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4

5 **Developing and validating a decision support tool for media selection to**  
6 **mitigate drainage waters**

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16

17 **Abstract**

18 The nitrate nitrogen (NO<sub>3</sub>-N) and ammonium (NH<sub>4</sub>-N) and/or dissolved reactive phosphorus  
19 (DRP) load in drainage water from farms can be managed by reactive or biological media filters.

20 The nutrient content of the drainage water can be obtained directly from water analysis, which  
21 immediately focuses attention on filter media selection. There are many factors that may be  
22 important before choosing a medium or media e.g. nutrient removal capacity, lifetime, hydraulic  
23 conductivity, the potential for “pollution swapping”, attenuation of non-target contaminants (e.g.  
24 pesticides, organic carbon, etc.), and local availability and transportation cost of media to site. In  
25 this study, a novel decision support tool (DST) was developed, which brought all these factors  
26 together in one place for five nutrient scenarios. A systematic literature review was conducted to  
27 create a database containing 75 media with an associated static scoring system across seven

28 criteria (% of nutrient concentration reduction, removal of other pollutants, lifetime, hydraulic  
29 conductivity, negative externalities) and a dynamic scoring system across two criteria (delivery  
30 cost and availability). The DST was tested using case studies from Ireland, Belgium and USA  
31 with different agricultural practices and nutrient scenarios. It was then validated by SWOT  
32 (strength, weakness, opportunities and threats) analysis. The DST provided a rapid, easily  
33 modifiable screening of many media-based treatments for specific dual or single nutrient-based  
34 water drainage problems. This provides stakeholders (farmers/regulators/advisors) with a  
35 versatile, flexible and robust yet easy-to-understand framework to make informed choices on  
36 appropriate media-based mitigation measures according to users' relevant technical, economic  
37 and logistical factors.

38

39 **Keywords:** Drainage water, farm pollution, nitrogen, phosphorus, agriculture

40

## 41 **1 Introduction**

42 Decades of research have shown that aquatic environments are under pressure due to population  
43 growth, waste generation (FAO, 2011; Jhansi et al., 2013), excessive loading of nutrients (Billen  
44 et al., 2013; Erisman et al., 2011; Addy et al., 2016; Fenton et al., 2017), pesticides (Gramlich et  
45 al., 2018), and sediment inputs (Sherriff et al., 2015). Nutrients such as reactive nitrogen (nitrate  
46 ( $\text{NO}_3\text{-N}$ ) and ammonium ( $\text{NH}_4\text{-N}$ )) and dissolved reactive phosphorus (DRP) in drainage waters  
47 from intensively farmed agricultural sites have contributed significantly to impairment of water  
48 quality (Daly et al., 2017; Fenton et al., 2017; Rosen and Christianson, 2017; Clagnan et al.,  
49 2018a,b). The interception of single pollutants along surface or near surface drainage loss  
50 pathways using in-situ engineered structures filled with biological (e.g. woodchip in a  
51 denitrifying bioreactor) or reactive (e.g. steel slag in a P-sorbing structure) media is receiving  
52 increasing research attention (e.g. Penn et al., 2017). The removal rates of nitrogen (N) and

53 phosphorus (P) using these media can be high. For example, Hassanpour et al. (2017) measured  
54 50%  $\text{NO}_3$  removal from drainage water using woodchip media in a denitrifying bioreactor over a  
55 3-year period and Okello (2016) reported a 74% removal of DRP in drainage water using iron-  
56 coated sand in a reactive P-sorbing filter. However, the simultaneous removal of these pollutants  
57 in drainage water using dual media has mostly been examined at laboratory-scale (Healy et al.,  
58 2012, 2014; Ibrahim et al. 2015; Hua et al., 2016; Christianson et al., 2017; Fenton et al., 2017;  
59 Stroek et al., 2017). In addition, the transferability of these results to other locations due to the  
60 availability, suitability or delivered cost of media is often overlooked. An example here is the use  
61 of iron ochre to sorb P in drainage water; the availability of the ochre may not be a problem, but  
62 the form of ochre may be contaminated with heavy metals and its use may therefore be  
63 prohibitive (Fenton et al., 2009b).

64  
65 There is a vast catalogue of media in the literature that are reported to mitigate pollutants leaving  
66 farms. However, there is currently no decision support tool (DST) available to select a suitable  
67 medium, or a combination of media, for the targeted removal of  $\text{NO}_3$ ,  $\text{NH}_4$  and DRP, considered  
68 separately or together, while also considering factors other than pollutant removal capacity.  
69 These factors may include the media lifetime, hydraulic conductivity, the potential for “pollution  
70 swapping” (i.e. the creation of greenhouse gases (GHGs) or leaching of contaminants that may  
71 occur during operation), capacity to attenuate other (non-target) contaminants (e.g. pesticides,  
72 organic carbon, etc.), and availability and local price of the media.

73  
74 Decision Support Tools, usually software-based, manipulate data (often obtained through  
75 literature review or expert opinion) and recommend management actions through clear decision  
76 stages (SIP, 2018). In a review of DSTs for use in agriculture, Rose et al. (2016) found that in the  
77 UK 49% of farmers used some kind of DST to inform decisions whereas all advisors used DSTs,

78 and software versions were the preferred form of DST platform. In terms of selecting media to  
79 mitigate drainage water impacts, there is no DST that provides all the relevant information in one  
80 platform. Therefore, the objectives of this study were to: (1) develop a globally-applicable, user-  
81 friendly DST to assist the selection of locally sourced or available media, in order to reduce NO<sub>3</sub>,  
82 NH<sub>4</sub> and DRP, as single or mixed pollutants, from drainage water at farm-scale (2) evaluate the  
83 effectiveness and practicality of the DST in two phases: (a) applying it in different  
84 geographical/farming-practice case studies (b) validating the framework through SWOT  
85 (strength, weakness, opportunities, and threats) analysis.

86  
87 To meet these objectives, several steps were implemented to build a platform on which the DST  
88 could be developed. These included identifying a number of scenarios for N and P losses from  
89 farms and compiling a database of media for mitigation of nutrient losses. Figure 1 illustrates the  
90 steps taken in developing the FarMit (Farm Mitigation Tool) DST.

91

## 92 **2. Materials and methods**

### 93 ***2.1 Nutrient Scenarios***

94 Testing water samples for nutrients collected at the drainage discharge point can provide a  
95 spatial and temporal profile of single or mixed pollutants at a given site. Typically, reactive  
96 nitrogen (N<sub>r</sub>) losses from land drainage systems may occur as NO<sub>3</sub>-N (Nangia et al., 2010) or  
97 NH<sub>4</sub>-N (Clagnan, 2017), depending on various physical and biogeochemical factors that control  
98 the transformation of N<sub>r</sub> (Rivett et al., 2005; Fenton et al., 2009a; Clagnan et al., 2018a).  
99 Phosphorus losses from agricultural land, which are either retained or mobilized, may occur in  
100 particulate and dissolved forms (McDowell and Sharpley, 2001). Based on the complexities of  
101 nutrient losses from agricultural land, a conceptual model of different possible diffuse nutrient  
102 loss scenarios that may occur at farm-scale was developed.

103  
104 The FarMit DST is based around identifying materials to treat three nutrient loss scenarios  
105 (Figure 2). In Scenario A, mineralised  $N_r$  in the soil, in the form of  $NO_3$ , leaches to shallow  
106 pathways along low permeable layers or artificial drainage systems (e.g. Clagnan et al., 2018a,b)  
107 or along deeper groundwater pathways (Brouyere et al., 2003). In Scenario B, subsurface  
108 conditions, such as limited  $N_r$  and oxygen supply, combined with high soil carbon (C), may  
109 induce transformation of  $NO_3$  to  $NH_4$  (by dissimilatory nitrate reduction to ammonium, DNRA).  
110 In Scenarios A and B, DRP losses may also occur along surface, near surface, or deeper  
111 groundwater pathways. These losses could originate from the soil/subsoil, geological strata, or  
112 media used within an engineered bioreactor used to treat water and wastewater. Therefore, site-  
113 specific conditions (soil chemistry and drainage composition) or media characteristics may lead  
114 to the retention of P losses or the mobilisation of P. Finally, Scenario C represents a farm with  
115 only loss of P, where  $N_r$  in either form does not exceed a threshold or maximum allowable  
116 concentration (MAC). This may be due to the high attenuation capacity of the site, with  
117 conversion of  $N_r$  into gaseous forms (e.g. di-nitrogen or nitrous oxide), isolation from potential  
118 sources, or adaptation of perennial crop farming systems (Stanek et al., 2017).

119  
120 ***2.2 Systematic literature review to form media database***  
121 The five steps of a systematic review were followed, as outlined in Khan et al. (2003). The  
122 problem to be addressed was specified as follows (Step 1): what media have been used in the  
123 literature to attenuate  $NO_3$ ,  $NH_4$  and DRP from drainage waters? What is the efficacy of a  
124 medium to remove  $NO_3$ ,  $NH_4$  and DRP, or other pollutants in drainage waters? What is the  
125 hydraulic conductivity of the media? What is the lifetime of the media? What pollution swapping  
126 may occur using these media?

127

128 Next (Step 2), relevant work within the literature was identified. For this purpose, several  
129 keywords were selected to ensure relevancy for the literature search of over 175 media-based  
130 water treatment studies published during the last 20 years (150 papers were considered in final  
131 review). These included: water/wastewater treatment, water quality, agricultural waste,  
132 denitrification, denitrifying bioreactor, nutrient pollution, leaching, nutrient removal, adsorption,  
133 drainage, nitrate, phosphorus, and ammonium. The database search engines used were Google  
134 Scholar, Agricultural Research Database (AGRICOLA), International System for Agricultural  
135 Science and Technology (AGRIS), Web of Science, Scopus, American Society of Civil  
136 Engineering (ASCE), and the National Agricultural Library. To assess the quality of these  
137 relevant studies (Step 3), the following criteria were imposed: use of standard methods, and  
138 experimental design including replication and data interpretation. This enabled a database of 75  
139 distinct media types to be assembled. Data were then synthesised (Step 4) in tables and grouped  
140 as follows: wood-based (Table S1), vegetation/phytoremediation (Table S2) and inorganic  
141 materials (Table S3). Media were then assigned nine criteria (seven static and two dynamic),  
142 based on Steps 1-4, and a corresponding scoring system (Step 5 data interpretation) was  
143 developed for each criterion. In the static component, these criteria were  $\text{NO}_3\text{-N}$ ,  $\text{NH}_4\text{-N}$  and  
144 DRP removal capacity (Static Criteria 1-3 in the FarMit DST), removal of other pollutants of  
145 concern (Static Criterion 4), hydraulic conductivity (Static Criterion 5), lifetime of media before  
146 saturation (Static Criterion 6), and negative externalities such as emission of GHGs, contaminant  
147 leaching, or the presence of other pollutants in the final effluent (Static Criterion 7) (Table 1).  
148 For example, Criterion 1 (%  $\text{NO}_3\text{-N}$  removal) had a score range of -1, 0, 1, 2, 3, 4 corresponding  
149 to < 10%, 10-30%, 30-50%, 50-70%, 70-85%, and >85% reduction, respectively. Although  
150 many studies report % removal, there are other factors that affect this criterion, such as hydraulic  
151 residence time in denitrifying bioreactors and contact time in P-sorbing filters.

152

153 In the dynamic component of FarMit, media were scored according to geographically-based  
154 criteria such as availability and delivery cost to the treatment site or farm. These criteria are  
155 country/region-specific and will change over time. As the amount of media needed will vary  
156 depending on the drainage flow and composition at the site of concern, local knowledge is  
157 required and only the end-user can obtain the most appropriate ranking of media by assigning  
158 scores to these two components. The score ranges for these two final dynamic criteria are  
159 presented in Table 1.

160  
161 The nutrient combinations identified (A, B and C) in Figure 2 and the scoring system developed  
162 as part of Step 5 (Table 1) for all criteria (1-9) were combined to form the FarMit DST (Figure  
163 1). In order to test the DST, case studies from Ireland, Belgium (Flanders), and the USA  
164 (highlighted in grey in Table S4) were used.

165  
166 *2.4 Testing of FarMit DST using different case studies*

167 Three case studies each with their own distinctive nutrient scenario from Ireland, Belgium and  
168 the USA were used to test the DST (see Table S4 for details). Nutrient losses from drainage  
169 systems are ubiquitous, but water quality regulation standards differ worldwide. For example, in  
170 an Irish dairy system, cattle are kept outdoors for most of the year with both organic and  
171 inorganic fertilizer being land spread. Studies have shown high N surpluses on dairy farms due  
172 to low N utilisation efficiencies, e.g. Clagnan et al. (2018a) found a range from 211 to 292 kg N  
173 ha<sup>-1</sup> on heavy textured sites. As drainage waters are not governed directly by water quality  
174 legislation, other standards for surface or groundwater (e.g. drinking water standards) can be  
175 used to quantify the level of pollution. For example, in Ireland surface waters are of “high” and  
176 “good” status if their DRP is <0.025 mg L<sup>-1</sup> and < 0.035 mg L<sup>-1</sup>, respectively (EU, 2014; EPA,  
177 2016). For NO<sub>3</sub>-N, an average drinking water concentration of 11.3 mg NO<sub>3</sub>-N L<sup>-1</sup> applies for

178 groundwater, whereas a lower standard of  $<0.9 \text{ mg L}^{-1}$  and  $<1.8 \text{ mg L}^{-1}$  are indicative of surface  
179 waters with “high” and “good” status, respectively (EPA, 2016). Although a drinking water  
180 standard, and not specific to drainage waters, an indicative  $\text{NH}_4\text{-N}$  concentration of  $<0.23 \text{ mg L}^{-1}$   
181 may be considered to be non-polluting.

182

183 The region of Flanders in Belgium is mostly dominated by fruit production and arable farming in  
184 the east, with livestock production and production of vegetables for the frozen food market in the  
185 west (Flemish Agriculture and Fisheries, 2017). This region comprises 75% of agricultural  
186 production in Belgium, and is considered by the Government of Flanders, Investment and Trade  
187 Body to be a “global leader in intensive farming”. The water standard for  $\text{NO}_3\text{-N}$  should be  $<$   
188  $11.3 \text{ mg L}^{-1}$  and the same standard for  $\text{NH}_4\text{-N}$  as in Ireland applies. In terms of DRP, there is a  
189 range of concentrations for “very good” and “good” status of surface water from 0.04 to 0.06 mg  
190 DRP  $\text{L}^{-1}$  and 0.07 to 0.14 mg DRP  $\text{L}^{-1}$ , respectively.

191

192 Finally, the sites selected in the USA were in the states of Iowa, Minnesota, Wisconsin and  
193 Maryland, in which the dominant agricultural systems are corn, soybean, livestock, vegetables,  
194 fruits, and tree nuts (Hatfield, 2012). As with Ireland,  $\text{NO}_3\text{-N}$  standards in the USA are specific  
195 to drinking water, and not drainage water, but with a slightly lower standard at  $10 \text{ mg NO}_3\text{-N L}^{-1}$ ,  
196 which is termed a “maximum contaminant level”. In terms of DRP in the USA, there is a limit of  
197  $0.037 \text{ mg DRP L}^{-1}$  (USEPA, 2000) in surface waters.

198

### 199 *2.5 Validation of DST (SWOT analysis)*

200 The procedure of Andersson-Sköld et al. (2014) was followed to validate the DST. The FarMit  
201 DST was validated by running several SWOT (Strength, Weakness, Opportunity, Threat)  
202 analysis sessions with end-users. This allowed the DST to be critically reviewed by independent

203 stakeholders and external experts (researchers/scientists in the fields of water/soil quality  
204 monitoring/remediation and environmental protection, agricultural consultants/advisors) at the  
205 following SWOT analysis workshops:

206

- 207 i. PCFruit, Fruit Research Centre, Belgium (May 2018; 5 attendees)
- 208 ii. Department of Environment Research Centre of Teagasc, Agriculture and Food Development  
209 Authority of Ireland, Ireland (December 2018; 14 attendees)
- 210 iii. Water Research Group/ Groundwater Protection Group in Sheffield University, UK (February  
211 2019; 10 attendees)
- 212 iv. Network Meeting of EU Horizon2020 Early Stage Researchers representing different partner  
213 countries in the INSPIRATION (Managing soil and groundwater impacts from agriculture for  
214 sustainable Intensification) Independent Training Network (ITN), Netherlands (March 2019;  
215 14 attendees)

216

217 The process was carried out by presenting the FarMit DST to participants, starting with a  
218 summary of current media-based mitigation measures for removing/remediating nutrients in  
219 drainage water at farm-scale. The attendees were then divided into groups of three to four and  
220 participants were given a chart explaining each criterion. The groups were then asked to use the  
221 DST with a view to making best management decisions from a farmer/advisor point of view. The  
222 opinions of groups on the performance of FarMit DST with regard to its strengths and  
223 weaknesses as attributes of the DST and opportunities and threats as attributes of the  
224 environment were recorded and discussed among attendees.

225

### 226 **3. Results**

227 The FarMit DST is available in the supplemental Excel file. It may be used by first accessing the  
228 ‘INPUT’ tab on the file. The results of the three case studies are now presented.

229

### 230 **3.1 Case studies**

#### 231 **3.1.1 Ireland**

232 The results of the Irish case study are presented in the supplemental Excel file (Tab:  
233 EXAMPLES). The following steps were taken to obtain the final results:

234 1- Based on the drainage water test results (Table S4), the “Ammonium/DRP” icon in the DST  
235 user interface was selected.

236 2- The DST recommends the top 10 media based on *static* criteria for treatment of this scenario.  
237 For example, the top three media for NH<sub>4</sub>-N removal are zeolite, crushed glass and  
238 peat/sphagnum peat with a cumulative score of 10, 9.5 and 8.5, respectively. The equivalent  
239 media for DRP removal are vetiver grass, lime and sand with cumulative scores of 10, 9 and 8,  
240 respectively.

241 3- The *dynamic* criteria 8 and 9 were assigned scores considering local conditions and resources  
242 available at farm-scale. For example, in Ireland sand and gravel can be delivered to site at 0.21  
243 and 0.15 € kg<sup>-1</sup>, while zeolite, lime, and limestone cost over 0.70, 0.95, and 1.3 €, respectively.  
244 Any media priced below and over 0.5 € kg<sup>-1</sup> were assigned scores of 3 and 2, respectively, while  
245 media over 2 € kg<sup>-1</sup> (e.g. andesite, charcoal, nitrolite, etc.) were assigned a score of 1. The DST  
246 sums the total scores of static and dynamic criteria.

247 4- After pressing “Run”, the DST presented a high to low ranking of media for the mitigation of  
248 pollutants in the Irish case-study. These are presented graphically (by a histogram) and in table  
249 format.

250

251 The order of the top five media for NH<sub>4</sub>-N removal was (from best to worst): zeolite,  
252 peat/sphagnum peat, soil (no clay), sand and pea gravel. The top five media for DRP removal  
253 were (from best to worst): sand, lime, vetiver grass, zeolite, and crushed concrete. The ranking  
254 implied the influence of wide (local) application of some media over others in the dynamic  
255 criteria scoring. For example, zeolite is highly available despite being imported, therefore it has  
256 higher availability with lower delivery cost. Similarly, the extensive peat harvest/extraction from  
257 peat deposits along with the geology of Ireland, which provides limestone rocks or sand with  
258 various compositions, influenced the dynamic criteria scoring and therefore the final ranking of  
259 media.

260

### 261 **3.1.2 Belgium**

262 The results of the Belgian case study are presented in the supplemental Excel file (Tab:  
263 EXAMPLES). The following four steps were taken to obtain the final results:

264 1- Based on the drainage water test results (Table S4), the “Nitrate/DRP” icon in the DST user  
265 interface was selected.

266 2- The DST recommends the top 10 media for treatment of this scenario. For example, the top  
267 three media based on *static* criteria for NO<sub>3</sub>-N removal are woodchips, vetiver grass, and coco-  
268 peat, with a cumulative score of 9, 9 and 8.5, respectively. The media for DRP removal are  
269 similar to the Irish case study.

270 3- The *dynamic* Criteria 8 and 9 were assigned scores considering local conditions and resources  
271 available at farm-scale. This information was confirmed through consultation and face-to-face  
272 communication with a local private soft fruit company. A medium such as woodchip costs about  
273 €15 m<sup>-3</sup> to be delivered to a farm, which is considered inexpensive (i.e. Score 3) and similar to  
274 barley straw, or pea gravel. Some media such as apatite, limestone or vetiver grass are  
275 considered to be very costly, and must be imported to the site (with an associated high delivery

276 cost). This was therefore assigned a Score of 1. The DST sums the total scores of the static and  
277 dynamic criteria.

278 4- After pressing “Run”, the DST presented a high to low ranking of media for the Belgian case-  
279 study.

280  
281 The top five ranked media for mitigation of NO<sub>3</sub> were (from best to worst): woodchips,  
282 cardboard, barley straw with native soil, coco-peat and sand. Soil (no clay) together with crushed  
283 concrete, peat/sphagnum peat, sand, and vetiver grass together with lime and zeolite, were the  
284 highest ranked media for mitigation of DRP. The feedback from face-to-face communication  
285 with farmers indicated that considering the availability of resources at farm-scale, waste  
286 cellulose (combination of leaf compost, wood mulch and saw dust) could gain more interest than  
287 woodchips. In addition, availability of locally sourced barley straw and peat with high NO<sub>3</sub>  
288 removal potential could consequently change the scores for the dynamic criteria to compensate  
289 for a low score for a static criterion (e.g. lifetime). Farmers perceived “pollution swapping” as  
290 being important and the final material needed to have a low pollution swapping potential. This  
291 was perceived as important to avoid monetary fines in terms of water regulations in the future.

292

### 293 **3.1.3 USA**

294 The results of the US case study are presented in Supplement Excel Sheet (Tab: EXAMPLES).

295 The following four steps were taken to obtain the final results:

296 1- Based on the drainage water test results as in Table S4, the “Nitrate” icon on the DST user  
297 interface was selected.

298 2- The DST recommends the top 10 media for treatment of NO<sub>3</sub> pollution scenario (similar to  
299 Belgium Case Study for NO<sub>3</sub>-related media).

300 3- The *dynamic* Criteria 8 and 9 were assigned scores based on a comparative scale using online  
301 information in consultation with the USA stakeholder, considering local conditions and  
302 resources available at farm-scale within the vicinity of case study region. The use of woodchips  
303 (to be used in denitrifying bioreactors) receive financial support from the government and the  
304 existence of numerous wholesale suppliers/or producers of coco-peat (coconut coir), vetiver  
305 grass, and zeolite made these media accessible and available. The DST then summed the total  
306 scores of static and dynamic criteria.

307 4- After pressing “Run”, the DST recommended a high to low ranking of media for USA case-  
308 study.

309  
310 The DST recommended woodchips, coco-peat, vetiver grass together with sand and zeolite,  
311 barley straw with native soil, as the highest ranked media from best to worst. This result supports  
312 the common use of denitrifying woodchip bioreactors in the USA as a well-established NO<sub>3</sub>  
313 remediation technology (Christianson et al., 2012a). The installation of woodchip bioreactors at  
314 the end of tile drainage systems is also financially supported by the US Department of  
315 Agriculture Natural Resources Conservation Service (USDA NRCS) (NRCS, NHCP, 2015).  
316 Such schemes, along with the major local productions, industry needs and wholesale  
317 suppliers/distributors/importers, have a direct influence on media availability and cost and,  
318 consequently, the scoring and final selection. The output of the FarMit DST considers only  
319 selection of a medium/media. Future research is required to test the medium/media under  
320 controlled laboratory conditions to elucidate design and operational parameters.

321

### 322 **3.2 SWOT analysis**

323 The overall SWOT analysis results from different workshops is summarised in Table 2. It was  
324 perceived that the major strengths of the FarMit DST were its easy concept and worldwide

325 applicability for targeting dual removal of nutrient pollution, regardless of farming practice and  
326 considering specific local economic conditions and media-availability to individual users.  
327 Weaknesses identified included the absence of a sustainability factor (i.e. possible reusability of  
328 saturated media as a fertilizer or a soil amendment) and impracticality of using certain media  
329 regardless of their high ranking in nutrient mitigation. The major opportunity provided by FarMit  
330 was that it may be a long-term efficient decision support framework that can be implemented at  
331 the initial stage of decision making. The threats were seen as the risk of extreme weather events  
332 or social/economical/political changes that may have an impact of availability and price of media  
333 for farmers.

334

## 335 **4. Discussion**

### 336 *4.1 Performance of DST in case-study applications*

337 The DST application in different case studies representing different geographical locations and  
338 showcasing different farming practices, provided a ranking of media with high potential to  
339 remove nutrients in drainage water for various farm pollution scenarios. SWOT analysis showed  
340 the DST to be an effective tool to communicate management options to different stakeholders. It  
341 provided a list of options to the stakeholder and the results are clear enough to provide applicable  
342 information.

343

344 The results were consistent with the hypothesis that the dynamic criteria (availability and  
345 delivery cost of media to site) would vary spatially and temporarily. This was due to reasons  
346 such as geopolitical situation and proximity to a national border (e.g. to the French border for  
347 Flanders in Belgium), size of the country and therefore availability of wholesale  
348 manufacturers/suppliers/distributors, local production (e.g. wood-based or corn-based media like  
349 corn cob/stover may suit farmers in USA better than Belgium or Ireland), levies on recyclable

350 materials (e.g. glass in Ireland or cardboard in Belgium), financial support from government (e.g.  
351 installation of woodchip denitrifying bioreactors in USA), the extent of application of media  
352 according to the dominant industry/use, etc. A good example for the latter is zeolite, which is a  
353 natural mineral medium with high potential for removal of both NH<sub>4</sub>-N and DRP. Although  
354 imported in Ireland, this has wide application in Ireland and thus higher availability with lower  
355 delivery cost compared to Belgium, for example. Conversely, coco-peat is more available in  
356 Belgium than Ireland due to the wide application of coco-based media for other purposes (e.g.  
357 coco-chips in pesticide biofilter), while this medium is readily available and may be purchased at  
358 a relatively low cost in the USA.

359

#### 360 *4.2 SWOT analysis*

361 Generally, the ranking of media is similar based on static (non-geographical) criteria for  
362 comparable case studies in different locations, although it is expected to change when  
363 considering the dynamic criteria (8 and 9) at specific sites. The operator may choose from 75  
364 options (Table S5) according to their local knowledge and personal preference. This was  
365 considered as a strength in the SWOT analysis. This flexibility enabled the operators  
366 (farmer/adviser/engineer) to make a quick and informed medium selection based on possible  
367 future costs. This strength of the FarMit DST was welcomed in Belgium, where farmers were  
368 willing to take an active role in implementing sustainable solutions to minimize pollution caused  
369 by nutrient losses and they may opt for natural/organic media with zero pollution swapping and  
370 longer saturation time regardless of nutrient adsorption capacity. For example, despite the high  
371 availability of cardboard or crushed concrete at farm-scale and their high nutrient removal  
372 efficiency, the stakeholder (farmer) was concerned about the media lifetime and potential  
373 negative externalities. Therefore, the preference was to implement a more sustainable, but more  
374 expensive, alternative (e.g. zeolite).

375

376 In addition, if an operator wishes to avoid expensive pre-treatment or post-treatment of media  
377 due to pollution swapping caused by, for example, leaching of heavy metals (e.g. andesite and  
378 re-used concrete), they may wish to select a medium further down the ranking that may be more  
379 expensive but which has a lower environmental footprint. In addition, after the selection and  
380 operation of an engineered treatment system, the FarMit DST can be used again to minimize the  
381 effects of pollution swapping. For example, woodchip has been shown in some studies to release  
382 DRP (e.g. Fenton et al., 2016). In these cases, the DST can be used to select a Scenario C  
383 medium instead.

384

385 Another SWOT strength, as well as opportunity of FarMit, is the flexibility to be further  
386 developed and to adjust with time of application, as the dynamic criteria may also change over  
387 time. For example, a non-native plant such as vetiver grass has a high pollutant removal  
388 efficiency (Ash and Truong, 2004; Mayorca, 2007; Donaldson and Grimshaw, 2013) and can be  
389 purchased at a relatively low cost in the USA. It was initially only available at international-scale  
390 to Ireland and Belgium (where it was imported from Asia), but now has a growing market in  
391 Europe (with ensuing lower supply costs and higher availability). Here, the SWOT threats lie in  
392 the fact that changes in geopolitical landscapes impact commercial trade directly and extreme  
393 weather might change availability (and price) of local products.

394

395 The SWOT analysis identified a lack of a criteria considering environmental sustainability and  
396 post-implementation cost (e.g., disposal of used media and associated costs). This can be  
397 addressed in the future as the tool has the flexibility to be further developed.

398

399 **5. Limitations and future recommendations**

400  
401 Phytoremediation and organic materials, presented in Table S2, have limitations (such as type of  
402 vegetation plant, geology, geographical features), which may affect their selection and  
403 application. For example, peat sourced from different areas may not achieve results similar to  
404 cited reports. Similarly, soils and sands may differ in metal content and geochemistry, which  
405 could influence their nutrient adsorption capacity. Therefore, the user can subsequently decide to  
406 test several highly ranked media in batch studies to confirm their performance in specific  
407 contexts. This would then help to screen suitable materials and identify the most efficient type or  
408 chemistry of locally sourced media (thus with highest nutrient mitigation potential or longer  
409 lifetime) to be used in the site under examination.

410  
411 In terms of final selection for an engineered structure, further media testing may be needed to  
412 elucidate on-site removal capacity, which may differ from literature or even laboratory  
413 conditions e.g. woodchip and denitrification rate. Additionally, the design of a system for dual  
414 nutrient mitigation will usually require the user to consider the sequence of media needed to  
415 address pollution swapping (Fenton et al., 2016).

416  
417 Future development of this FarMit DST should consider incorporation of other factors by  
418 individual users (e.g. circular economy/agronomic value of saturated media) for scoring and  
419 finalising media selection, as well as aligning the ranking of media for removal performance  
420 based on similar conditions, e.g. residence time, and to factor in other issues that influence the  
421 removal efficiency, e.g. atmospheric conditions such as temperature. Furthermore, dynamic  
422 criteria could outweigh all other components if weightings are assigned. This would exclude all  
423 media for which access is not possible (e.g. vetiver grass in some areas). Another factor which

424 could be included in the DST at a later stage would be maintenance costs pertaining to the  
425 selected medium/media at the field site.

426

427 The flexibility of the FarMit DST provides a tool with the capability to be updated by adding  
428 media emerging from new studies as well as new tests on the current 75 media reviewed, but in  
429 different experimental settings. This would consequently update the “static component” of the  
430 DST as new results indicate higher or lower removal rates, lifetime, or new insights into the  
431 pollution swapping potential of a media.

432

## 433 **6. Conclusions**

434

435 A decision support tool (“FarMit”) was developed and validated. This tool enables the end-user  
436 to select locally sourced media which can be used in drainage ditch structures to mitigate  
437 polluted outflows. The tool provides seven static criteria for 75 media and the operator provides  
438 dynamic criteria (availability and delivery cost) to adjust the final ranked list for local conditions.  
439 SWOT analysis, conducted in a series of workshops, showed the tool to be systematic,  
440 transparent and user-friendly, providing the user with a wide catalogue of options, and considers  
441 users’ local economic and market conditions. Despite the fact that the tool does not provide an  
442 end-use for the saturated medium (media) or insight about re-use potential, it provides the  
443 opportunity of knowledge transfer between different stakeholders, and therefore can positively  
444 impact decision making.

445

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449

450

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585 Table 1. Static (1-7) and dynamic (8-9) criteria and corresponding scoring ranges

Criteria	Performance within each criterion	Score
<b>Static scores based on an average performance reported<sup>1</sup></b>		
1- NO <sub>3</sub> -N removal rate	NO <sub>3</sub> -N concentration reduction > 85%	4
	NO <sub>3</sub> -N concentration reduction: 70-85%	3
	NO <sub>3</sub> -N concentration reduction: 50-70%	2
	NO <sub>3</sub> -N concentration reduction: 30-50%	1
	NO <sub>3</sub> -N concentration reduction: 10-30%	0
	NO <sub>3</sub> -N concentration reduction < 10% and increase in concentration	-1
2- NH <sub>4</sub> -N removal rate	NH <sub>4</sub> -N concentration reduction > 85%	4
	NH <sub>4</sub> -N concentration reduction: 70-85%	3
	NH <sub>4</sub> -N concentration reduction: 50-70%	2
	NH <sub>4</sub> -N concentration reduction: 30-50%	1
	NH <sub>4</sub> -N concentration reduction: 10-30%	0
	NH <sub>4</sub> -N concentration reduction < 10% and increase in concentration	-1
3- DRP removal rate	P concentration reduction > 85%	4
	P concentration reduction: 70-85%	3
	P concentration reduction: 50-70%	2
	P concentration reduction: 30-50%	1
	P concentration reduction: 10-30%	0
	P concentration reduction < 10% and increase in concentration	-1
4- Removal of other pollutants of concern	Removal of other nutrient/pollutant > 80%	2
	Removal of other nutrient/pollutant < 80%	1
5- Hydraulic conductivity <sup>2</sup>	Very good: > 4 cm/h	3
	Good: 1.5-4 cm/h	2
	Acceptable/depending on compactness: <1.5 cm/h	1
6- Lifetime	Lifetime >10 years	2
	Lifetime : 5-10 years	1
	Lifetime <5 years	0
7- Negative externalities	GHG emission	-3
	Contaminant leaching/other pollutants in effluent	-2
	Expensive pre-treatment	-1
<b>Dynamic scores subject to change based on geographical region<sup>3</sup></b>		
8- Scale of Availability	Scale of Availability: farm scale	4
	Scale of Availability: local/country scale	3
	Scale of Availability: EU/continent scale	2
	Scale of Availability: International scale	1
9- Cost	Cost (low)	3
	Cost (medium)	2
	Cost (high)	1

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<sup>1</sup> Extracted from the developed Media Database (Table S2, S3, S4) based on average performance of conducted studies

<sup>2</sup> Required additional data from other sources

<sup>3</sup> Scoring should be defined by individual users (requires case study knowledge on temporal/spatial factors)

590 Table 2. Summary of SWOT analysis results: strength and weakness (attributes of the tool), and  
 591 opportunities and threats (attributes of the environment) of FarMit DST identified through different  
 592 workshops.

STRENGTH	WEAKNESS	OPPORTUNITIES	THREATS
Clear concept, provides an overview of best media, and easy to understand		Flexibility for the DST to be further developed	
User friendly without any complications, thus suitable for any software skill level.		Easy to change scores from time to time depending on environmental circumstances	The use of the tool/scorings depend on local/national legislation
Time saving, as it provides a list of best performing media	Not showing raw/waste nature of a medium	Positive impact on decision making as it is an easy to use tool	
Static criteria do not change from region to region, but are important in any mitigation option regardless of farm size.	Does not consider environmental sustainability and post-implementation cost (disposal of used media and associated costs)		Impact of local geographical conditions on removal efficiency (e.g. weather, humidity)
Low-cost DST which is easy to disseminate		Enabling knowledge transfer between different stakeholders	
Robust selection of media (based on literature review and actual experiments)			
Informative and presents several media options	Bar graphs may be misleading for non-scientific community	Supporting document to be used for legal purposes	
A ranking list (from best to worst) of potential media is provided	Lack the factor of unfeasibility at site, regardless of its good adsorption capacity	Possibility to add a factor considering the applicability at site	Farmers' constraints might not let them to choose top ranked media based on lower "cost" or higher "availability"
Provides the user with options which helps in making a more informed selection that considers environmental impacts	Does not consider greenhouse gas emissions caused by transport of media		Information on availability/efficiency of some media depends on extreme weather conditions, land use changes, growing/failure

			of an industry, etc.
			Changes in geopolitical landscapes may have a direct impact on commercial and import/export agreements
			Fluctuation of exchange rate in the case of importation can alter the cost
Considers negative externalities (pollution swapping), thus prevents further post-treatment in near/far future	“Pollution Swapping” has not been considered in many studies so not sufficient information on all 75 media in this regard	Highlights pollution swapping as an issue	
			Knowledge presented could affect end decision thereby moving to a material with a lower environmental footprint
			Influence mindset by considering several criteria of importance for overall pollution remediation
Considers both N and P individually or simultaneously			
Considers environmental, economic and logistical criteria	Some media listed may not be familiar to the user depending of geographical location where the tool is applied		
The DST considers the users’ incomes	The scoring range for “Cost” is narrow	Possibility to add a weighting factor to show importance of dynamic criteria	
	Lack of differentiating between organic/inorganic components of media and information on nonlocal media <sup>1</sup>		
Provides a decision support framework comprising long term goals		Possibility of data collection regarding farmers’ preferences in order to improve decision making	

processes

Encourages farmers to monitor water quality more often to avoid possible contamination of water by the end of medium's lifetime

Can be further developed to include new emerging media, as well as results from new laboratory and field experiments on currently listed media

Lack of information on amount of required media and their exact lifetime<sup>2</sup>

593 1 All 75 media are differentiated based on being wood-based, vegetation/phytoremediation based or  
594 inorganic in Table S2, Table S3, Table S4, respectively, documenting detailed list of  
595 advantages/disadvantages of media and already tested amendments to improve their efficiency.

596 <sup>2</sup> Acquisition of this information requires batch or column adsorption studies and modeling of adsorption  
597 capacity of selected media based on nutrient load and targeted removal percentage of pollution in a  
598 defined time period.

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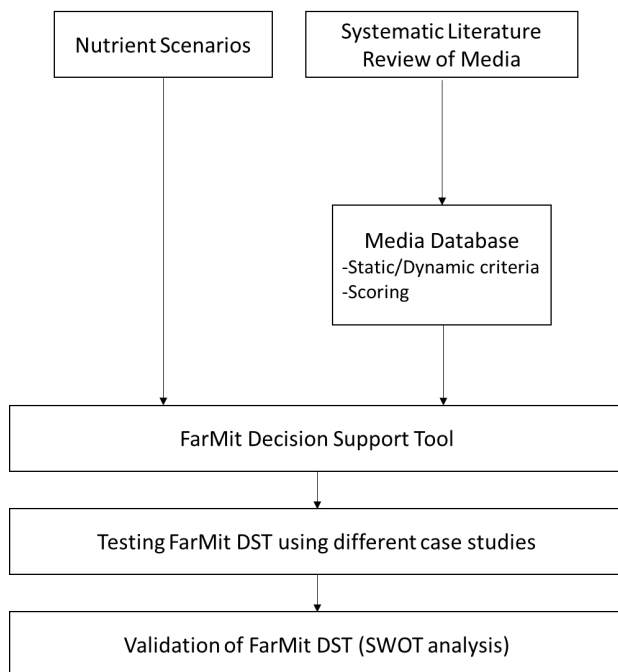


Figure 1. Flowchart for the development of FarMit DST

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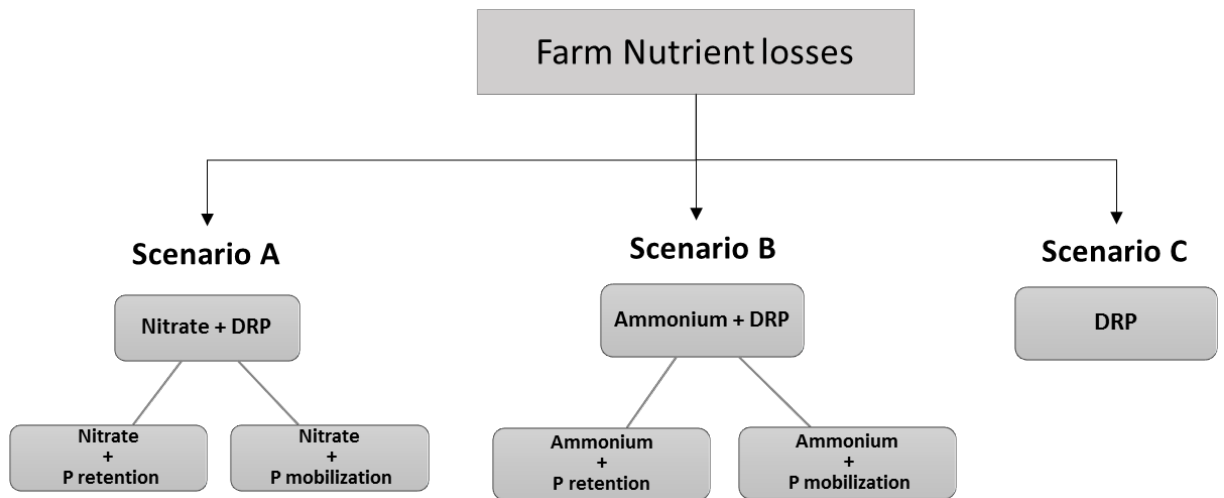


Figure 2. Farm pollution scenarios: A: Farm pollution with leaching of  $\text{NO}_3\text{-N}$  and retention of P, or Farm pollution with leaching of  $\text{NH}_4\text{-N}$  and mobilization of P, B: Farm pollution with leaching of  $\text{NO}_3\text{-N}$  and retention of P, or Farm pollution with leaching of  $\text{NH}_4\text{-N}$  and mobilization of P, C: Farm pollution with DRP mobilization and no leaching of N.

609