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

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11 **Abstract**

12 Eutrophication of wetlands caused by urban, industrial and agricultural run-off is an important
13 environmental problem. Eutrophication is characterized by excessive plant and algal growth
14 due to the increased availability of one or more growth “limiting nutrients”, in freshwater
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
17 inputs which leads to nutrient contamination of the inflow waters, to the extent that they fail
18 Water Framework Directive Good Status targets for P concentrations. In 2021, Natural
19 England downgraded the status of the SLMs Sites of Special Scientific Interest (SSSIs) to
20 ‘Unfavourable Declining’, owing to poor water quality, mostly associated with P
21 concentrations and associated duckweed and filamentous algal blooms. Macro-plant nutrient
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
24 and reservoirs. Here we present a combined dataset of stores, fluxes and loadings of P. The
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
28 peat body could be mobilized by flooding and over time evacuated from the wetland. The
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
31 interactions occur during the rewetting process and how the need to export P via new land

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

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

36

37 **1. Introduction**

38 Peatlands occupy around 12% of the UK land area (Evans et al., 2017); provide over a quarter
39 of the UK's drinking water and store a significant amount of carbon making them an important
40 habitat for providing both provisioning and regulating ecosystem services in the UK (ONS
41 2019). Agriculture on lowland peats, in the west of England mainly includes livestock grazing.
42 Farming on peatlands has a negative impact on the peat through drainage, nutrient addition,
43 loss of fenland vegetation and ploughing activities. In the UK, 80% of the land area of
44 peatlands have been drained or damaged by agriculture, peat extraction, and forestry; adding
45 3.5% to the UK's total annual GHG emissions in 2019 (ONS 2019). Peatlands that have been
46 drained for grassland, occupy 8% of the UK's peat area and emit 6.3 million t CO₂e/yr,
47 accounting for 27% of total UK peat GHG emissions, intensively managed and drained lowland
48 grasslands being the primary source (Evans et al., 2017).

49

50 Peatlands are important for the ecosystem services they provide such as carbon storage,
51 agriculture, water storage, biodiversity, flood resilience and recreation (Joosten, 2016).
52 Intensively managed and deeply drained agricultural peatlands lose on average 1 cm depth
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
55 by 2050: 1) 25% of the area of lowland grassland on deep peat should be rewetted by 2035,
56 rising to half by 2050. 2) 75% of lowland cropland on deep peat should be rewetted and 15%
57 of this rewetted land area be switched to paludiculture (farming under wetland conditions
58 using species tolerant to these conditions) (BEIS, 2021). Wetlands International and the
59 International Union of the Conservation of Nature (IUCN) have recommended the use of
60 paludiculture to reduce peatland carbon emission, restore biodiversity and wetland function
61 (Cris et al., 2014; Budiman et al., 2020; Wichtmann et al., 2017).

62 Perennial wetland reeds have been used for millennia as a construction material, especially
63 for thatched roofing with potential for use of *Typha* (cattails) and *Phragmites* (common reed)
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;
68 Vroom et al., 2022). Mean concentrations of P in dry shoot biomass of 0.21% have been
69 recorded in paludiculture crops such as cattails (Geurts et al., 2020). Adoption and uptake of
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.

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

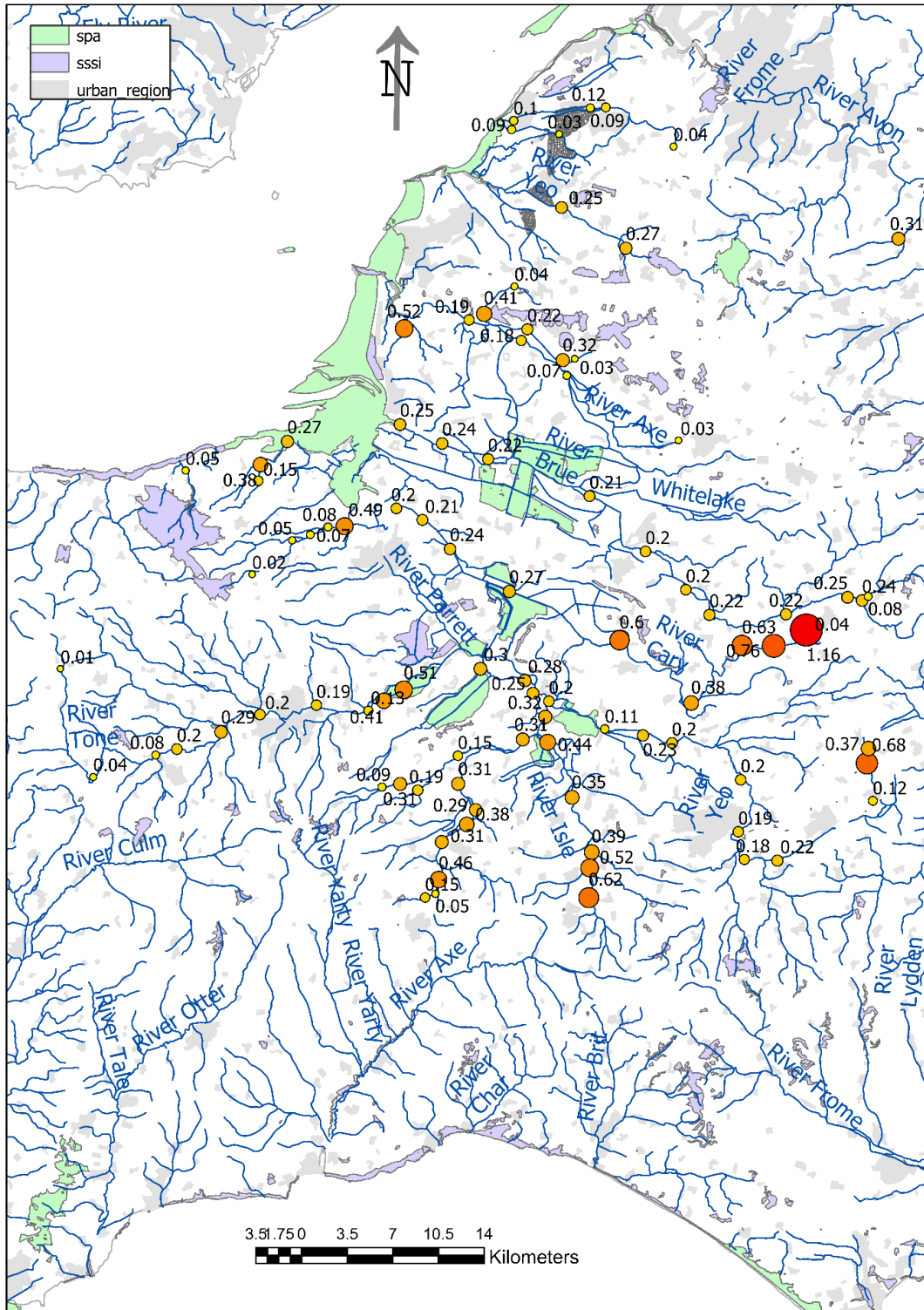
78 The potential sources of excess phosphate in the surface waters of the Levels include:

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

89 Peatland restoration can yield significant public benefits with improvements in nature
90 conservation value, carbon sequestration, attenuation of flood water and improvements in
91 water quality. For the SLMs catchments, considerable investment by the local Water

92 Company (Wessex Water) over the past two decades has seen loads from WwTW significantly
93 decrease (Wessex Water, 2018, 2020), leading to agricultural loads probably now dominating
94 (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

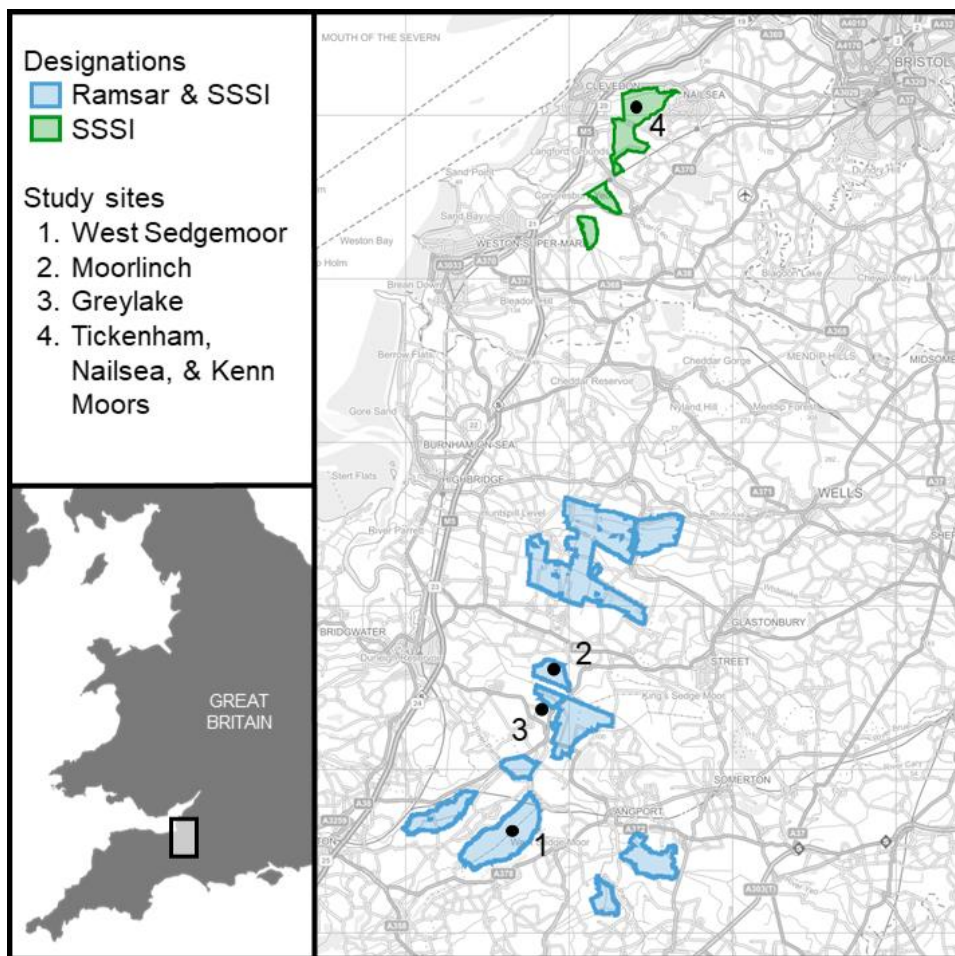
101 **Figure 1 Mean total reactive phosphorus (mg-P/L) for the main rivers of West Sedgemoor,**
 102 **the Parrett, Tone, Isle, Yeo, Cary, Brue and Axe concentrations (2015-2021).** *All data*
 103 *for rivers in the Wessex catchment which supply the SLMs was downloaded from the*
 104 *Environment Agency’s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

107 Over the past 5 years, a considerable amount of data have been independently generated
108 across a number of sites for various purposes and it is timely to collate and analyse these data
109 in order to feed into a strategy to improve water quality across the SLMs. Although for a
110 number of studies soluble reactive and total reactive phosphorus was determined, for this
111 data analysis, because the SLM phosphorus target is TP, only this fraction has been assessed
112 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,
123 drained and modified peat bog, fen and reedbed, which provides habitats for rare
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,
127 broadly being lowered in winter for flood capacity and penned in summer to maintain water
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.
131 These catchments are subject to intensive agriculture which leads to nutrient contamination
132 of the rivers, to the extent that they fail the Water Framework Directive (EU, 2000), good
133 targets for phosphate, as well as a TP target to protect 'Favourable Conditions' of the SSSIs
134 and Ramsar sites (Natural England, 2021). In addition, a 'nutrient-neutrality' approach for
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
137 exceeding TP targets (Natural England 2022).



139

140 **Figure 2 Ramsar and wetland sites of special scientific interest on the Somerset Levels**
 141 **and Moors**

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

150 2.1 Sampling and Analysis

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

154 **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	<ul style="list-style-type: none"> • Summer grazing • Hay/silage • RSPB Bird reserve 	<ul style="list-style-type: none"> • Summer grazing 	<ul style="list-style-type: none"> • RSPB Bird reserve • Summer grazing • Hay/silage 	<ul style="list-style-type: none"> • Summer grazing • Hay/silage • Arable
Pressures	<ul style="list-style-type: none"> • Inlet water quality • Legacy nutrients • Farm runoff • Cattle manure • Bird guano 	<ul style="list-style-type: none"> • Inlet water quality • Legacy nutrients • Farm runoff • Cattle manure 	<ul style="list-style-type: none"> • Inlet water quality • Legacy nutrients • Farm runoff • Cattle manure • Bird guano 	<ul style="list-style-type: none"> • Inlet water quality • Legacy nutrients • Farm runoff • Cattle manure
Sampling	<ul style="list-style-type: none"> • Surface drainage water • Sediment • Groundwater • <i>Lemna</i> • Emergent vegetation 	<ul style="list-style-type: none"> • Surface drainage water • Groundwater • Peat • Terrestrial vegetation 	<ul style="list-style-type: none"> • Surface drainage water • Groundwater 	<ul style="list-style-type: none"> • 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, 5	2,3,5	3,5	4,5

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
 159 as the overlying vegetation and so is a key metric with which to assess the levels of pollution

160 present. A series of dipwells (approximately 1.5 m deep) were sunk at West Sedgemoor (at
161 1, 3, and 5 m away from the ditch bank) at two control sites where dredging had not occurred
162 for 1 year (C1) and at least 7 years (C2) and at 3 locations scheduled to be dredged (Figure 3).
163 Six samples were taken from before dredging then up to 58 days after dredging at each site.
164 A further ten dipwells were sunk at Moorlinch to a depth of 1.5m, geographically distributed
165 across the study site. Monthly samples were taken for SRP and TP at West Sedgemoor and
166 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**

168 Particulate phosphorus in the sediment of the watercourses and within the peat on the moors
169 act as reservoirs of nutrient pollution and offer an assessment of integrated loads over time
170 from all sources. Surface sediment samples (59) were collected in March 2018 from West
171 Sedgemoor (Crocker et al., 2021). Samples were collected using a Van Veen Grab sampler and
172 transferred into hydrochloric acid (10% - Fisher Scientific Primar Plus) and Ultra high purity
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.

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

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

190 elements based on aqua regia digestion, Inductively Coupled Plasma-Optical Emission
191 Spectrometry (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 existing 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
198 from West Sedgemoor to determine P content. Vegetation was aggregated for 3 positions
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
204 (0.1 mg-TP/L). Any assessment of ecological status therefore requires TP in water to be
205 determined. Water samples collected from the selected sites were measured for a range of
206 phosphate forms; namely soluble reactive phosphorus (SRP), total reactive phosphorus (TRP),
207 total soluble phosphorus (TSP) and TP depending on the location. However, for this
208 assessment only TP is reported here to align with the CSMG targets. Further detail regarding
209 P speciation and bioavailability for West Sedgemoor is available in Crocker et al. (2023).
210 Analysis was performed with appropriate certified reference materials and further details are
211 available in S1 of the ESI.

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

214 **2.6 Vegetation analysis**

215 Plant biomass and ability to accumulate phosphorus is key to any remediation strategy. The
216 species are frequently occurring and locally dominant wetland plants and the mixed grass
217 sward is the typical existing vegetation of the SLMs. Plants were harvested from low-lying

218 areas of meadow at 11 randomly allocated 0.5x0.5 m quadrats at Moorlinch in early October
219 of 2021:

- 220 • *Glyceria maxima* (reed sweet-grass)
- 221 • *Phalaris arundinacea* (canary-grass)
- 222 • *Phragmites australis* (common reed)
- 223 • *Sparganium erectum* (branched bur reed)
- 224 • Mixed species wetland grass sward

225 Standing biomass production (kg/m²/yr) was calculated for each sample. Replicate samples
226 were dried to a constant weight and dry-matter (DM) production calculated for each species
227 and a mixed species grass sward. Percentage carbon content of the DM was used to calculate
228 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:

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

237 To determine the significant phosphorus reservoirs and main cycling pathways of P through
238 a peatland – porewater – surface water system a number of parameters need determining
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;
241 kilograms of soil, sediment or biomass). The mass balance for West Sedgemoor relied on
242 Geographic Information Systems (GIS) analysis using ArcMap Pro to estimate areas of land
243 and water across the moor. The ditches were split into three types large (>3 m width),
244 medium (1.9 to 3 m width) and small (<1.9 m width), their lengths were calculated using
245 ArcGIS pro, then a total volume of water present was calculated by multiplying an average
246 depth of 2, 1.5 and 1 m for the large, medium and small ditches respectively. The volume was
247 multiplied by a typical mean concentration of Total P in the water of 0.3 mg-P/L for all types
248 of ditches, to derive a load. Sediment loads were assumed to be related to the first 10 cm of

249 sediment and mean concentrations from core data collected in the field derived a
250 concentration of 1311, 1191 and 1223 mg-P/kg dry weight for large, medium and small
251 ditches respectively. A volume was generated assuming a density of 1800 kg/m³, allowing a P
252 load in the top 10 cm of sediment to be calculated. The soil P reservoir was calculated from
253 measured by subtracting the area of water on West Sedgemoor from the total area and
254 converting to a volume using a density of 1330 kg/m³, then multiplying by a concentration of
255 2447 mg-P/kg dry weight (a mean of soil data from 10 cores down to a depth of 20 cm) to
256 calculate a load of P held within the soil. The P load held within floating vegetation was
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,
264 assuming a 5-year cycle of dredging ditches greater than 1.9 m in width.

265 Literature data were used to estimate P loading from cattle manure, bird guano and rainwater
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
269 be combined with P excretion rates to calculate a load. Loads from cattle were set as based
270 on 53 g-P/cow/day being excreted (Natural England, 2009) multiplied by 1700 head of beef
271 cattle grazing the West Sedgemoor for 6 months of the year. Finally, rainwater loads were
272 simply calculated by multiplying together typical rainwater P concentrations (0.0304 mg-P/L,
273 Berthold et al., 2019) by annual rainfall of 846 mm on the area of land and water within West
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
280 0.26-0.211 mg-P/L) concentrations of total phosphorus over 10 times the compliance value
281 (Table S3). Nailsea and West Sedgemoor exhibit high levels of non-compliance (76%), with
282 levels (annual mean 0.22 mg-P/L, seasonal mean range 0.09-0.44 mg-P/L) up to 4 times the
283 standard and no improvement between 2015-16 and 2019-20 (Table S2). These data,
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
286 SSSI ditch systems to Unfavourable Declining. A similar downgrading of status is also in
287 progress for the Nailsea site.

288 **3.2 Groundwater quality**

289 At West Sedgemoor concentrations of P varied spatially and temporally with mean SRP in
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
295 in concentrations appears to be mainly driven by dilution with rainwater and physico-
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
299 combinations of rainfall (Figure S4) which leads to dilution of concentrations as well as
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).

303 Mean and median nitrate concentrations in peat body waters ranged from 1.9 - 2.5 mg-N/L
304 (Figure S5). The highest concentrations of 2.5 mg-N/L occurred in the surface waters with no
305 significant difference ($p \leq 0.05$) between waters. Nitrate readings in river waters of less than
306 1.0 mg-N/L is considered excellent. Seasonal differences occurred in median nitrate water
307 concentrations; winter (January 2021) available N was significantly higher ($p \leq 0.05$) than levels
308 recorded at the peak of the growing season (June 2021) across all sample sites.

309 **3.3 Inlet water quality**

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

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

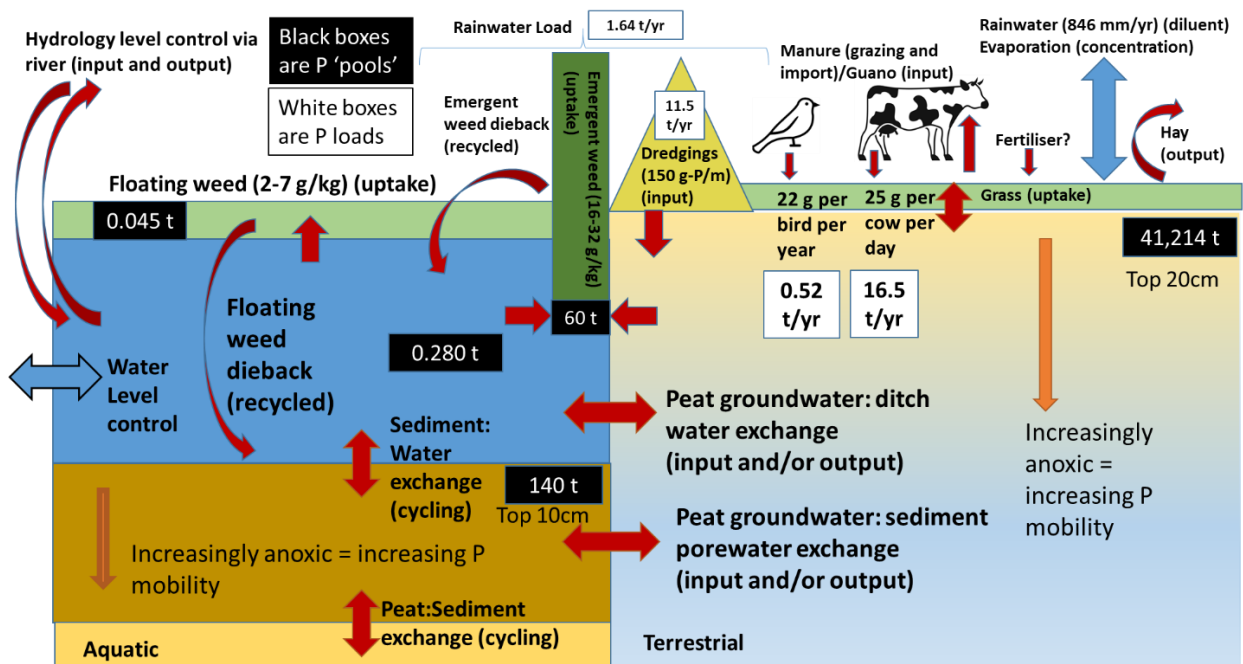
River	Replicate Number	Mean (mg-P/L)	SD (mg-P/L)	no. >0.1 (mg-P/L)	% non-compliance
Kings Sedgemoor Drain	15	0.217	0.0439	15	100%
Yeo	62	0.239	0.1720	52	84%
Parrett	48	0.375	0.1818	40	83%
Cary	43	0.480	0.3188	30	70%
Brue	62	0.193	0.0719	41	66%
Isle	38	0.264	0.1581	24	63%
Tone	62	0.200	0.1804	36	58%
Land 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%

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,

331 loads were estimated based on the relationship between reported mass of bird (known for
 332 all species at West Sedgemoor) versus P excreta known for 10 of the 26 bird species observed
 333 at the site ($P \text{ excreted (g/d)} = 0.0579 \times \text{mass of bird (g)}$; $R^2 = 0.9439$). Using this approach a
 334 total load of P from birds was estimated to be 522 kg-P/yr; significantly less than that from
 335 cattle (see Figure 3). The majority of the P inputs from cattle and birds are likely to have
 336 originated from vegetation consumed from within the site's catchment (closed loop). The
 337 most significant impacts to water quality will result from redistribution and increases in
 338 nutrient bioavailability of phosphorus.



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.**

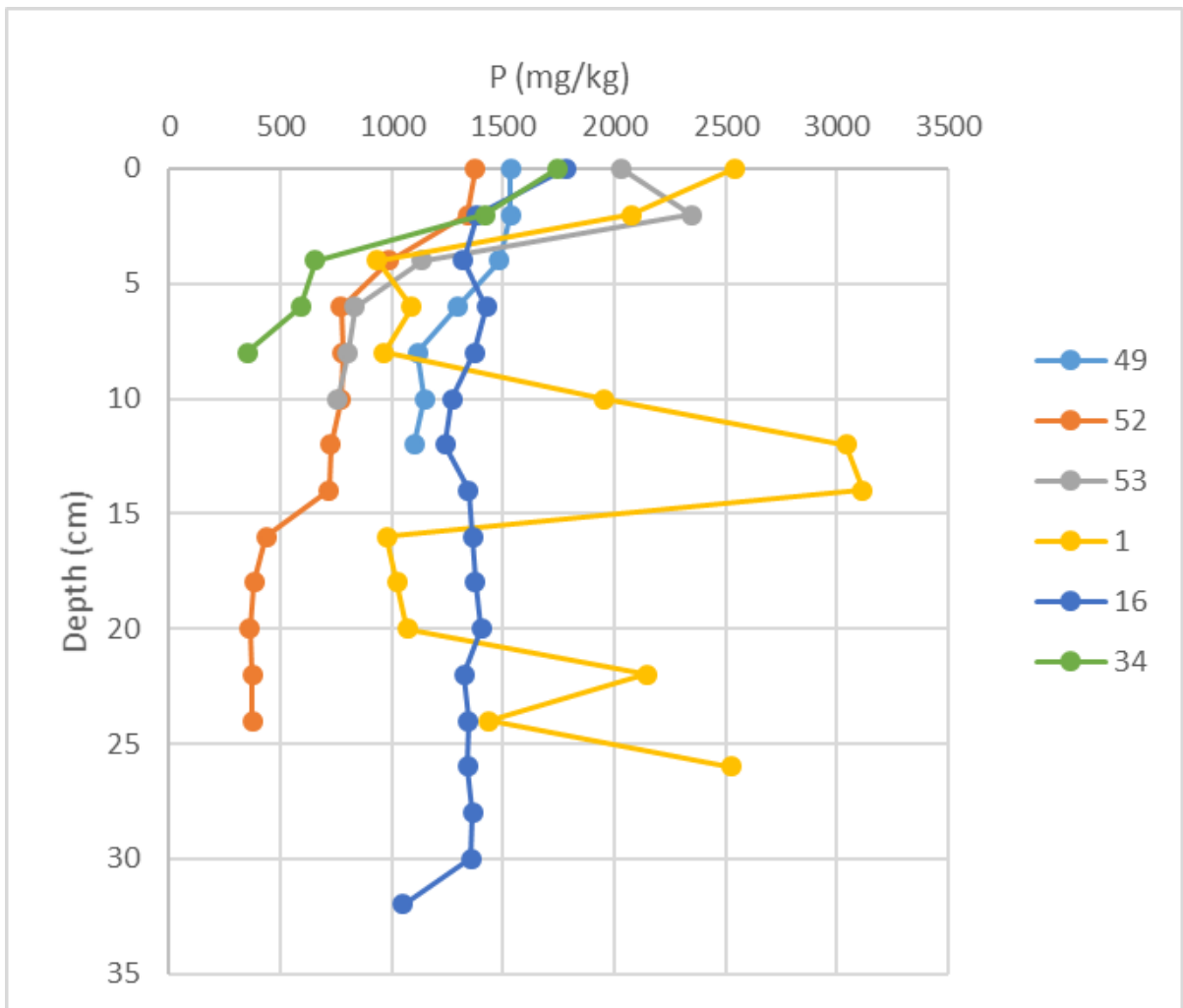
343

344 **3.5 Atmospheric deposition**

345 Atmospheric concentrations of P are low and deposition is not considered a significant source
 346 of P to the UK environment (Comber et al., 2012), however, over a large surface area amounts
 347 can be significant and easily calculated (excluding dry deposition) to give 1642 kg-P/yr from
 348 this source.

349 **3.6 Internal Loadings – Sediment and Peat**

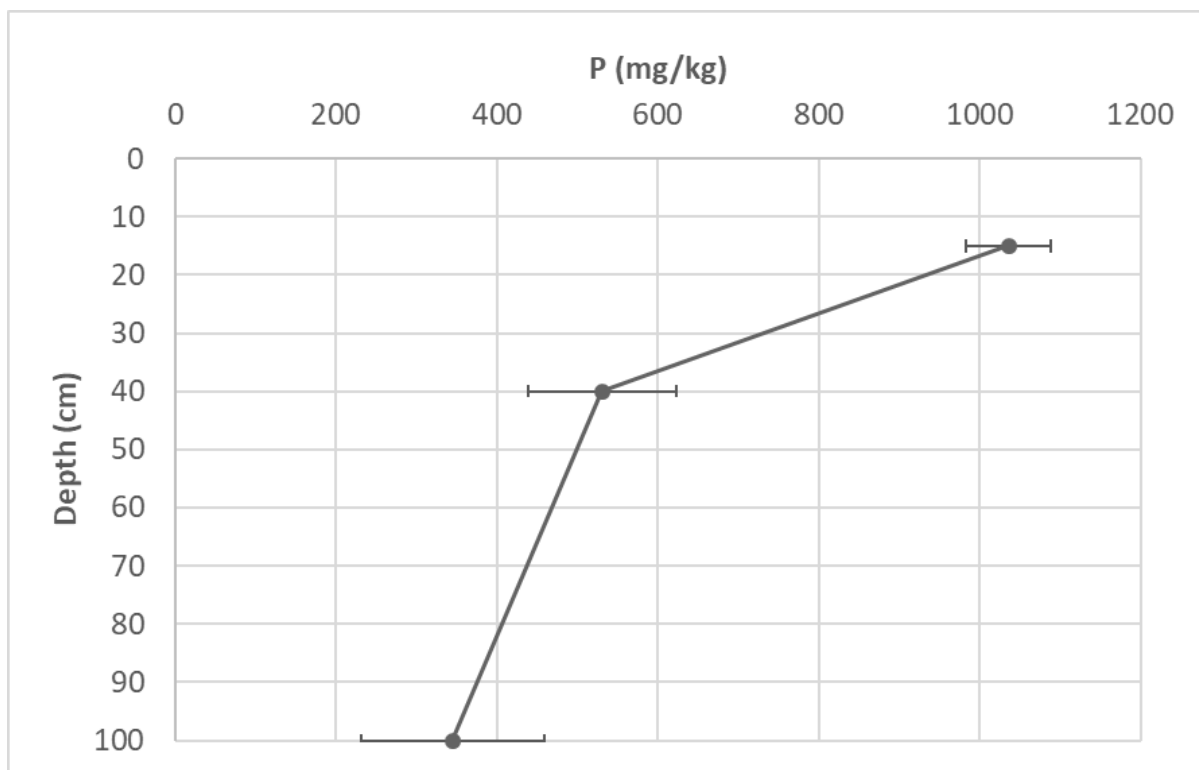
350 Sediment background concentrations for P are typically 500 mg/kg dry weight (Crocker et al.,
 351 2021). However, detailed spatial analysis of West Sedgemoor has shown concentrations are
 352 at least twice this level and up to almost 10 times background in places (Crocker et al., 2021)
 353 (Figure S6). Similarly high levels of P have been reported downstream of intensive agriculture
 354 and industry discharges such as dairies (Burns et al., 2015). Elevated concentrations were
 355 influenced by contaminated river feedwaters (Figure 2). Sediment core data (Figure 4)
 356 typically showed elevated levels in the upper layers, likely to reflect post war intensification
 357 and nutrient use as well as P mobilisation within the sediment. Mean concentrations of total
 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.*

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

374



375

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

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

379 from acid extractable aqua regia digestions

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 =

384 1.2 g/kg). Furthermore, bankside vegetation dredged from the ditches as part of a
385 maintenance programme was washed and determined for TP. Nine samples were taken from
386 each of three sites (A1, A2, A3 – Figure S2) giving mean concentrations of 16.6, 18.1 and 32.8
387 g P/kg dry weight respectively, the variability likely to reflect the different plant species
388 present in the dredgings. Overall, the mean was 22.5 g P/kg (n=27, SD = 8.4 mg/kg) which was
389 significantly higher than that of the duckweed. Previous reports state the reed *Phragmites*
390 *australis* can contain between 2 and up to 10 g P/kg (1%) (Kobbing et al., 2013). Lower
391 concentrations have been reported elsewhere (only up to 1 g P/kg) but soil P concentrations
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**

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

402 **4.1 Options for improving water quality**

403 Given the available data presented above, it is possible to generate a mass balance of P
404 present within the specific environmental compartments for the most studied area: West
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
409 will require a holistic approach to removing P from the system, thus preventing the cycling
410 currently associated with the minimal exchange of water available across hydrologically
411 inactive and often isolated systems.

412 The data indicates significant pollution within the SLMs. It is clear that improvements can only
413 be made by a combination of reducing input loadings to the system from contaminated rivers

414 and removal of legacy P from the sites themselves. There are a number of options regarding
415 remediation that are explored in Table 3.

416 **4.2 Improving inflow water quality**

417 Wessex water operate 155 WwTW, 601 sewage pumping stations and 311 storm overflows
418 within catchments such as the Parrett, Tone, Bristol Avon, Brue and Axe, which provide feed
419 water into the SLMs. Ongoing investment has seen significant load reductions of P, 108 tonnes
420 per year between 2015 and 2020, with a further 70 tonnes per year to be removed by 2025.
421 For example, this will half the current load of P coming from Wessex Water WwTW within the
422 Parrett catchment (Wessex Water 2021). Furthermore, there are agricultural schemes to
423 reduce P loads to catchments such as agri-environment schemes, which are being
424 transitioned to Environmental Land Management Schemes (ELMS, Environment Agency,
425 2019), nutrient neutrality mitigation methodologies (Natural England 2022) and Catchment
426 Market approaches, such as EnTrade, employed within the Wessex Catchments (Entrade,
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 agri-
430 environment incentives have only shown to deliver a modest reduction in P loading (5-10%)
431 (Environment Agency, 2019). Use of proportionate regulation alongside incentives for
432 landowners to provide nature-based solutions and innovative trading schemes such as
433 EnTrade, are currently the cornerstones of future reduction of agricultural inputs. Novel
434 schemes to export farmyard slurries and manures (Doody et al., 2020) to locations outside of
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
438 would have to be managed and vegetation removed to export P offsite for use in energy
439 generation or in building materials, otherwise yet further recycling of P will prevail.

440 **4.3 Altering water level management to mobilise and export phosphorus**

441 Existing data suggests that raising water levels to restore peatlands leads to anoxia within the
442 peat as it floods. The chemically reducing conditions lead to solubilisation of manganese
443 compounds and particularly iron species, which in turn release soluble P, bound to these

444 redox-sensitive substances, into the porewater (Zak et al., 2010; Gelbrecht, 2007). Van
445 Diggelen et al. (2014) and Van de Riet et al. (2013) report P mobilization rates from rewetted
446 fertilized peatlands of 10–50 kg/P/ha/y. The soluble P is then available for mobilisation and
447 transport from the wetland system, potentially spreading eutrophication on a wider scale.
448 The increase in available P could also be harnessed to grow a wet crop via paludiculture
449 (Section 4.6). However, there would likely be short-term impacts on ecology, which would
450 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
453 waterways open for the purposes of ‘wet fences’ for cattle segregation and as part of the
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
461 exported this may contribute to reducing the legacy P problem in the SLMs. Excessively
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
465 eutrophication, and the maintenance of hydrosereal succession (Table 3). The costs of
466 removing vegetation from site also have to be taken into account.

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

468 The data presented in Figures 4 and 5 show higher concentrations of P in the upper peat
469 layers, making topsoil removal advantageous, although problematic in terms of identifying an
470 outlet for the topsoil once removed and the associated financial costs. However, topsoil
471 removal can be used to create isolated, rain fed scrapes with lower levels of N and P (Cabezas
472 et al., 2014) and has been undertaken in peatland restoration especially for former
473 agricultural peatlands with high surface peat nutrient content where rewetting alone can risk

474 excessive nutrient and methane emissions (Harpenslager et al., 2015; Zak et al., 2017). Based
475 on limited data, it has been successful in boreal and temperate regions for nutrient
476 management and remediation (Emsens et al., 2015) but there are obvious implications for
477 ecosystem services (Table 3).

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

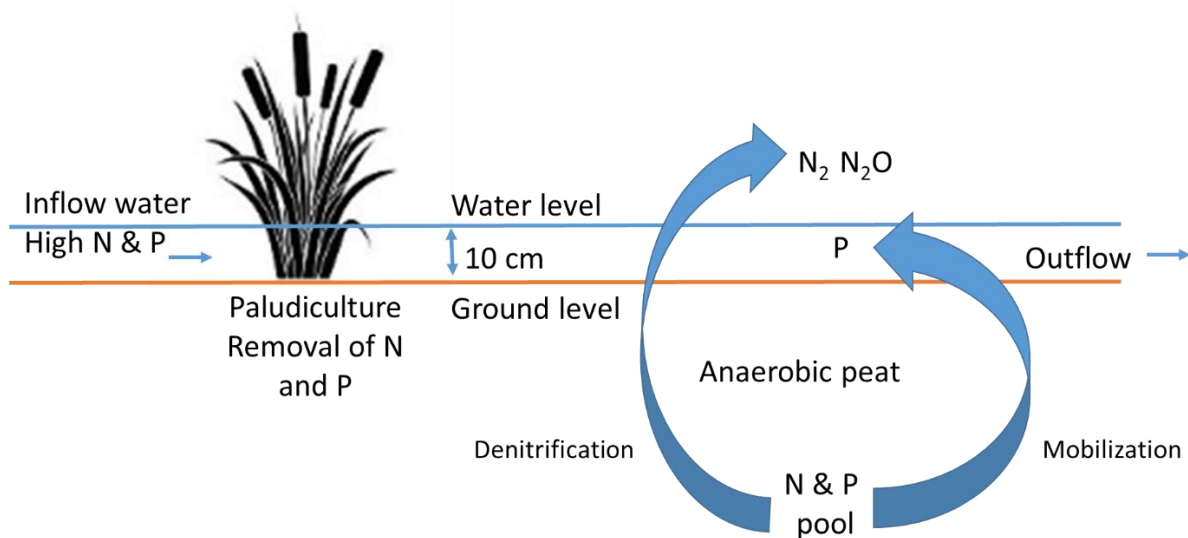
479 Paludiculture is a cost appropriate management solution (Table 3) which has the potential to
480 generate an alternative source of income for farmers and landowners whilst reducing
481 summer concentrations of P (and N) in inflow water to wetland Ramsar sites (Land et al.,
482 2016; Geurts et al., 2020; Vroom et al., 2022). In a review of 93 papers, Land et al., (2016)
483 found median removal rates of TN and TP of 93 and 1.2 g/m²/yr, respectively. Removal
484 efficiencies are correlated with inlet concentrations, loading rate, retention time and annual
485 average air temperature. However, given the practical difficulties of creating and managing
486 Integrated Constructed Wetlands on water feeds to the SLMs Ramsar, such as the lack of
487 gradient and flow, paludiculture may provide a more feasible option.

488 To remove P and reduce the damaging effects of excessive plant growth only one plant
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),
491 however, in static water bodies over peat, with lower O₂ concentrations and redox potential,
492 N may become plant growth rate limiting (Van Duren and Pegtel 2000; Vroom et al., 2022).
493 Under anaerobic conditions, denitrification and loss of N is stimulated, as facultative
494 anaerobic bacteria use nitrate (NO₃⁻) instead of oxygen (O₂) as the terminal electron acceptor
495 (Vroom et al., 2022). Analysis of summer N concentrations in peatland water bodies and
496 ditches suggest that available N is rapidly assimilated during spring plant growth and
497 therefore could limit P influenced eutrophication.

498 Paludiculture has the potential to combine peat preservation, carbon sequestration and the
499 removal of legacy nutrients from water and peat bodies to control nutrient effluxes at the
500 landscape scale, whilst producing commercially viable plant biomass (Geurts et al., 2020; Zak
501 and McInnes, 2022). *Phragmites australis* has been reported to contain between 2 and up to
502 10 g P/kg (1%) (Kobbing et al., 2013). However, lower P concentrations have been reported
503 (1 g P/kg) where soil P concentrations were only up to 600 mg/kg (Ge et al., 2017), lower than

504 observed in the samples on the SLMs. *Typha* is reported (Geurts et al., 2020) to have the
 505 highest removal rates of P under high N availability, however, based on our 1 g-P/kg peat
 506 concentrations, a 1% dry matter P content and a 10 t/ha/yr dry weight crop biomass (as
 507 shown by our data) it would take an estimated 100 *Typha* harvests to remove legacy P (~ 1 kg
 508 P m⁻²) from the peat body on the SLMs and several hundred harvests at the lower end growth
 509 rates report for *Phragmites* and also *Typha* (Geurts et al., 2020).

510 Figure 6 shows a schematic representation of the effects of rewetting on P mobilization in the
 511 water column and peat body. Following rewetting the previously oxygenated surface layers
 512 of peat become anoxic. The resulting redox conditions increase the mobility and
 513 bioavailability of P reducing in-situ peat P concentrations (Schindler and Comber, 2021). The
 514 absence of O₂ also results in the denitrification of mineralized N.



515

516 **Figure 6. Schematic representation of phosphorus and nitrogen exchange on rewetted of**
 517 **fen peatland**

518 Denitrification caused by rewetting combined with plant uptake can result in N becoming a
 519 plant growth-limiting nutrient. If N becomes limiting in the water body and, inflow waters can
 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
 522 in the diversity of emergent wetland plants irrespective of the availability of P. Removal of
 523 available P and N from the water column can be achieved by the placement of paludiculture
 524 crops in inflow waters along main drains to act as nutrient buffer zones (Walton et al., 2020)
 525 where high nutrient waters drain from adjacent intensively managed agricultural land.

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

535 More research is required to adequately predict potential impacts from hydrological
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
538 interface, oxygenation of surface layers may result in the excessive growth of floating *Lemna*
539 in unshaded water environments where rewetting has increased the mobilization of P
540 (Peeters et al., 2013). Invasive floating aquatic plants such as *Azolla*, which is a problem
541 species in the SLMs have N fixing capabilities and therefore may not be controlled by N
542 limitation alone.

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-nutriented	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 concentrations/internal P loading	Ecological considerations/impacts	Additional Pros/Cons
<p>Raise water levels and more closely mimic natural hydrological processes</p>	<p>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.</p>	<p>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 (e.g. egrets, herons, bittern, storks) may do well in this new environment.</p>	<p>Reduction of CO₂ emissions from drained peat is a clear benefit. It should also be noted that methane (CH₄) emissions are typically higher when water levels are above the peat surface, although CH₄ emissions are more than offset by increased CO₂ 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.</p> <p>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</p>

Intervention	Likely effects on P concentrations/internal P loading	Ecological considerations/impacts	Additional Pros/Cons
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	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

Intervention	Likely effects on P concentrations/internal P loading	Ecological considerations/impacts	Additional Pros/Cons
		ditch habitats, but may be negative if ditch infilling to restore peat is also an objective. Potentially conflicting objectives need to be reconciled.	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.

545 **5. Conclusions**

546 The data presented in this paper clearly indicates P legacy and ongoing P pollution of the
547 Somerset Levels Ramsar site. This can only be remediated via a combination of reducing the
548 input concentrations to below the ditch quality standard (currently 0.1 mg-P/L but this may
549 need to be even lower) and removing the legacy P pollution locked up in the peat and
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
552 SLMs, this is unlikely to be sufficient for site restoration given inflow water pollution from
553 agriculture and ongoing water level and flood risk management approaches.

554 A more sustainable vision for the SLMs would include naturally functioning wetland
555 ecosystems with nutrient buffer zones, lower internal water conveyance and a greater
556 proportion of wetland habitats that are fen or wet woodland. Whilst in the short-term, this
557 could have some negative implications for habitat diversity and specialist wet grassland
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
561 fully evaluate the biogeochemical implications of this management option for the SLMs.

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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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