiveness of farm management practices are not as easily measured as those 428 for WwTW discharges and so the improvements proposed by ELMS in combination with 429 Catchment Sensitive Farming (CSF) is unclear. Existing data for CSF and linked agrienvironment incentives have only shown to deliver a modest reduction in P loading (5-10%) 430 431 (Environment Agency, 2019). Use of proportionate regulation alongside incentives for 432 landowners to provide nature-based solutions and innovative trading schemes such as EnTrade, are currently the cornerstones of future reduction of agricultural inputs. Novel 433 schemes to export farmyard slurries and manures (Doody et al., 2020) to locations outside of 434 435 the SLMs catchments to sites where there is demonstrable crop need may also be required. 436 Paludiculture systems at inlets to Ramsar sites could serve to reduce incoming loads, the P 437 being actively accumulated into plant crop biomass (see Section 4.6). However, the sites would have to be managed and vegetation removed to export P offsite for use in energy 438 generation or in building materials, otherwise yet further recycling of P will prevail. 439

440 **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).

451 **4.4** Nutrient removal in ditches via the of export of dredged sediment

452 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 453 454 wider water level and flood risk management. Dredged material (sediment, plant material 455 and water) is placed on the bank within 5 m of the ditch. The dredging stirs up the 456 unconsolidated sediment and significantly increases the suspended solid concentrations in 457 the water column (Schindler and Comber, 2021). Following dredging TP levels significantly 458 exceed the 0.1 mg-P/L level, the disturbance is a temporary effect, lasting around one week 459 before returning to P concentrations typical of the ditch before the perturbation. As already 460 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 461 462 frequent ditch dredging, however, can have significant negative impacts on aquatic ecology, 463 leading to floating plant-domination (van Zuidam and Peeters, 2013), so a balance must be 464 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 465 removing vegetation from site also have to be taken into account. 466

467 **4.5 Export of nutrients by topsoil removal**

The data presented in Figures 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).

478 **4.6 Biogeochemical restoration, paludiculture and rewetting**

479 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 480 481 summer concentrations of P (and N) in inflow water to wetland Ramsar sites (Land et al., 482 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/m²/yr, respectively. Removal 483 efficiencies are correlated with inlet concentrations, loading rate, retention time and annual 484 485 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 486 487 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 488 489 macronutrient needs to be growth rate limiting (Schindler et al., 2008). In mineral soils and 490 freshwater bodies that nutrient is normally P (Tallowin and Jefferson 1999; Zak et al., 2010), however, in static water bodies over peat, with lower O₂ concentrations and redox potential, 491 492 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 493 anaerobic bacteria use nitrate (NO₃⁻) instead of oxygen (O₂) as the terminal electron acceptor 494 (Vroom et al., 2022). Analysis of summer N concentrations in peatland water bodies and 495 496 ditches suggest that available N is rapidly assimilated during spring plant growth and 497 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 and 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).

Figure 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 O₂ also results in the denitrification of mineralized N.



515

516Figure 6. Schematic representation of phosphorus and nitrogen exchange on rewetted of517fen peatland

Denitrification caused by rewetting combined with plant uptake can result in N becoming a 518 plant growth-limiting nutrient. If N becomes limiting in the water body and, inflow waters can 519 520 be kept below 1 mg-N/L (Vroom et al., 2022), this can neutralise the damaging effects of 521 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 522 523 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) 524 where high nutrient waters drain from adjacent intensively managed agricultural land. 525

Under rewetted, anoxic conditions, mobilised P could then be exported from the fen peat 526 system to estuarine waters using a sustainable pump system overtime drawing down legacy 527 P that has built up in the peat body over decades of inputs from nutrient rich inflows. It is also 528 529 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 530 water bodies over peat with low conveyance or the absence of an N rich inflow a Typha 531 532 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 533 534 experimental paludiculture field trials

More research is required to adequately predict potential impacts from hydrological 535 536 restoration and paludiculture crops (Sandin et al., 2022). The diversity of emergent vegetation 537 is likely to increase with N limitation and lower competition. However, at the water-air interface, oxygenation of surface layers may result in the excessive growth of floating Lemna 538 539 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 540 species in the SLMs have N fixing capabilities and therefore may not be controlled by N 541 limitation alone. 542

543 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)

Intervention	Likely effects on P	Ecological	Additional Pros/Cons
	concentrations/internal P	considerations/impacts	
	loading		
Raise water levels and	Raising water levels to	Further assessment is	Reduction of CO ₂ emissions from
more closely mimic	saturate and protect peatland	required to understand	drained peat is a clear benefit. It
natural hydrological	resources is likely to lead to a	likely changes. Whilst	should also be noted that
processes	change in P chemistry, through	evaluating the balance of	methane (CH ₄) emissions are
	redox changes, making more P	winners and losers and the	typically higher when water levels
	bioavailable and more mobile.	significance of this is	are above the peat surface,
	This may be negative initially	subjective, a future wetter	although CH ₄ emissions are more
	though through time it may	environment is likely to lead	than offset by increased CO ₂
	help to export the existing	to a more sustainable	sequestration. It may well be
	internal P burden. Retaining	ecology with more	more sustainable wetland
	more direct rainfall to the	ecosystem-services	management in light of climate
	Ramsar could help dilute P	provided. MG5 grasslands,	change and reduced future water
	pollution. Reducing lateral	which are a key SSSI	availability. Relying less on
	flow from peat to ditch by	interest feature, are likely	summer water from the rivers to
	maintaining high water levels	to decline if saturated	maintain the wetland is
	may also lessen the	continually. SPA waterfowl	potentially a significant benefit.
	translocation of P into the	may be relatively	
	ditch from heavily	unaffected if fen habitats	On the downside the current
	contaminated porewater.	remain open and grazed.	agricultural regimes will need to
		Peatland habitats are likely	change and such transition will
		to prosper comparatively,	need to be supported.
		and many newly colonising	Perceptions on increased flood
		wetland birds (e.g. egrets,	risk will need to be addressed.
		herons, bittern, storks) may	Uncontrolled flooding events
		do well in this new	must be avoided in any new
		environment.	management regimes

Intervention	Likely effects on P	Ecological	Additional Pros/Cons
	loading	considerations/impacts	
Raise water levels plus	As above with the added	As above although the	As above though a crop for
paludiculture and	benefit of exporting additional	'crop' grown and the	sustainable building materials or
subsequent export of	P and N.	associated level of wetness	green energy is likely to be a
plant material		could have significant	significant carbon sink.
		effects on biodiversity but	
		could allow the restoration	
		of diverse fen communities	
		in the longer term.	
Change in ditch	Likely to reduce the rate of	Likely to be beneficial for	Concerns will be raised about risk
management –	water conveyance through the	plant and invertebrate	of flooding and could be at odds
frequency and spatial	system if less cutting is done.	communities so that	with the current Water Level
extent of plant removal	This could reduce the loads of	submerged plant species	Management status quo. Flood
	P in, if the inflow source is	are not repeatedly removed	risk and the effects on water
	poor quality.	promoting floating plant	conveyance would need to be
		dominance. There could be	carefully considered.
		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.	
Sediment removal from	Export of P offsite is beneficial	If done in line with best	Cost and feasibility of exporting
ditches and export	in terms of P balance, but its	practice cycles and balance	sediment off site will be
material away from	value if it is retained close by	of early/mid/late	questioned. However, the risings
aquatic habitats	ditch watercourses is	successional ditches (see	may have a future economic
	questionable.	JNCC ditch CSM) positive for	value in terms of P recovery for

Intervention	Likely effects on P	Ecological	Additional Pros/Cons
	concentrations/internal P	considerations/impacts	
	loading		
		ditch habitats, but may be	agriculture where additional
		negative if ditch infilling to	fertilizer is required for
		restore peat is also an	production.
		objective. Potentially	
		conflicting objectives need	
		to be reconciled.	
Removal of heavily P	Could be an effective way of	Likely to be ecologically	Obvious concerns about moving
contaminated topsoil	reducing P index quickly which	positive all round given the	peat and C emissions linked to
	will also reduce the	high nutrient status of the	this. Also links to concerns above
	contamination of open water	soils which will adversely	about changes in water level
	habitats.	affect peatland habitat	management regime, with the
		restoration. This could also	necessary adjustments in the
		help with rewetting and the	farming systems possible.
		establishment of a high	
		value diverse vegetation	Possible tension between the
		community from a	need to move material offsite to
		biodiversity perspective.	protect flood storage capacity
		Conceivably some bird	and gropeat protection
		species which have	objectives.
		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.	

545 **5. Conclusions**

The data presented in this paper clearly indicates P legacy and ongoing P pollution of the 546 Somerset Levels Ramsar site. This can only be remediated via a combination of reducing the 547 input concentrations to below the ditch quality standard (currently 0.1 mg-P/L but this may 548 need to be even lower) and removing the legacy P pollution locked up in the peat and 549 550 sediment. An increasing body of evidence shows that although significant efforts are being 551 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 552 agriculture and ongoing water level and flood risk management approaches. 553

A more sustainable vision for the SLMs would include naturally functioning wetland 554 ecosystems with nutrient buffer zones, lower internal water conveyance and a greater 555 proportion of wetland habitats that are fen or wet woodland. Whilst in the short-term, this 556 could have some negative implications for habitat diversity and specialist wet grassland 557 558 species (Table 3), in the long-term there would be significant benefits to ecosystem function. 559 Paludiculture could help in the transition to higher summer wet levels and has the potential 560 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. 561

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565 **Declaration of interests**

566 The views expressed in this paper are those of the authors and do not necessarily represent 567 the organisations to which they are affiliated.

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