

1 **Assessing the risk of phosphorus transfer to high ecological status rivers:**
2 **Integration of nutrient management with soil geochemical and hydrological**
3 **conditions.**

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21 management, soil type, organic matter.

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23 Abstract

24 Agriculture has been implicated in the loss of pristine conditions and ecology at river sites
25 classified as at 'high ecological status' across Europe. Although the exact causes remain
26 unclear, diffuse phosphorus (P) transfer warrants consideration because of its wider
27 importance for the ecological quality of rivers. This study assessed the risk of P loss at field
28 scale from farms under contrasting soil conditions within three case-study catchments
29 upstream of near-pristine river sites. Data from 39 farms showed P surpluses were common
30 on extensive farm enterprises despite a lower P requirement and level of intensity. At field
31 scale, data from 520 fields showed that Histic topsoils with elevated organic matter contents
32 had low P reserves due to poor sorption capacities, and received applications of P in excess of
33 recommended rates. On this soil type 67 % of fields recorded a field P surplus of between 1
34 and 31 kg ha⁻¹, accounting for 46 % of fields surveyed across 10 farms in a pressured high
35 status catchment. A P risk assessment combined nutrient management, soil biogeochemical
36 and hydrological data at field scale, across 3 catchments and the relative risks of P transfer
37 were highest when fertilizer quantities that exceeded current recommendations on soils with a
38 high risk of mobilization and high risk of transport as indicated by topographic wetness index
39 values. This situation occurred on 21 % of fields surveyed in the least intensively managed
40 catchment with no on-farm nutrient management planning and soil testing. In contrast, the
41 two intensively managed catchments presented a risk of P transfer in only 3 % and 1 % of
42 fields surveyed across 29 farms. Future agri-environmental measures should be administered
43 at field scale, not farm scale, and based on soil analysis that is inclusive of OM values on a
44 field-by-field basis.

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47 **1. Introduction**

48 Diffuse, non-point pollution remains a major threat to surface waters due to eutrophication
49 caused by nitrogen (N) and phosphorus (P) transfers originating, in part, from agricultural
50 land (Carpenter et al., 1998; EEA, 2012; OECD, 2008). In Ireland, phosphorus (P) transfer
51 from agricultural land has been asserted as the primary cause of degradation in 53 % of the
52 river water bodies that failed to achieve ‘good’ ecological status under the WFD (Byrne and
53 Fanning, 2015). However, it is difficult to make the same assertion about rivers that are at
54 risk of failing to maintain ‘high’ ecological status due to the uncertainty around the causes of
55 degradation (Irvine and Ni’ Chuanigh, 2013; Roberts et al., 2016) and also due to natural
56 variations in high status conditions (Irvine, 2004). Nevertheless, P transfer from agriculture
57 does warrant consideration given its wider importance for the ecological quality of rivers.

58 In productive agricultural systems, nutrient transfer to surface water can be conceptualized
59 along a continuum from source, via mobilization and delivery, to impact (Haygarth et al.,
60 2005). Sources of P include native soil P or P applied in excess of crop demand that can be
61 mobilized during the initial separation of P molecules from their source via geochemical
62 desorption, biological solubilisation, or physical detachment. These processes can be
63 increased under certain soil conditions and managements (Daly et al., 2001; McDowell et al.,
64 2001). From the point of mobilisation, P is transported via subsurface or surface pathways,
65 depending on soil hydrological conditions, until it is “delivered” to the water where it can
66 have an “impact” by stimulating excessive algal growth (Beven et al., 2005; Haygarth et al.,
67 2005).

68 In the European Union (EU), designations under the Water Framework Directive (WFD -
69 OJEC, 2000) include those water bodies deemed at ‘high status’, i.e. not deviating from
70 pristine or reference conditions according to ecological classifications (Pardo et al., 2012),

71 and which may be particularly sensitive to any external pressure (del Mar Sánchez-Montoya
72 et al., 2012). The number of high status water bodies varies across the EU either due to a
73 natural dearth of water body types or due to ubiquitous impacts that reduce the percentage
74 number overall (Table 1 - EEA, 2012). Ireland and Austria stand out as particularly rich
75 member states in terms of both the number of water bodies (7,401 and 5,670, respectively)
76 and percentage at high status (both at 18%). The WFD requires member states to maintain
77 high status water bodies and convergence to at least good status for all other water bodies
78 using the same harmonised ecological classification system (ECOSTAT, 2003). This
79 harmonization is based on all EU member states calibrating biological indicators with
80 physico-chemical parameters and based on river typologies.

81 A key concept underlying the WFD is the integration of existing water policies such as the
82 Nitrates Directive (OJEC, 1991) which is designed to improve water quality by regulating on-
83 farm nutrient use and reduce nutrient and sediment losses to water. To transpose this
84 complex legislation into law, each EU member state must implement measures through a
85 Nitrates Action Programme (NAP) either in specific zones or on a whole territory basis
86 (OJEC, 1991). For example, Ireland's NAP sets limits on P use and requires farms to
87 maintain a zero farm-gate P balance with optimised soil test P (Morgan's $P < 8 \text{ mg l}^{-1}$) values
88 across the farm (SI 31 of 2014). On intensive farms these measures have resulted in reducing
89 P balances at farm scale and reducing the occurrence of fields with excessive soil test P
90 values; however, they fail to account for soil geochemical and hydrological conditions that
91 vary spatially across the agricultural landscape. High ecological status river catchments
92 located in upland areas with a mosaic of mineral and organic soils support a mix of extensive
93 and intensive farm enterprises (Irvine and Ni' Chuanigh, 2013; White et al., 2014). Whilst
94 current legislation regulates nutrient use at farm scale, agri-environmental measures in these

95 areas need to take account of soil geochemical and hydrological variation at smaller scales
96 (field) to minimize nutrient losses to water and maintain high ecological status.

97 Grassland agriculture in Irish high status catchments varies greatly in extent from being
98 completely absent to covering up to 88 % of catchment areas. The latter catchments are at the
99 highest risk of failing to maintain high ecological status (Roberts et al., 2016). However,
100 several studies have found a high proportion of fields on low intensity farms with excessive P
101 levels due to surplus P applications over time (Gibbons et al., 2014; Schulte et al., 2009).
102 This risk of P transfer would be elevated further when P surpluses are applied to P saturated
103 soils and soils with poor P retention capacities. Grassland soils that cannot assimilate added P
104 and build up P reserves for draw down by a growing crop have been characterised in Ireland
105 and elsewhere (refs). These include soils with a high % of organic matter (OM) in the surface
106 horizon and categorised here as Histic topsoils. High organic matter content in the surface
107 horizon of soils occludes sorption sites on clay minerals and competes with P for sorption,
108 thereby reducing the soils P sorption capacity and P retention. The implications for P
109 management on these soils centers on their low P sorption capacity which prevents build-up
110 of P reserves onto the soil matrix. Instead, P remains in the soil solution and added fertiliser P
111 is susceptible to leaching and runoff (Daly et al., 2001; Guppy et al., 2005). In addition, if
112 these soils coincide with conditions that promote saturation excess overland flow such as
113 high water tables, large contributing areas and shallow slopes (Beven and Kirkby, 1979;
114 Holden, 2006), there is likely to be a high potential for P transport to streams. However, the
115 importance of these factors have not always been fully appreciated in previous risk
116 assessments or nutrient management approaches for P transfer, which may have, in part, led
117 to the perception that only intensive agriculture with high fertilizer inputs and high stocking
118 rates and/or tillage frequencies can pose a threat to aquatic ecosystems (Doody et al., 2014,
119 2012; Watson et al., 2009).

120 Building on this background the objectives of this research were to 1) characterise the
121 geochemical and hydrological setting for agriculture in high status catchments in Ireland, and
122 2) assess current nutrient management at field scale and the relative risk of P loss under
123 different biogeochemical and hydrological condition. To address these objectives, field-scale
124 nutrient management data and soil geochemical and hydrological characteristics were
125 collected from 520 fields surveyed within three case study catchments. Field-scale P
126 requirements, P applications, and P balances were examined along with field characteristics
127 and combined in a field based risk assessment scheme to explore the extent to which current
128 nutrient management practice poses a risk in high status catchments.

129

130 **2. Methods**

131 *2.1 Characterisation of high status catchments*

132 Three case study catchments were selected from an existing database on 508 high status
133 catchments delineated in Roberts et al. (2016). Catchment selection used a simple multi-
134 criteria decision approach to represent agriculture on the dominant soils across the wider high
135 status catchment population. Of the 508 high status catchments those that had monitoring
136 sites situated below 200 m in elevation and on river segments with Strahler stream orders
137 ranging from 2 to 5 were selected for further analysis. Further analysis was initially by K-
138 means cluster analysis, which aims to partition observations into a number of pre-specified
139 clusters in which each observation belongs to the cluster with the nearest mean. In this case,
140 K-means cluster analysis was used to identify the three main groups of catchments based on
141 soils mapped and categorised in Teagasc/EPA Indicative Soils Map
142 (<http://gis.epa.ie/GetData/Download>). These were characterised by a high percentage cover of
143 either, poorly drained acid mineral/peaty mineral soils, well-drained acid mineral soils, and

144 peat soils as previously mapped in the Teagasc/EPA soils and subsoils map, and these are
145 listed in Table 2. To help select the three study catchments and to ensure they were
146 agriculturally pressured, the 356 catchments were ranked by percentage agricultural cover
147 three times, each time in combination with one of the three soil classes. The final three
148 catchments were selected by expert judgement by avoiding excessively large or small
149 catchments, catchments in inaccessible locations, and those with large urban areas or
150 industrial workings; these were the River Allow in County Cork, the River Black in County
151 Galway/Mayo and the River Urrin in County Wexford (Figure 1).

152 The upstream catchment of the River Allow is dominated by poorly drained surface water
153 gleys underlain by siliceous drift and shale bedrock with blanket peat in the upland areas
154 toward the river's source (Figure 2). The catchment of the River Black is dominated by well
155 drained brown earth mineral soils underlain by calcareous drift and limestone geology but
156 interspersed with large areas of lowland raised bog peat (Figure 2). Situated in the south east,
157 the River Urrin catchment is dominated by well drained acid brown earth, mineral soils
158 underlain by siliceous drift and shale and slate geology, blanket peat exist in the upland areas
159 near to the source of the river (Figure 2).

160 Land use is dominated by grassland agriculture which covers 66, 63 and 41 % of the Rivers
161 Allow, Black and Urrin catchments, respectively. For nutrient management purposes, grazing
162 intensity in Ireland is calculated as the total annual nitrogen (kg) excreted by grazing
163 livestock averaged over the net grassland area (grazing and silage area). 85 kg of organic
164 nitrogen (ON) excreted annually equates to 1 livestock unit per hectare in the traditional
165 measurement. Catchment grazing intensities are 115, 90 and 61 kg ON ha⁻¹ yr⁻¹, which
166 equates to approximately 18, 14 and 9 kg organic P ha⁻¹ yr⁻¹, for the Rivers Allow, Black and

167 Urrin, respectively. The grassland coverage and stocking rate are lower in the River Urrin
168 catchment due to the presence of arable land (30 %) (Figure 2).

169

170 *2.2 Farm surveys*

171 In total 10, 13 and 16 farm surveys were completed in the Allow, Black and Urrin
172 catchments, respectively, to gather soil samples and information on farm and field nutrient
173 management practices. These farms were selected to represent the range of farming systems
174 present. The farms selected were also spatially distributed across the catchments to reduce the
175 possibility for spatial auto-correlation between farm and field-scale measurements. Farmers
176 were initially contacted through a national advisory network (Teagasc, The Irish Agriculture
177 and Food Research Authority) and then through word of mouth, which meant that some
178 participating farmers had no prior contact with advisory services or researchers. Across the
179 39 farms surveyed, a total of 520 fields (195 in the Allow, 112 in the Black, and 213 in the
180 Urrin catchments), were sampled and records of P management were assessed. This data
181 represented 11, 3 and 9 % of agricultural land in the rivers Allow, Black and Urrin
182 catchments being surveyed, respectively. Thus the data reported here is not on a whole
183 catchment basis, rather on a whole-farm basis and field-by-field basis on farms under the
184 unique biogeochemical and hydrological settings of the selected catchments.

185 Soil samples were collected from each field over the 2014/2015 winter whilst ensuring at
186 least six weeks since the last fertilizer application to allow suitable time for equilibration of
187 fertilizer P with the soil (Agbenin and Tiessen, 1995; Vadas et al., 2007). However, farmers
188 reported spreading 90 % of fertilizers during spring and summer leaving ample time for
189 equilibration before sampling. Spreading of fertilizers was almost always by surface

190 broadcasting but arable farmers often incorporated fertilizers into the soil and occasionally
191 placed fertilizer granules with seeds. The fields were sampled by collecting at least 20 soil
192 cores using a bucket sampler to 10 cm depth in a 'W' pattern across the field avoiding
193 gateways and dung patches (SI 31, 2014). The cores were then composited, dried at 40 °C
194 and sieved to 2 mm prior to laboratory analysis for chemical properties. Morgan P was used
195 to estimate soil P (plant available) status, which involves extracting 6.5 ml of soil with a
196 buffered (pH = 4.8) acetate-acetic acid reagent at a 1:5 (v/v) soil to solution ratio for 30 min
197 and then analysed colorimetrically using a Camspec UV-VIS spectrometer (Byrne 1979;
198 Morgan 1941). Soil pH was determined in deionised water at a 1:2 soil to solution ratio using
199 a Jenway pH meter with glass electrodes. Organic matter (OM) contents were determined by
200 loss on ignition using 5 g samples ignited for 4 hours in a Northerm muffle furnace at 400 °C.
201 Total P was determined on 1 g sample suspended in 2 ml deionized water followed by a
202 reagent combination of 7.5 ml nitric acid (69 %) and 2.5 ml concentrated hydrochloric acid.
203 Sample digestion was carried out using microwave digestion using MARS6 microwave after
204 which samples were filtered and analysed using an Agilent inductively coupled plasma
205 spectrometer to determine TP content. This method (Kingston and Haswell, 1997) was
206 performed on a subset of samples categorised as Histic topsoil ($n = 62$) and mineral ($n = 88$)
207 across all catchments.

208

209 *2.3 Field scale nutrient management*

210 To calculate field P requirements, use and balances, records collected from each field
211 surveyed and included, organic and chemical fertilizer inputs, farm stocking densities and
212 feed concentrate use were obtained from the farmers through a semi-structured interview and
213 integrated with soil test P results to estimate field P requirements, applications and balances.

214 These were based on current advisory fertilizer guidelines, which form the basis of Ireland's
215 National Action Programme (NAP) of measures to regulate fertilizer use for the Nitrates
216 Directive (Coulter and Lalor, 2008). Morgan's soil P is used in Ireland for agronomic advice
217 with levels categorised as indices; 1 (deficient), 2 (low), and 3 (agronomic optimum) and 4
218 (excessive) (Coulter and Lalor, 2008). The magnitude of the rates prescribed are dependent
219 on this P index and also on factors such as farming system, intensity, organic matter contents
220 and crop type (Coulter & Lalor 2008) the limits are described in footnotes to Table 4. The P
221 requirement for each field is then determined as the rate identified minus feed concentrate P
222 used per hectare of the farm. A P balance can then be calculated by then subtracting the
223 actual amounts of P applied to individual fields as organic and chemical fertilizers to give the
224 final balance (Murphy et al., 2015; Wall et al., 2012). These parameters were also calculated
225 at farm scale to examine farm gate P balances for each farm surveyed.

226 Evidence of poaching, the damage caused to turf by the feet of livestock, was noted whilst
227 sampling the fields. These observations were then considered in relation to soil drainage
228 properties as inferred from the Irish EPA/Teagasc Soils and Subsoils Map Indicative Soil
229 Map (<http://gis.epa.ie/GetData/Download>).

230 Topographic wetness index (TWI - Beven and Kirkby, 1979) was calculated in ArcGIS and
231 considered as a factor promoting P transport since slope and contributing area are key for
232 generating saturation excess overland flow, a common generation process in temperate
233 agricultural landscape settings (Heathwaite et al., 2005; Peukert et al., 2014). The
234 topographic wetness index at which soil saturation actually occurs varies between studies due
235 calculation methods or natural factors such as soil water storage capacity and preferential
236 flow pathways, but typically occurs above the median value of indices across study areas
237 (Leh et al., 2008; Rodhe and Seibert, 1999). For this reason, maximum TWI was determined

238 for each field and the arbitrary threshold value for separating the fields with the driest and
239 wettest areas was the 75th percentile of TWI values across the three catchments (hereafter
240 termed 'runoff potential').

241

242 *2.4 Field P risk assessments*

243 Soil biochemical data, hydrological condition and agronomic management data for 520 fields
244 were combined into a risk assessment scheme was to assess the relative risk of edge-of-field
245 losses of P from each field based on source, mobilization and transport factors. The risk
246 assessment included the field P balance as the source factor, percentage organic matter and
247 evidence of poaching or erosion as mobilisation factors, and topographic wetness index
248 (TWI) and surface drainage as transport factors and are described in Table 3. Each factor
249 was assigned a weighting in terms of relative risk and combined to produce a risk score for
250 each field. Previous field risk assessments typically only use the absolute amount of fertilizer
251 applied to estimate the risk due to applications (e.g. Hughes et al., 2005; Lemunyon and
252 Gilbert, 1993; Sharpley et al., 2003), which may have previously biased source risks towards
253 intensive farms. However, because the amount of P required to replace plant offtakes (soil P
254 requirement) varies depending on field management, a P balance approach that takes account
255 of this may be a more accurate indicator of over-application of P. Percentage organic matter
256 was included as a mobilisation risk factor as those soils with more than 20% organic matter
257 have a reduced capacity adsorb any excess P applied and build up P reserves.

258 Assigning the risk from surface drainage involved summing the drainage density (total length
259 as percentage of field perimeter) of streams, sloping surface ditches (>5 % slope) and flat
260 surface ditches (<5 % slope), on the premise that higher drainage density indicates greater
261 connectivity and a reduced potential for overland flow to re-infiltrate (Shore et al., 2013).

262 Streams were given the highest weight (1) to reflect the risk of fields having a direct

263 connection, sloping ditches were given an intermediate weighting (0.6) and flat ditches were
264 given the lowest (0.3) as some sediments and P may be retained (Shore et al., 2015). Those
265 fields scoring above the 75th percentile of drainage risk scores were assigned a high risk for
266 surface drainage due to increased connectivity (Table 3).

267 Transport factors were given equal or lower weightings than source factors in many previous
268 assessments (Lemunyon and Gilbert, 1993; e.g. Magette et al., 2007), but here overland flow
269 risk was given the highest weighting to reflect the realisation that hydrology may be
270 dominant in P transfer (Buda et al., 2009; Jordan et al., 2012; Mellander et al., 2015).
271 Conversely, the connectivity risk due to surface drainage features was given a lower
272 weighting as fields can still be connected in the absence of these features. Finally, to
273 determine the overall risk score for each field, the risk score for each factor was multiplied by
274 the factor weighting, the resulting risk scores for mobilisation factors were summed as were
275 those for transport factors and then the resulting risk score for source, mobilisation and
276 transport were multiplied in ArcGIS.

277

278 *2.5 Data and statistical analysis*

279 To examine the differences in nutrient management on fields with different biogeochemical
280 and hydrological properties, statistical linear modelling included 'OM' and 'TWI' with two
281 levels each as fixed factors. However, the data were arranged in a hierarchical structure as
282 fields were nested within farms and farms were nested within catchments. This design often
283 leads to spatial dependence, for example, fields in one farm or catchment are more similar
284 among each other in P management than to fields on another farm or catchment due to spatial
285 location. To account for this spatial structure, 'farm' and 'catchment' were included in the
286 model as random factors in a nested structure to separate their effects from those of OM and

287 TWI. An interaction term was also included to test whether P management on fields with
288 differing OM contents and TWI values varied depending on the catchment. All analyses were
289 carried out using R statistical software (Version 3.2.2) with the 'nlme' and 'Lme4' packages
290 (Bates 2010; Pinheiro et al. 2017). Results were considered significant when probability
291 values were equal to or less than 0.05.

292 **3. Results**

293 *3.1 Farm scale nutrient management planning within the case study catchments*

294 Farm scale data are presented in Table 4. The farms surveyed in the River Black catchment
295 ranged in size from 17 to 56 ha with an average farm size of 34 ha and were limited to mixed
296 cattle and sheep farms with a low average grazing intensity (96 kg ON ha⁻¹ ranging from 57
297 to 129 kg ON ha⁻¹). This was in contrast to the larger farm size and greater enterprise
298 diversity observed in the Allow (dairy enterprises and cattle enterprises ranging in size from
299 11 to 84 ha with an average size of 46 ha and grazing intensity of 155 kg ON ha⁻¹ ranging
300 from 69 to 243 kg ON ha⁻¹) and River Urrin catchments (dairy, cattle, cattle and sheep,
301 arable, and arable and sheep farms ranging in size from 15 to 78 ha with an average size of 39
302 ha and average grazing intensity of 154 kg ON ha⁻¹ ranging from 43 to 250 kg ON ha⁻¹).

303 The results from the farm surveys revealed that none of the ten farmers participating in the
304 river Black catchment had up-to-date nutrient management plans based on soil testing,
305 whereas 8 of the 13 and 11 of the 16 farmers surveyed in the Allow and Urrin catchments,
306 respectively, did. This was mainly because dairy farmers were farming at grazing intensities
307 above 170 kg ON ha⁻¹ and soil testing is mandatory at this intensity. This was reflected in
308 their farm gate P balances in which most of the farms in Allow and Urrin catchments
309 recorded negative P balances (Table 4). In contrast, 6 of the 10 farms in the Black catchment
310 recorded positive farm gate P balances, despite a lower P requirement and level of intensity at

311 farm scale. At this scale, the P requirement was lowest for farms in the Black catchment, and
312 highest for those in the Urrin catchments, possibly due to the presence of cropping systems in
313 the Urrin which have higher P requirements for arable crops than grassland. Despite good
314 uptake of soil testing on farms in the Allow and Urrin catchments, soil pH was suboptimum
315 in 89 % of surveyed fields and the distribution of P around the fields within farms according
316 to nutrient guidelines was poor in all catchments, indicating poor adoption and
317 implementation of plans where they existed.

318

319 *3.2 Field scale soil P and P management*

320 Nutrient management and soil data at field scale are presented in Table 4 and follow a
321 broadly similar pattern to farm scale observations in P balances and requirement. Compared
322 to the other two catchments, fields in the Black catchment had lower P requirements largely
323 due to lower grazing intensities, as mentioned earlier, but also because of the presence of
324 Histic topsoils on these farms. These soils are characterised with poor P retention and
325 sorption capacities, with $> 20\%$ OM in the top 10 cm as previously reported by Daly et al.
326 (2001). Soil OM analysis allowed for the identification of these fields across the farms
327 surveyed.

328 Using the complete field dataset, Morgan P, P applications, P requirement and P balance
329 were delineated for both mineral ($\leq 20\%$ OM) and Histic topsoils ($> 20\%$ OM) for statistical
330 linear modelling and these values are displayed in Table 5. Although the surveyed fields
331 represented only a relatively small sample of fields from the catchments, the observed
332 differences in P management on fields with delineated as mineral and Histic topsoil (based
333 on means and standard errors) were validated statistically by linear modelling. The P

334 requirement of the fields dominated by Histic topsoils were significantly lower than for those
335 dominated by mineral soils because of lower grazing intensities, and because of limitations
336 on P applications on this soil type. Fields characterised as Histic topsoils have lower P
337 recommendations than mineral soils and current recommended P applications on Histic
338 topsoils is limited to application that replace P removed in crop offtakes, known as
339 'maintenance rates'.

340 Despite this, these fields received applications in excess of the advised maintenance rates and
341 hence had increased and largely positive P balances (Table 5). When nutrient management is
342 displayed by OM contents within each catchment (Figure 3) the highest number of Histic
343 topsoils soils were found in the River Black catchment indicating highest risk of P
344 mobilization from farms under these catchment conditions. Across the fields surveyed in the
345 Black catchment, % OM ranged from 8 to 91 %, with 46 % of fields surveyed categorized as
346 Histic topsoils with > 20 % OM. The absence of field-by-field soil testing to identify parts of
347 the farm where Histic topsoils occur coupled with a lack of nutrient management planning,
348 led to over applications of P which resulted in positive farm gate and field P balances in the
349 Black catchment. Across the 10 farms surveyed in this catchment, 65 % of fields with Histic
350 topsoils recorded field P balances, in surplus, ranging from 1 to 31 kg ha⁻¹.

351 Statistical analysis also indicated significantly higher Morgan's P values recorded in Histic
352 topsoils (Table 5) compared to mineral soils with < 20 % OM. In the subset of soils analysed
353 for total P, Morgan P results for Histic topsoils soils ranged from 1.4 to 40.3 mg l⁻¹ with a
354 mean value of 9.8 mg l⁻¹ indicating higher P status in these soils compared to mineral soils
355 whose values ranged from 0.9 to 29.5 mg l⁻¹, with a mean of 4.9 mg l⁻¹. High Morgan's P
356 values typically indicates build-up of P with values above 8 mg l⁻¹ indicative of elevated soil
357 P and high P reserves in mineral soils. However, TP concentrations for Histic topsoils ranged

358 from 65 to 1235 mg l⁻¹ (mean: 505 mg l⁻¹), lower than concentrations for mineral soils which
359 ranged from 308 to 1754 mg l⁻¹ (mean: 797 mg l⁻¹). In addition, TP and Morgan's P were
360 correlated in mineral soils ($r = 0.84$, $P < 0.001$), however there was no significant correlation
361 (Pearson) between P parameters values in Histic topsoils ($r = 0.00$, $P > 0.05$) (Figure 4). These
362 findings indicate a lack of accumulation as P reserves in Histic top soils due to their low
363 sorption capacities and P retention. This indicates that Morgan's P test is over-estimating P
364 availability and accumulation, possibly because organic P forms are hydrolysed by the acid
365 matrix of the reagent. In addition, it is suggested here that soluble organic matter in the
366 Morgan's extract may cause interference with the colorimetric step which affects the
367 accuracy of the test for agronomic recommendations. Morgan P test is therefore not
368 appropriate for soils where % OM > 20 at the surface 10 cm, and does not provide an
369 accurate reflection of P status and for P balance estimates in nutrient management planning

370

371 *3.3 Soil hydrological conditions influencing P loss risk*

372 The mobilisation potential associated with poaching was lowest in the extensively farmed
373 River Black catchment since only one of the surveyed fields showed clear evidence of
374 poaching. However, 11 and 6 % of the fields surveyed in the River Allow and Urrin
375 catchments exhibited evidence of poached soils, respectively; typically occurring around
376 gateways, feeding and drinking troughs, and points where cattle could access the stream.

377 Specific field survey data were also investigated by TWI indices which theoretically
378 estimated the driest and wettest fields. Field data was separated by TWI and data for Morgan
379 P, P requirement, P applied and P balance for the driest and wettest soils are shown in Table
380 5. Statistical linear modelling indicated that in the overall data and within individual

381 catchments, Morgan P, P requirements, P use, and P balances were similar on fields with
382 driest soils as they were on fields with the wettest soils, as confirmed by probability values
383 greater than 0.05 for main effects and interactions (Table 5). When calculated at field scale,
384 these estimates indicated that the river Black catchment showed the highest number of fields
385 with a high runoff potential ($n = 54$) followed by the Allow catchment ($n = 48$) and then the
386 Urrin catchment ($n = 30$). When calculated at whole catchment scale, TWI means and
387 medians also followed this same order as above. Compared to the other two catchments,
388 slopes are relatively shallow and contributing areas large in the River Black catchment, and
389 the large areas of lowland raised bog are also indicative of wet conditions. In both the Allow
390 and Urrin catchments, where slopes were steeper, wetness indices were generally highest
391 around tributary streams, and in the Allow catchment also around the shallow slopes of the
392 flood plain of the main stem of the river, a landscape feature that was much less defined in
393 the Urrin catchment.

394 Artificial and natural surface drainage features also increased P transfer risk by potentially
395 increasing connectivity between any overland flow generated and the stream. As a result, 48,
396 37 and 18 % of fields surveyed in the Rivers Allow, Black and Urrin catchments,
397 respectively, achieved high drainage risk scores in the assessment. Risks were most elevated
398 in the River Allow catchment due to shallow ditches, steep ditches and streams surrounding
399 an average of 6.3%, 4.0% and 7.3% of field perimeters, respectively. There were no steep
400 ditches observed in the River Black catchment, but an average of 12.4 and 5.3% of field
401 perimeters were bordered by shallow ditches and streams, respectively. Although the artificial
402 drainage density was extremely low in the River Urrin catchment the overall risks were
403 elevated due to an average of 3.9% of field perimeters being bordered by streams.

404

405

406 3.4 Risk Assessment Scores

407 Fields surveyed in the River Black catchment had the highest median and widest range of
408 field risk scores, followed by fields in the River Allow Catchment and then those in the River
409 Urrin catchment (Figure 5). The highest risks were assumed where elevated P sources (P
410 index 4 or positive P balances), a high potential for mobilisation (Histic soils or poached
411 soils) and a high potential for transport (high TWI indices indicating high runoff potential)
412 combined to form critical source areas, a situation that occurred in 3, 21 and 1 % of surveyed
413 fields in the Allow, Black and Urrin, respectively. Inside those areas mean values of
414 Morgan's P, P balance, OM and TWI were 11.8 mg l⁻¹, 7.5 kg ha⁻¹, 44.2 % and 17.9,
415 respectively, compared outside of those areas where they were 5.1 mg l⁻¹, -6.0 kg ha⁻¹, 13.9 %
416 and 14.1, respectively.

417

418 4. Discussion

419 Based on a carefully selected series of case study of catchments, this study shows that
420 agriculture in pressured high ecological status catchments is not limited to intensive farming
421 but instead exists at a range of intensities and systems that vary greatly within and between
422 catchments. In this present study the spatial analysis of high status catchments in Ireland
423 revealed a mix of well-drained and poorly drained mineral soils and Histic topsoils with
424 elevated % OM values at the surface. In this data, OM ranged from 5 % to 91 % which has
425 implication for the assimilation and retention of added P and the risk of P loss to water. Risks
426 of P transfer were present across these ranges, but were particularly high within the River
427 Black catchment, which contained the lower intensity drystock farms. Schulte et al. (2009)
428 uncovered a similar situation in the Lough Melvin catchment, Northern Ireland, a catchment

429 with a grazing intensity of approximately 41 kg ON ha⁻¹, where 31 % of fields surveyed
430 posed a high risk of P transfer (using the risk assessment approach of Magette et al. (2007)).

431 *4.1 Nutrient management practice in high status catchments*

432 The adoption of soil testing and farm nutrient management plans also varied, with none of the
433 farms in the most extensively farmed Black catchment currently using soil testing or nutrient
434 management planning as a tool to manage nutrients, whereas most of the farms in the more
435 intensively farmed catchment had adopted nutrient management planning based on soil
436 testing.

437 Phosphorus applications above the recommended rates were common in the extensively
438 managed River Black catchment on Histic topsoils as indicated by positive P balances. While
439 other studies indicate that farm-scale P balances in Ireland have declined since the
440 introduction of the Nitrates Directive measures (Buckley et al., 2016; Mihailescu et al., 2015;
441 Ruane et al., 2043), the results of this study showed that positive P balances occurred when
442 nutrient management failed to take account of soil type, specifically, soils with OM > 20 %
443 within the agronomic depth for soil sampling. In line with previous studies (Wall et al., 2012)
444 poor nutrient management and the absence of on-farm nutrient management planning gave
445 rise to poor distribution of nutrients across the farm resulting in fields with excessively high P
446 values receiving P applications. Previous studies focusing on intensively farmed agricultural
447 catchments, with predominantly mineral soils, have demonstrated that elevated soil P levels
448 can be corrected with regular soil testing and nutrient management planning. However, this
449 approach will only work in high status catchments if soil analysis for agronomic
450 recommendations includes % OM testing on a field-by-field basis so that Histic topsoils can
451 be identified from mineral soils and on-farm nutrient management tailored for soil type.

452 4.2 Soil testing on mineral and Histic topsoils

453 Nutrient management planning and the regulation of P use on farms is inextricably linked
454 with soil testing, however, this has resulted in an over-reliance of testing for P and pH only to
455 guide nutrient applications and record farm-gate P balances. Relying on Morgan's P values
456 alone, without including organic matter values, masks the effect of soil type on recommended
457 P rates, P balance and P loss risk as illustrated by the data collected in this study. Where soil
458 samples exhibit > 20 % OM current nutrient management guidelines recommend P
459 applications that replace crop offtakes, and prohibits build-up rates on these soils, due to poor
460 P sorption capacities (Coulter and Lalor, 2008; Daly et al., 2001). An important step towards
461 accounting for this issue has been the incorporation of OM into fertilizer recommendations in
462 Ireland and in other European countries (Amery and Schoumans, 2014; Coulter and Lalor,
463 2008; Jordan-Meille et al., 2012). In Ireland rates of P that replace P removed in crop
464 offtakes, known as maintenance rates are permitted, however, the occurrence of Histic topsoils
465 across farms in high status catchments will only be identified by soil sampling and analysis
466 that includes % OM as a parameter. Soil analysis that does not include % OM will not allow
467 for delineation of Histic topsoils on the farm and will lead to misguided over-applications of
468 P to these soils. For mineral soils P applications are guided by soil test P levels and
469 corresponding P index, however, as there is currently no P index system for Histic topsoils,
470 rates of P applied rely on the inclusion of % OM in soil analytical suites.

471

472 Positive P balances on Histic topsoils occurred in 67 % of fields surveyed and ranged from
473 surpluses of between 1 and 31 kg P ha⁻¹. The reasons for this were two-fold: Firstly, the
474 absence of soil testing to identify the occurrence of these soils across the farm and secondly,
475 the lack of nutrient management plans to guide P application meant that P was applied in

476 excess of recommended rates, often at rates typically applied to build-up soil P reserves on
477 mineral soil. Losses of applied P from these soils can be high, for example, McDowell and
478 Monaghan (2015) studied P losses from managed pastures on podzol and peat soils in New
479 Zealand. Although P loads from the podzol soils were high ($>8 \text{ kg ha}^{-1}$) over the 18 month
480 study period, they were extreme from the peat soil (80 kg ha^{-1}) equalling 89 % of the fertilizer
481 P applied. Previous studies in Ireland and elsewhere (Daly et al., 2001; Guppy et al., 2005)
482 have characterised these soils with low P sorption capacities and poor P retention due to
483 competitive reactions between organic matter and P on the surface of clay minerals. This
484 means that these soils cannot build up P reserves and retain added P through the physico-
485 chemical reactions that typically happen in mineral soils. The results from this study
486 demonstrated an absence of accumulation in total P concentrations for Histic topsoils despite
487 the application of P build-up rates indicative of these soils inability to build up P reserves and
488 their potential for high P losses of applied P (Simmonds et al., 2015).

489

490 *4.3 Field Soil hydrological conditions in high status catchments*

491 The Allow catchment recorded a relatively higher incidence of soil disturbance by poaching
492 of soil by livestock. Amongst other effects poaching of the soil damages the protective cover
493 that would otherwise be provided by vegetation and therefore leaves the soil vulnerable to
494 erosion (Bilotta et al., 2008; Haygarth et al., 2012; McDowell et al., 2003). For example, on a
495 hillslope in the UK the removal of the vegetation cover through severe poaching led to an
496 increase in the rate of suspended sediment and total phosphorus delivery in overland flow by
497 30 and 16 times, respectively (Heathwaite et al., 1990). Poorly drained soils are most
498 susceptible (Creamer et al., 2010; Heathwaite et al., 1990), and fields in the Allow catchment

499 where these soils were common and grazing intensities high, showed the greatest incidence of
500 poaching, increasing the risk of sediment delivery into streams and rivers.

501 Shallow sloping topography and large contributing areas promote saturation excess overland
502 flow (Agnew et al., 2006; Beven and Kirkby, 1979), which is further exacerbated by poorly
503 drained soils (Buda et al., 2009; Needelman et al., 2004). In terms of P transfer, these
504 hydrological factors are thought to over-ride the effects of management. For example, Buda
505 et al. (2009) measured P in runoff from small plots and found that overland flow volumes and
506 P loads were larger at foot slope positions compared to at upslope positions where legacy soil
507 P concentrations and therefore P concentrations in runoff were high, but runoff volumes were
508 much lower. This has also been observed at the catchment scale, where catchments with
509 flashy hydrographs, yet with lower P sources, showed the greatest stream P loads (Basset,
510 2010; Jordan et al., 2012; Mellander et al., 2015). Despite this importance, no European
511 country's fertilizer guidelines currently consider soil hydrological conditions as a risk factor
512 (Amery and Schoumans, 2014; Jordan-Meille et al., 2012), and hence field P management
513 appeared to be similar on the driest soils as it was on the wettest soils. Although outside of
514 nutrient management recommendations, current Irish NAP measures discourage the
515 spreading of fertilizers on wet and sloping areas of the farm, but there is currently no formal
516 method to identify such areas and adjust management accordingly.

517 *4.4 Field scale risk assessment in high status catchments*

518 Across the three catchments, the assessed relative risks of P transfer from fields was higher
519 from fields located within the extensively farmed River Black catchment, as evidenced by the
520 high proportion fields where high source, mobilisation and transport potentials coincided.
521 Schulte et al. (2009) proposed a similar situation in the Irish Lough Melvin catchment with a
522 grazing intensity of approximately 41 kg ON ha⁻¹, where 31 % of fields surveyed posed a

523 high risk of P transfer due to over-application of slurry to drier fields and a resulting build-up
524 of soil P above agronomic optimum levels. These results are in contrast to the intensively
525 farmed River Urrin catchment, where the number of fields showing high risks were
526 consistently fewer for all P transfer factors individually and combined (1 % of fields
527 surveyed). Overall, these data question the perception that only intensive agriculture can pose
528 a P risk to water quality and suggests that if research and policy places more focus on specific
529 farming systems that are considered to be intensive there will be a risk of non-compliance
530 especially in the context of maintaining high ecological status at river sites. Although this
531 risk assessment served well to compare relative risk between catchments and fields, as with
532 all field scale P risk assessments, there is a great deal of uncertainty around how well the
533 measured risk actually reflects absolute risk. For example, there are a lack of data from Irish
534 studies measuring P loss from agricultural fields with which to validate risk assessments
535 (Hughes et al., 2005), the national DEM resolution was insufficient in resolution to identify
536 flow sinks created by micro-topographic features that cause overland flow to become
537 disconnected (Thomas et al., 2016) and TWI alone does not account for the soil water storage
538 capacity, which, when low, can increase overland flow risk (Quinn et al., 1995; Walter et al.,
539 2002). However, the greatest uncertainty relates to the issue of scale, and specifically, around
540 how well risks identified at field scale are realized in water quality and ecological status at
541 catchment scales.

542

543 **5. Conclusions and recommendations**

544 This study characterised the soil geochemical and hydrological properties of farms in high
545 status catchments in Ireland and examined field scale nutrient management and the relative
546 risk of P loss from fields, under different soil conditions. Low adoption of soil testing and

547 nutrient management planning on extensive farms led to increased risks of P transfer on
548 Histic topsoils when application of P sources failed to account for soil conditions that
549 promote the mobilisation and transport of P such as highly organic matter and wet soils.
550 Furthermore, the risk assessment based on fields surveyed revealed that the catchment, with
551 the highest occurrence of Histic topsoils, (wet soil) posed the greatest risk of P loss, based on
552 positive P balances and fields with high % OM. Current EU water policy measures for
553 agriculture centers on nutrient management planning and soil testing on intensive farms,
554 however, this study has illustrated the need for better nutrient use efficiency on extensive
555 grassland farms on marginalized land. To increase nutrient use efficiency and reduce P loss
556 risk and based on the results of this study the following recommendation include:

- 557 • Regular soil testing to monitor soil P and pH on should be used to optimize nutrient
558 management on mineral soils, but not be relied upon for nutrient management on
559 Histic topsoils.
- 560 • Extensive farm enterprises in high status catchments should have access to soil
561 information on % OM on a field-by-field basis. Organic matter testing at high spatial
562 resolution need only be carried out once to establish which parts of the farm are
563 comprised of mineral and Histic topsoils. This will ensure that nutrient management
564 is soil type specific and will restore P surpluses to balance at both field and farm scale.
- 565 • Hydrologically sensitive areas within high status river catchments could be delineated
566 using simple topographic indices as done here, and the timing and rates of P
567 applications tailored to account for risk, as is the case for high OM soils.
- 568 • Agricultural measures for high status catchments will need to be administered at field
569 scale (not farm scale) with the aid of appropriate soil geochemical and hydrological
570 data at this scale.

- 571 • Future agri-environmental schemes under the EU Common Agricultural Policy and
572 Rural Development Programme could consider providing % OM surveys on a field-
573 by-field basis to farms in high status catchments.

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580

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826 **Figure Captions**

827 **Figure 1.** Ireland, showing county boundaries (Republic of Ireland) and the
828 location and characteristics of the three case study catchments. Average
829 annual rainfall and temperature are Met Éireann 10 year averages.

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831 **Figure 2.** Agricultural land use (A) and soil classes (B) in the three case study
832 catchments.

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834 **Figure 3.** Mean Morgan P (A), P requirement (B), P applied (C) and P balance
835 (D) by organic matter contents within each catchment showing standard
836 error bars. The number of samples (*n*) used for summarising those variables
837 were as follows: River Allow - OM \leq 20 %, *n*=184; River Allow - OM >20

838 %, $n=11$; River Black - OM ≤ 20 %, $n=61$; River Black - OM >20 %, $n=51$;
839 River Urrin - OM ≤ 20 %, $n=211$; River Urrin - OM >20 %, $n=2$.

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841 **Figure 4.** Scatterplots of soil TP and Morgan P by organic matter (OM) contents
842 (Mineral soils: ≤ 20 % OM; Histic topsoils: >20 % OM). Pearson's r
843 correlation was only significant ($r = 0.84$, $P < 0.001$) for mineral soils.

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845 **Figure 5.** Box (25, 50 and 75 percentiles) and whisker (1.5 x interquartile range)
846 plots of the risk scores by catchment.

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877 **Table 1.** EU member state water body numbers, percentage and river length at

878 high status (EEA, 2012 – [www.eea.europa.eu/data-and-](http://www.eea.europa.eu/data-and-maps/data/wise_wfd-european-data)

879 [maps/data/wise_wfd-european-data](http://www.eea.europa.eu/data-and-maps/data/wise_wfd-european-data)).

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EU Member State	Number of water bodies	Number at High Status	Percentage at High Status	Total length	Length at High Status	Percentage at High Status
Malta	9	4	44.4	0	0	0
Slovakia	1760	487	27.7	18944	3786	20
Lithuania	1183	287	24.3	14251	2605	18.3
Croatia	1315	281	21.4	13041	1800	13.8
Austria	7401	1332	18.0	31393	4291	13.7
Ireland	5670	1012	17.8	21039	1864	8.9
Finland	6153	681	11.1	28875	4659	16.1
Sweden	23418	2043	8.7	79467	6181	7.8
Spain	5124	425	8.3	82276	5396	6.6
Slovenia	155	11	7.1	2619	168	6.4
Greece	1689	112	6.6	13030	206	1.6
France	11523	747	6.5	241684	10881	4.5
Denmark	15988	965	6.0	18842	1436	7.6
Portugal	1945	94	4.8	598575	79628	13.3
Bulgaria	759	36	4.7	25569	862	3.4
Romania	3399	145	4.3	74473	2346	3.2
United Kingdom	10961	441	4.0	99748	1653	1.7
Cyprus	260	8	3.1	2579	0	0
Latvia	470	14	3.0	7752	535	6.9
Estonia	750	12	1.6	12107	295	2.4
Belgium	560	7	1.2	9309	95	1
Italy	8614	91	1.1	78812	655	0.8
Poland	5643	52	0.9	111485	749	0.7
Germany	9863	76	0.8	126158	152	0.1
Hungary	1082	5	0.5	18802	0	0
Czech Republic	1140	0	0.0	18596	0	0
Netherlands	724	0	0.0	4757	0	0
Luxembourg	102	0	0.0	0	0	0

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884 **Table 2.** Results of K-means clustering analysis showing mean soil class
 885 coverage for the three main clusters of catchments based on soils and the
 886 overall data.

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Cluster number:	1 (n=158)	2 (n=102)	3 (n=96)	Overall (n=356)
Soil class (% coverage):				
Alluvium	2.15	1.32	3.09	2.17
Acid mineral poorly drained	26.23	11.21	11.94	18.07
Acid mineral well drained	14.59	4.42	66.16	25.58
Basic mineral poorly drained	1.54	1.60	0.23	1.20
Basic mineral well drained	4.06	2.51	1.37	2.89
Acid peaty mineral poorly drained	10.54	6.25	3.94	7.53
Basic peaty mineral unclassified drainage	17.75	6.48	8.03	11.90
Basic peaty mineral poorly drained	0.26	0.58	0.07	0.30
Peat	19.87	63.88	4.48	28.33
Miscellaneous	3.00	1.76	0.70	2.02

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896 **Table 3.** Structure and components of the field risk assessment.

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	Factor	Description	Weighting	Low risk (1)	High risk (3)
Source	P application risk	P balance	0.8	P deficit	P surplus
	*				
	Desorption risk	Organic matter contents	0.6	Mineral ($\leq 20\%$ OM)	Histic ($>20\%$ OM)
	+				
Mobilisation	Detachment risk	Grassland - poaching	0.4	No signs of poaching	Clear signs of poaching
		Grassland or Arable - erosion	0.4	No signs of erosion	Clear signs of erosion
	*				
	Overland flow risk	Topographic wetness index	1	Driest ($\leq P_{75}$)	Wettest ($>P_{75}$)
Transport	+				
	Connectivity risk	Surface drainage features	0.6	Least connected ($\leq P_{75}$)	Most connected ($>P_{75}$)

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