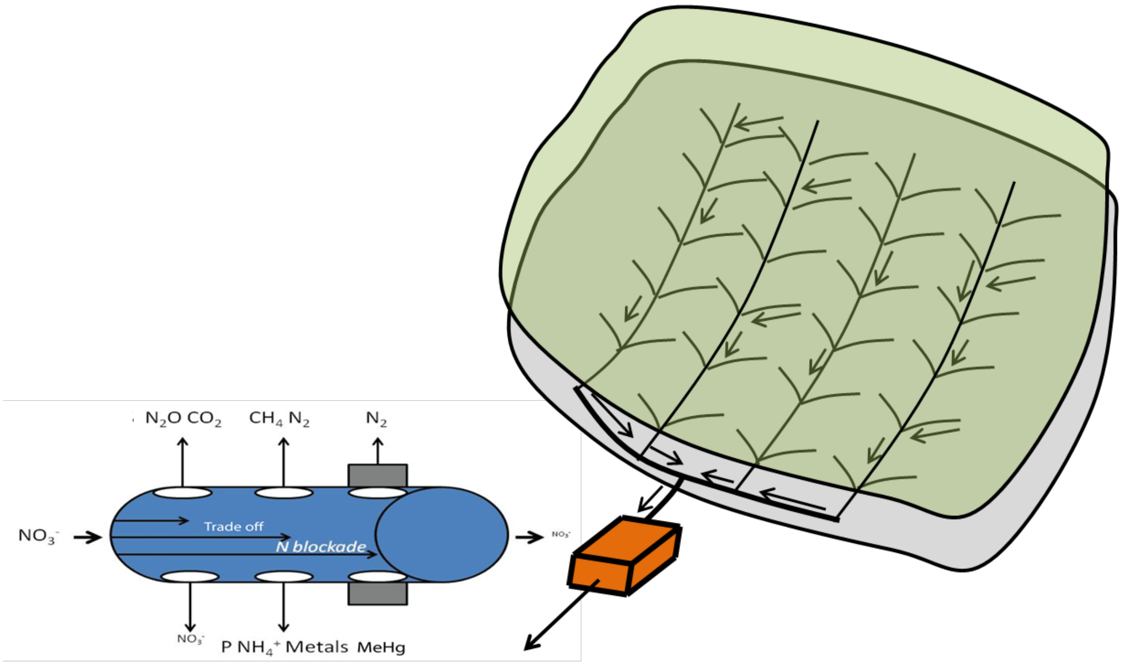
Suitability Criterion for Treatment Technologies:

Denitrifying Bioreactor

Deliverable D4.3 / Work Package 4



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Introduction

Artificial drainage systems installed in agricultural landscapes often are designed to control the water table height based on crop requirements. Drainage waters and emissions to the air from artificial drainage systems also can have unwanted environmental side effects. Internationally there has been a move to design smart drainage systems (through drain spacing, watertable control or an end-of-pipe solution) that have considered both production and environmental provisions. Specifically, in terms of water quality there has been a successful move towards trapping and mitigating mixed nutrients before they can negatively affect water quality. Engineered structures such as "denitrifying bioreactors" are organic carbon-filled excavations designed to enhance the natural process of denitrification for the simple, passive treatment of nitrate-nitrogen (Christianson and Schipper, 2016). Research on and installation of these bioreactors is on-going, particularly in the USA and agriculture in the European Union can learn a lot from laboratory and field experiments which have consider the sustainability of these engineered systems. The end goal here is to mitigate pollutants that discharge from drainage systems without pollution swapping (that is, mitigating one pollutant while releasing another). It is also recognised that at some sites many different types of pollutants discharge from drainage systems and this list will change into the future to include all types of pesticides, herbicides, sediment and emerging pollutants.

Within the current Marie Curie Inspiration ITN project Work Package 4 has focused on drainage water abatement and recycling of filter materials. In particular the focus of the present report will be to develop an awareness of sustainability research around woodchip bioreactors. Such systems effectively convert nitrate into di-nitrogen gas and are positioned at the end of tile drainage systems (Figure 1) (Christianson and Schipper, 2016).

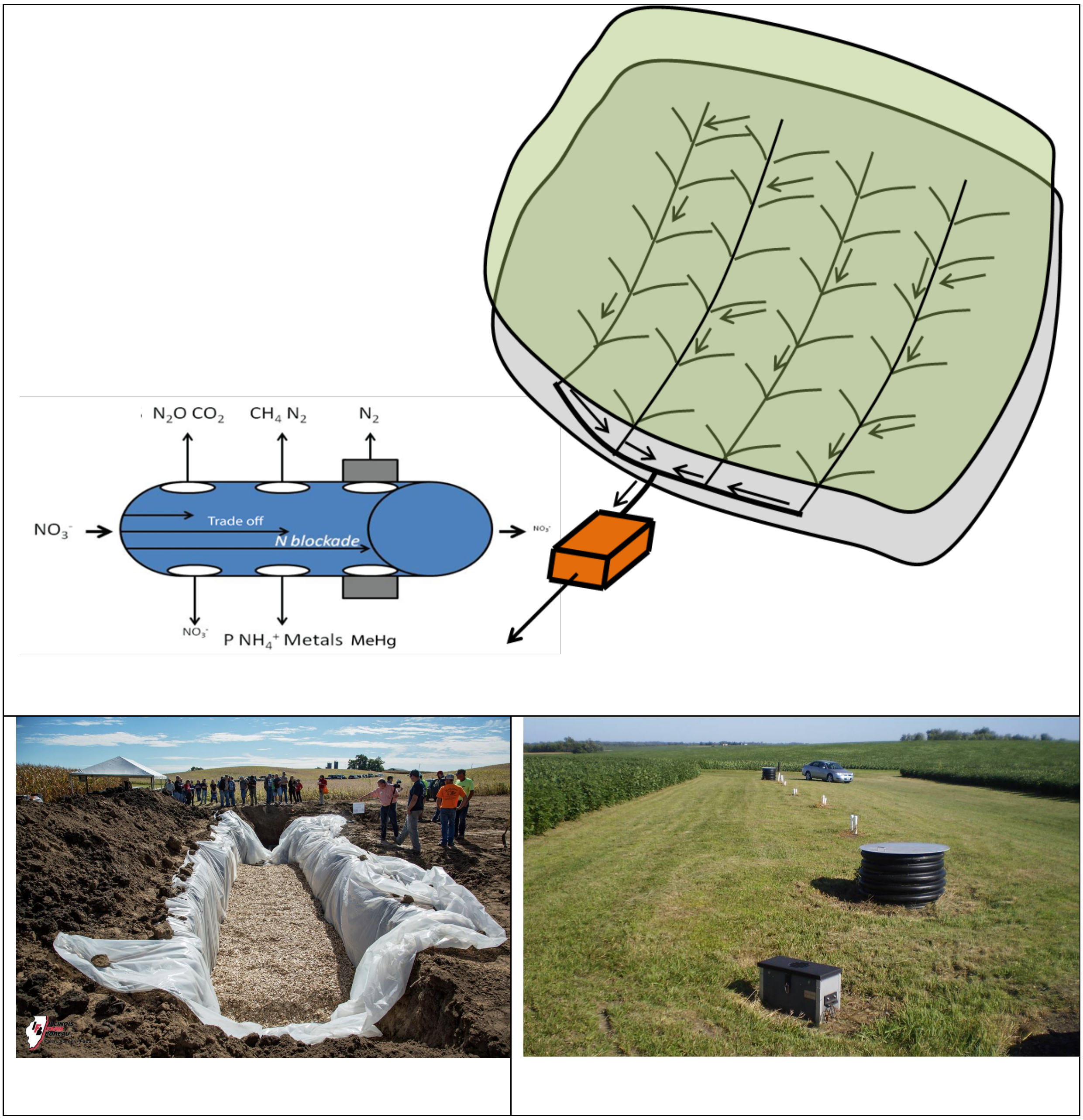


Figure 1: Top – concept of the location of a denitrifying bioreactor at the end of a tile drainage system. N blockade – this is a schematic of a leaky pipe which outlines the pollution swapping potential of systems even where N output is less than N input. Bottom – photo of a woodchip filter installation and a soil capped system.

The biophysical and biogeochemical processes occurring within denitrifying bioreactors could generate other contaminants, such as nitrous oxide (N_2O), ammonia (NH_3), carbon dioxide (CO_2), and methane (CH_4), through "pollution swapping" (Fenton et al., 2014, Davis et al., 2019). Therefore, it is prudent to have a method to assess the sustainability of these systems over time. For the most part emissions to air are small or can be abated simply by placing a soil cap on the bioreactor or manipulating the flow in the systems. However, other elevated nutrients may be dissolved in the drainage waters e.g. dissolved reactive phosphorus (DRP) and these also need to be treated (Sharrer et al., 2016). Therefore, for the present report both nitrate and phosphorus will be considered.

Sustainability starts with the filter medium itself and how such a medium will affect the surrounding landscape within and after the lifetime of the bioreactor. Therefore some thought should be given to sustainability criterion whilst choosing a medium or set of media where more than one nutrient is targeted for mitigation. Recently some research has focused on the washing of the media before installation into the bioreactor e.g. woodchip.

In terms of P sorption materials, such as sand or zeolite (Ibrahim et al., 2015; Ezzati et al., 2019), the medium may become saturated quickly depending on the concentration of the drainage water, the flow and the maximum adsorption capacity (q_{max}) of the medium. These materials if deemed suitable could be applied to the soil as a fertilizer source, thus contributing to a circular economy. There has been much debate about a material's ability to act as an adsorbent in the first instance and then to act as a slow release P fertilizer later on. Therefore, the characteristics of the media should be carefully considered before land application to avoid transferring contaminants (e.g. heavy metals) or pathogens to the soil, affecting the pH, increasing the salinity or wrongly assuming the nutrients will be plant available. Specifically for P adsorbing media, the fractions of P (labile P, Ca/Mg-bound P, Al/Fe-bound P, residual P) present after saturation is a more important parameter than their P maximum adsorption capacity to determine if the medium can provide plant-available P under specific soil conditions after being used as a filter medium for P removal.

Various steps could be followed to assess the sustainability of a denitrifying bioreactor. It should be noted that this procedure does not need to be followed for every site but knowledge should be developed by the community to guide future designs of systems to make them more sustainable. In the present document these "steps" are divided into the following:

Step 1: Filter medium selection and considerations

Step 2: Sustainability Research

Step 3: Denitrifying woodchip bioreactors: design and construction overview

The deliverable provides information on the sustainability of treatment technologies such as denitrifying bioreactor systems and covers the projects as outlined in work package 4 (WP4) within INSPIRATION ITN.

Step 1: Filter medium selection and considerations

Although the vast majority of denitrifying bioreactors that are operational at field scale contain woodchip only, there has been a shift at least in the literature to consider other nutrients such as dissolved reactive phosphorus (DRP). An easy to use decision support tool (FarMit –Farm Mitigation Tool) is now available for free to match a water quality issue (e.g. nitrate) with a suitable medium (e.g. woodchip) or media (e.g. sand and zeolite in a scenario that aims to treat both DRP and ammonium for example). The following link can be used to access the FarMit decision support tool (DST):

https://doi.org/10.1016/j.ecoena.2019.100010

The FarMit database contains 75 distinct media types, which are further categorised into different types as follows: wood-based, vegetation/phytoremediation and inorganic materials. The database contains information on nutrient, biochemical oxygen demand (BOD) and chemical oxygen demand (COD), pesticide, oil, metal, coliforms and suspended solid attenuation capacity. In addition, information was collected on the hydraulic conductivity of the media, the reported period of operation before saturation, the potential for *pollution swapping*, and possible timely/expensive pre-treatments. From this review process seven static scores (which do not change) were assigned to each of the 75 media. In the static component, these criteria were NO_3^-, NH_4^+ and DRP removal capacity, removal of other pollutants of concern, hydraulic conductivity, lifetime of media before saturation, and negative externalities such as emission of GHG, contaminant leaching, or the presence of other pollutants in the final effluent. For the purposes of the present report the FarMit was run for a nitrate and DRP scenario.

Figure 2 shows the user interface of the FarMit Tool which enables the user to click on the water quality issue that they are concerned with. This immediately brings up a list of potential media based on the nutrients selected and the static criteria. For the purposes of the present report which focuses on mitigation of nitrate and DRP from a tile drainage system, nitrate and mobilised DRP shall be selected. Therefore in this example the DST user would click "Nitrate DRP". Once this selection is made, a table of the top ten media based on static criteria for each nutrient are presented. In this screen, the user can also insert the dynamic categories based around local availability and cost (Figure 3). Then the list is re-shuffled by pressing "Run" and a final selection is presented in Figure 4.

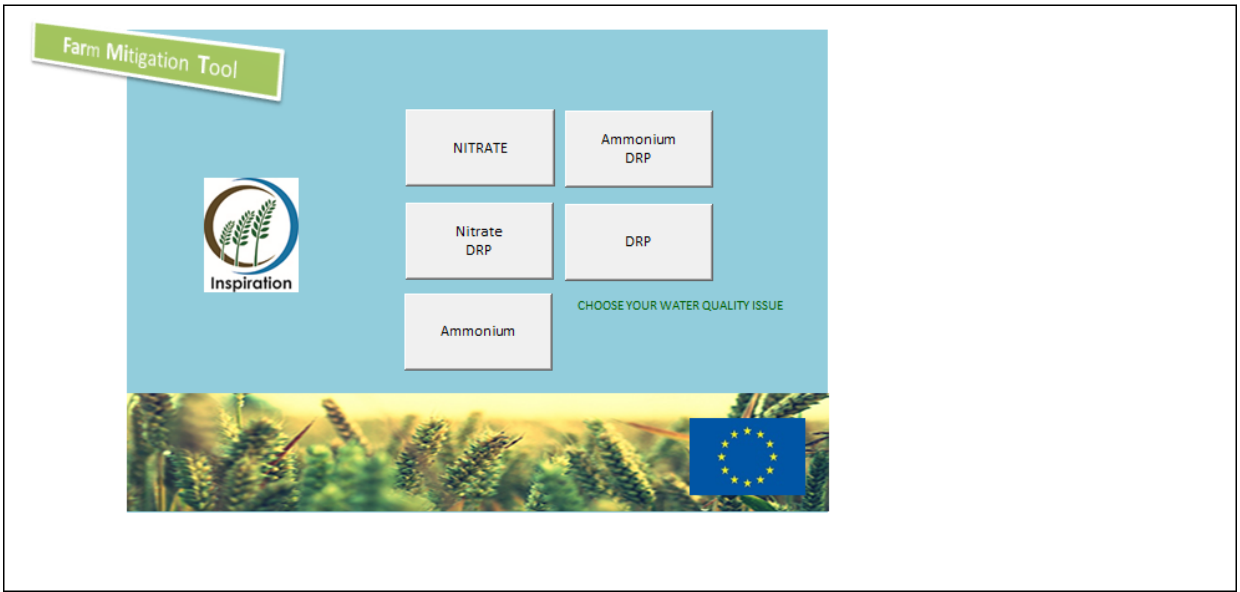
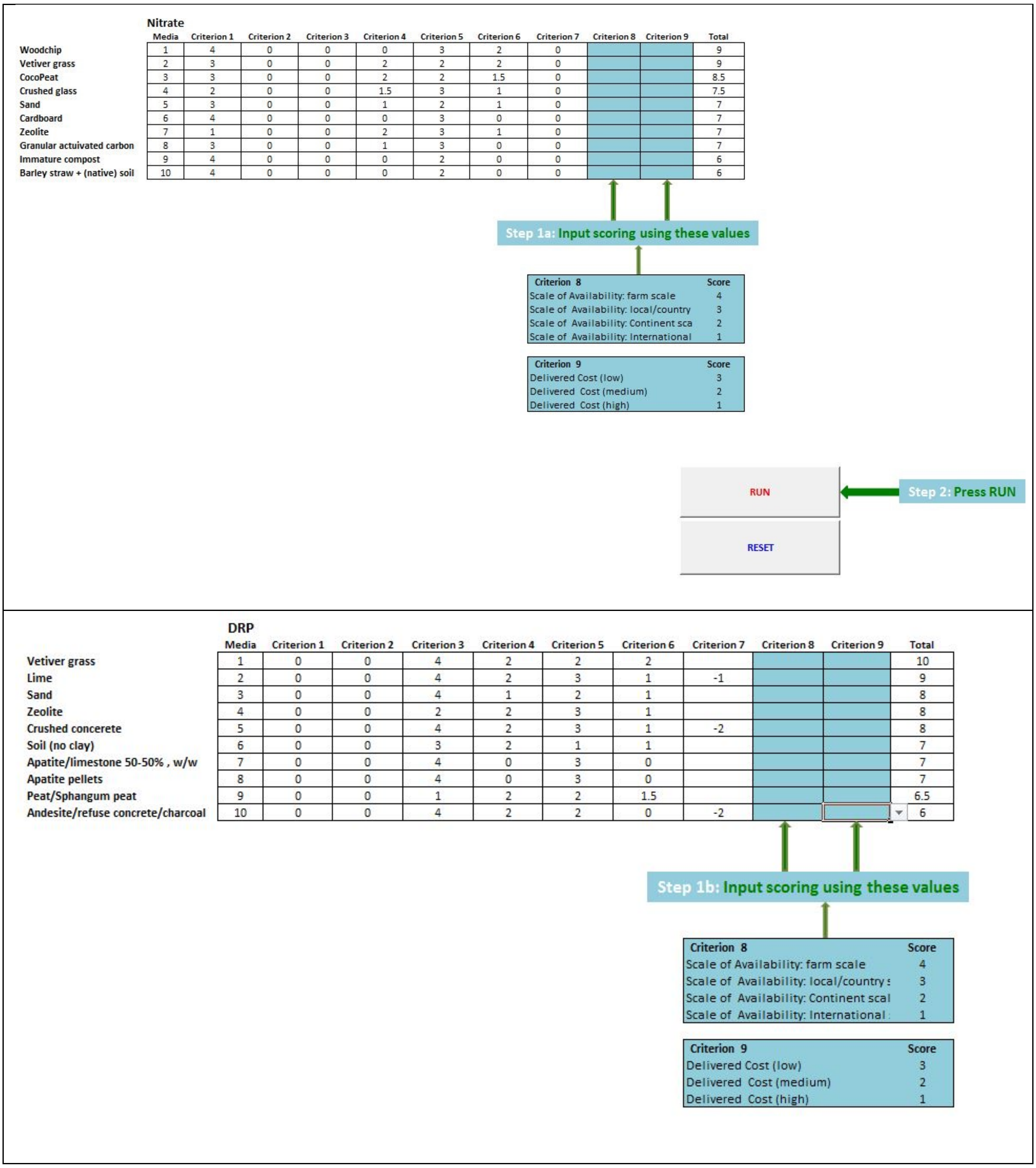


Figure 2: FarMit interface for the selection of the nutrient of concern or combination of nutrients.



Nitrate

	Media	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8	Criterion 9	Total
Woodchip	1	4	0	0	0	3	2	0			9
Vetiver grass	2	3	0	0	2	2	2	0			9
CocoPeat	3	3	0	0	2	2	1.5	0			8.5
Crushed glass	4	2	0	0	1.5	3	1	0			7.5
Sand	5	3	0	0	1	2	1	0			7
Cardboard	6	4	0	0	0	3	0	0			7
Zeolite	7	1	0	0	2	3	1	0			7
Granular actuivated carbon	8	3	0	0	1	3	0	0			7
Immature compost	9	4	0	0	0	2	0	0			6
Barley straw + (native) soil	10	4	0	0	0	2	0	0			6

Criterion 8	Score
Scale of Availability: farm scale	4
Scale of Availability: local/country	3
Scale of Availability: Continent sca	2
Scale of Availability: International	1

Criterion 9	Score
Delivered Cost (low)	3
Delivered Cost (medium)	2
Delivered Cost (high)	1

DRP

	Media	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8	Criterion 9	Total
Vetiver grass	1	0	0	4	2	2	2				10
Lime	2	0	0	4	2	3	1	-1			9
Sand	3	0	0	4	1	2	1				8
Zeolite	4	0	0	2	2	3	1				8
Crushed concerete	5	0	0	4	2	3	1	-2			8
Soil (no clay)	6	0	0	3	2	1	1				7
Apatite/limestone 50-50% , w/w	7	0	0	4	0	3	0				7
Apatite pellets	8	0	0	4	0	3	0				7
Peat/Sphangum peat	9	0	0	1	2	2	1.5				6.5
Andesite/refuse concrete/charcoal	10	0	0	4	2	2	0	-2			6

Criterion 8	Score
Scale of Availability: farm scale	4
Scale of Availability: local/country s	3
Scale of Availability: Continent scal	2
Scale of Availability: International	1

Criterion 9	Score
Delivered Cost (low)	3
Delivered Cost (medium)	2
Delivered Cost (high)	1

Figure 3: Nitrate (top) and DRP (bottom) examples with the top ten media options based on the static criteria.

Nitrate

	Media	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8	Criterion 9	Total
Voodchip	1	4	0	0	0	3	2	0	3	2	14
Cardboard	6	4	0	0	0	3	0	0	4	3	14
Barley straw •	10	4	0	0	0	2	0	0	4	3	13
CocoPeat	3	3	0	0	2	2	1.5	0	3	1	12.5
Sand	5	3	0	0	1	2	1	0	3	2	12
Immature compost	9	4	0	0	0	2	0	0	3	3	12
Crushed glass	4	2	0	0	1.5	3	1	0	3	1	11.5
Vetiver grass	2	3	0	0	2	2	2	0	1	1	11
Zeolite	7	1	0	0	2	3	1	0	3	1	11
Granular actuivated ca	8	3	0	0	1	3	0	0	3	1	11

Step 1a: Input scoring using these values

Criterion 8	Score
Scale of Availability: farm scale	4
Scale of Availability: local/country scale	3
Scale of Availability: Continent scale	2
Scale of Availability: International scale	1

Criterion 9	Score
Delivered Cost (low)	3
Delivered Cost (medium)	2
Delivered Cost (high)	1

DRP

	Media	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8	Criterion 9	Total
Crushed concerete	5	0	0	4	2	3	1	-2	3	3	14
Soil (no clay)	6	0	0	3	2	1	1		4	3	14
Peat/Sphangum peat	9	0	0	1	2	2	1.5		4	3	13.5
Sand	3	0	0	4	1	2	1		3	2	13
Vetiver grass	1	0	0	4	2	2	2		1	1	12
Lime	2	0	0	4	2	3	1	-1	2	1	12
Zeolite	4	0	0	2	2	3	1		3	1	12
Apatite/limestone 50-50% ,	7	0	0	4	0	3	0		2	1	10
Apatite pellets	8	0	0	4	0	3	0		2	1	10
Andesite/refuse	10	0	0	4	2	2	0	-2	1	1	8

Step 1b: Input scoring using these values

Criterion 8	Score
Scale of Availability: farm scale	4
Scale of Availability: local/country sca	3
Scale of Availability: Continent scale	2
Scale of Availability: International scal	1

Criterion 9	Score
Delivered Cost (low)	3
Delivered Cost (medium)	2
Delivered Cost (high)	1

Figure 4: Nitrate (top) and DRP (bottom) examples with the top ten media options re-shuffled due to inclusion of dynamic criteria scores. Criterion 8 gets a score of 4 if it is local but 1 if it needs to be imported into the area. The highest score ranks as the best media across all 9 scores.

Step 2: Sustainability Criterion

In the example used after running the DST the final selection of materials for nitrate is shown (Figure 4 top). From the highest to the lowest score, woodchip, vetiver grass, zeolite, granular activated carbon, crushed glass, immature compost, sand, cardboard and barley straw + (native) soil are the recommended media for nitrate removal. The DST already considers the sustainability criterion and the reuse potential of these materials as soil amendments, either as a fertilizer source or soil improver. Only the materials with the highest removal rates, which will in theory have a higher nitrate load after saturation, can be considered as a fertilizer source after they become saturated. According to Figure 4, the materials with higher removal capacity (criterion 4) are woodchips, immature compost, cardboard and barley + (native) soil. However, cardboard would not be recommended for land spreading and other disposal options for this material should be investigated. The materials with a lower nitrate removal capacity can be used as soil amendments instead. From the materials on the list, immature compost, coco-peat, woodchip, vetiver grass, and barley straw + soil can be used to improve the soil structure. For example, Luna et al. (2018) showed that woodchips increased soil porosity, improved water infiltration and reduced runoff against no other restoration technique in a mine soil. Other media, such as sand and zeolite, can be used for farm roadway fill. Crushed glass should in turn be disposed of in landfills with reduced possibilities for land application. It is important to note that besides from the characteristics of the materials, the presence of heavy metals or pathogens, concentration of organic matter and other characteristics of the water stream in the drainage system will determine the potential reuse of these media.

In terms of DRP removal, the final selection, from the highest to the lowest score, are crushed concrete, soil, peat, sand, vetiver grass, lime, zeolite, apatite/limestone, apatite pellets, and andesite (Figure 4 bottom). From the figure, the materials with highest DRP removal efficiency (criterion 3) are sand, zeolite, vetiver grass, concrete, andesite and apatite. This indicates that industrial by-products have high P removal capacity and are often readily available and cheap. Similar to nitrate removing media, after saturation of these materials is reached, they could potentially be applied to the soil as fertilizer. However, it is important to test beforehand how much of the adsorbed P will be plant available considering that some P-loaded filter media have been described as slow release fertilizers because most of the P is bound to Ca, Fe or Al and is only slowly available over time. When the availability or total concentration of P is low, some of these spent media could be applied to the soil to increase the pH (lime and apatite/limestone), to improve soil structure (peat, vetiver grass) or simply to fill farm roads (crushed concrete, sand, zeolite, apatite or andesite). Nonetheless, the risk of transferring secondary pollutants to the soil should be assessed and naturally sourced media should be considered as preferred options to avoid pollution swapping. Also, the lifetime of the medium should be investigated due to the fact that a saturated medium might turn into a source of P releasing the adsorbed nutrient back into the drainage water.

Fenton et al. (2014) proposed that denitrifying bioreactors should be analysed holistically during their lifetime. This of course is not always practical, but results from small scale laboratory testing could be used to infer design alterations or specifications that could prevent losses in a field scale installation. This involves developing a sustainability index (SI), which incorporates data from the bioreactor inlet and outlet data. This balance approach enables the "losses" (if any) in the system to be identified. Positive and negative balances of each parameter indicate removal or production, respectively, of the parameter of interest.

This analysis indicates which parameters require additional interventions for the system to be environmentally sustainable. For example use of a soil cap to prevent gaseous losses could be introduced or where DRP and sediment are issues these could also be remedied with bespoke cells at the start of the bioreactor. The iterative approach envisaged a dynamic denitrifying bioreactor (called a permeable reactive interceptor (PRI) with a baffled design) whereby knowledge regarding the operation of the system could be used to minimise the footprint of the system thereby increasing its sustainability. Complete removal of nutrients without pollution swapping is the ultimate goal, but thresholds imposed by environmental legislation may not be so stringent. Therefore, a SI may be developed for various scenarios, taking water and/or gaseous emissions into account. Healy et al. (2015) and Fenton et al. (2016) adopted this method of analysis in the evaluation of laboratory and pilot scale denitrifying bioreactors containing various C-rich media and found that the SI varied with the scenario being examined. All parameters are expressed in g m^{-2} (of bioreactor surface area) d^{-1}. A SI can be created by summation of all parameters found in Fenton et al. (2014) (Eq 1):

$$SI = a\left(B_{N_2O}\right) + b\left(B_{NO_3^-}\right) + c\left(B_{CH_4}\right) + d\left(B_{CO_2}\right) + \text{etc....}$$

where B_x denotes the net loss (either positive or negative) of a specific contaminant from the denitrifying bioreactor, and a, b, c, etc. are weighting factors (WFs) that depend on the context of the analysis (e.g., legislative, environmental, geographical).

As can be seen from a series of Figures 5-7 a pilot scale facility was built in the SE of Ireland to test the pollution swapping potential of these systems and to generate data for a SI and Eq 1.

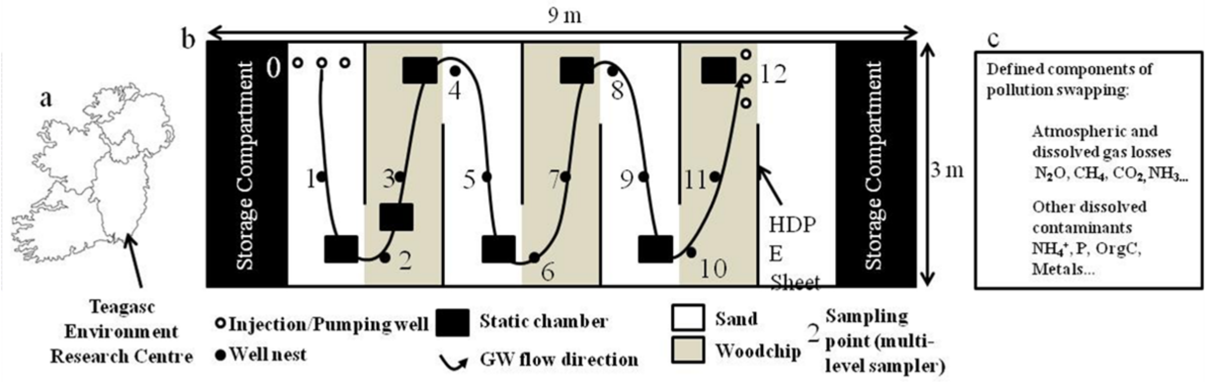


Figure 5: A pilot scale denitrifying bioreactor designed to test these systems in a holistic manner. a) The pilot scale facility is located in the SE of Ireland b) the design of the baffled system aims to create a longer pathway and c) explains the defined components of pollution swapping which were tested and used in Eq 1.

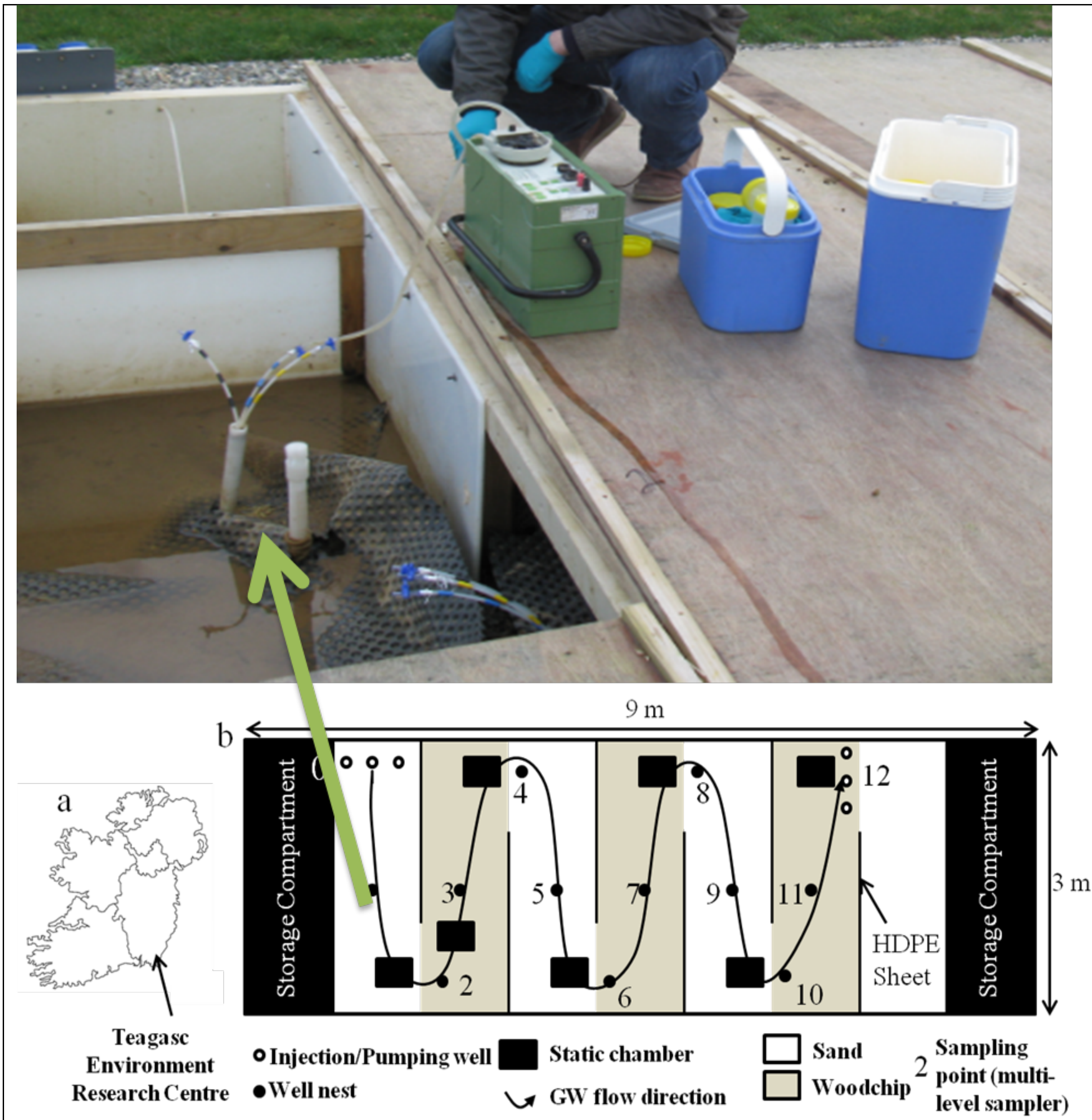


Figure 6a: Each of the cells has a series of multi-level piezometers to examine nutrient breakthrough at multiple depths. In addition, gas chambers were placed on top of the woodchip media over time to assess gaseous emissions. Such data is fitted into Eq 1.

Figure 6b: Private farm: Denitrifying woodchip bioreactor in Illinois, USA designed without a soil cover with surface gas emissions sampling chambers shown; Credit: L. Christianson/UIUC and Illinois Farm Bureau.

Figure 6c: Installation of monitoring points. Monmouth 2017: Denitrifying woodchip bioreactor installation in Illinois, USA with monitoring wells shown; Credit: J. Chandrasoma/UIUC.

Figure 7: The data obtained from the pilot scale denitrifying bioreactor is fed through Eq. 1 and the leaks (if any) in the system are realised. This knowledge can inform the next steps to be taken.

Step 3: Denitrifying woodchip bioreactors: design and construction guidelines

The design and construction of denitrifying woodchip bioreactors for the treatment of nitrate in subsurface drainage water in the US Midwest is generally guided by the federal design standard from the United States Department of Agriculture Natural Resources Conservation Service (Conservation Practice Standard 605: Denitrifying bioreactor) (USDA NRCS, 2015). Most bioreactors are designed based on principles of flow through porous media (e.g., Darcy's Law, Forchheimer's equation) paired with the concept of reactor hydraulic retention time (Christianson et al., 2011; Cooke and Bell, 2014; Ghane et al., 2014).

Reduced in-field drainage capacity due to a conservation practice like denitrifying bioreactors is not looked on favourably by producers and landowners, thus a bioreactor's by-pass flow pipe (Figure 8) is an essential design component to maintain drainage capacity during higher flow events. This means a portion of the total annual flow volume by-passes a bioreactor. However, most fields would require an impractically large bioreactor to treat all of the annual drainage volume, with such a bioreactor overdesigned for the low flow rates occurring much of the year.

Bioreactors for tile drainage have either one or two control structures to direct the water correctly and also internal plumbing manifolds to distribute (inflow side) and collect (outflow side) flow (Figure 8). The flow is driven by the head gradient created across the media chamber following principals of flow through porous media; no pumps are required, which helps minimize cost. The USDA NRCS design standard recommends a design hydraulic retention time of 3 hours, which is the minimum HRT the bioreactor should operate at (that is, water should stay in the bioreactor for at least 3 hours at the highest flow rate the bioreactor treats) (USDA NRCS, 2015).

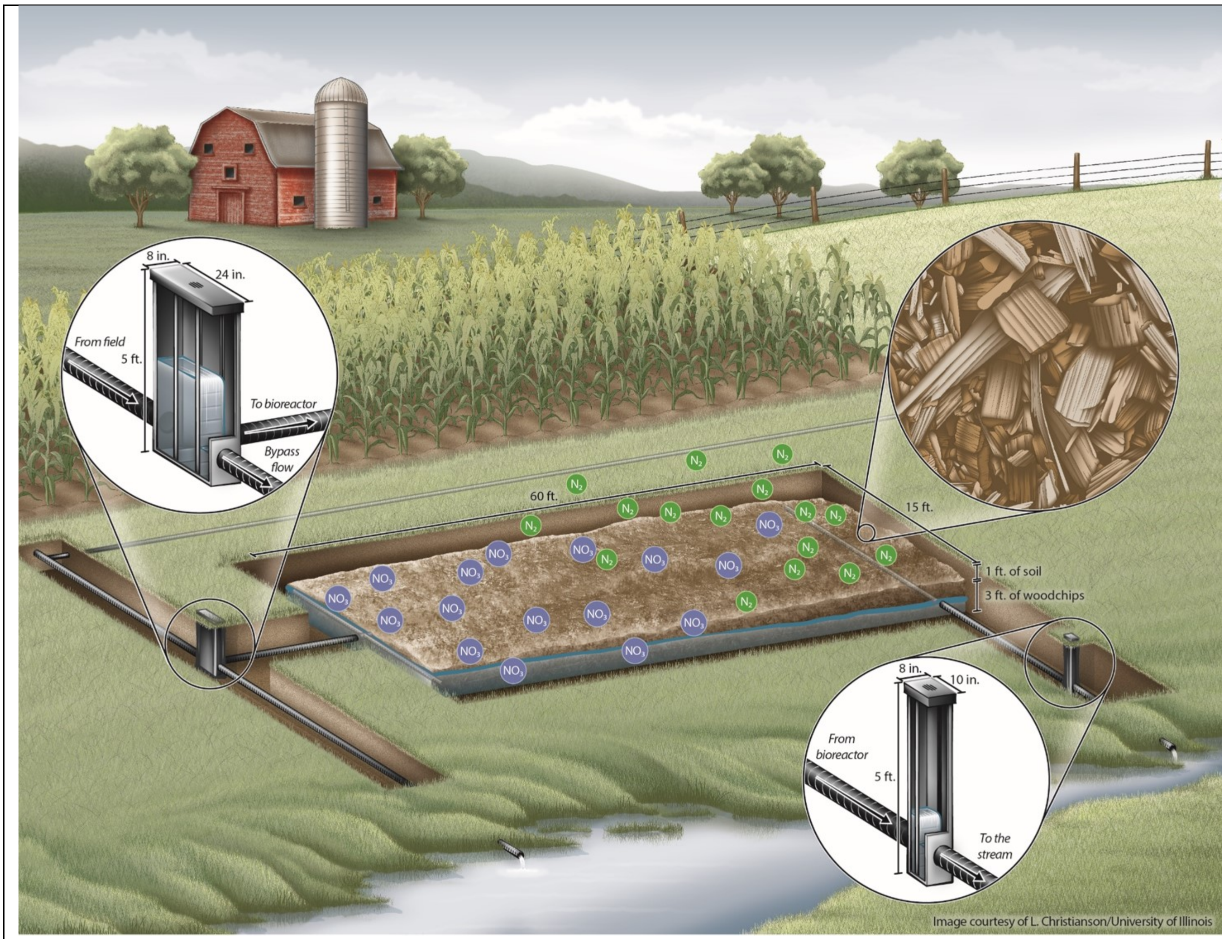


Figure 8: Generalized schematic of a denitrifying bioreactor to treat nitrate in subsurface drainage in the US Midwest. Credit: L. Christianson/University of Illinois.

Figure 9a: Denitrifying bioreactor during construction on a farm in Illinois, USA. *Credit: Illinois Farm Bureau.*

During construction (Figure 9a), the control structures are usually placed first based on what is generally an existing subsurface drainage system. The control structures are connected to the bioreactor plumbing manifolds using solid (non-perforated) drainage pipe for generally at least 3 m to minimize seepage around the bioreactor. The bioreactor chamber is then excavated and is lined with impermeable plastic. The chamber is filled with woodchips. As can be seen from Figure 9b, once the site is covered over the control structure is the only visible element above ground.

Use of a soil cover on top of the woodchips is optional. If a soil cover is used, a geo-fabric (breathable landscaping fabric) is placed on top of the woodchips and some of the excavated soil spoil is used to create the soil cover. The top of the bioreactor is mounded (either the woodchips themselves if no soil cover is used; or the soil cover itself) to shed water and prevent ponding as the woodchips degrade over time. If a soil cover is used, it should be seeded to prevent erosion. Woodchip excavation and replacement after the initial design life (that is, woodchip "recharge") is easier to do if a soil cover is not used. However, there is anecdotal evidence that using a soil cover may provide a benefit in terms of reduced nitrous oxide emissions, and a soil cover may help mitigate side wall cave-ins as the woodchips degrade and slump over time. Research consistently shows denitrifying bioreactors efficiently convert nitrate to stable di-nitrogen gas with little production of nitrous oxide (e.g., less than 5% of nitrate ends up as nitrous oxide; Elgood et al., 2010; Greenan et al., 2009; Warneke et al., 2011; Woli et al., 2010). Elevated phosphorus concentrations in bioreactor outflow compared to inflow have been observed in the field (Herbstritt, 2014), but laboratory studies (as well as unpublished field data; per. comm. L. Christianson) indicate woodchips may also have an ability to reduce dissolved phosphorus concentrations at least over short periods of time (Goodwin, 2012; Zoski et al., 2013).

Wood-based denitrifying bioreactors have never required denitrifier inoculation; nitrate removal is nearly always observed immediately upon flow initiation. The major start-up challenge is that bioreactors elute an organic flush in initial tea-coloured effluent which typically lasts a few days to weeks depending on the flow rate, start-up conditions, and media selection.

Figure 9b: Completed denitrifying bioreactor in Iowa, USA. The white pipes are water sample monitoring wells and dark gray rectangle is the inflow control structure. *Credit: L. Christianson.*

Concluding remarks

A denitrifying bioreactor is a bespoke engineered technology that is currently used worldwide to manage reactive nitrogen on agricultural land that has an artificial drainage system in place. Systems should be assessed in terms of their sustainability and where needed adopted to facilitate mixed contaminant mitigation. The filling material of the bioreactor can be adjusted based on the local requirements and availability of the reactive media using the FarMit Tool.

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