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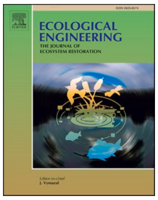

Nature-based solutions for nutrient pollution control in European agricultural regions: A literature review

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ABSTRACT

There is an increasing attention on Nature-based Solutions (NBS) to address social and environmental challenges in Europe, including the control of excess nutrients conveyed by agricultural regions. Indeed, the excess of nutrients has been recognized as one of the main reasons of failure to achieve a good ecological status of water bodies, according to the European Water Framework Directive 2000/60/EC. In this study we consider NBS to control two main sources of nutrient pollution in agricultural regions: excess manure from intensive livestock breeding, and diffuse pollution due to fertilizers applied on fields. The NBS typically adopted to address these two sources of pollution are wetlands in addition, for diffuse pollution, to vegetated drainage ditches and buffer strips. From a review of 767 peer review articles, we built a dedicated dataset including a total number of 444 NBS cases. These were analysed to obtain an overview of: (i) the range of climate, landscape and design variables under which the above typologies of NBS have been implemented; (ii) their performances for nutrient pollution control, in terms of removal efficiency on concentrations and mass load removal per unit of surface; (iii) the relationships between landscape, climate, and design variables and treatment performance. The results are presented in order to guide future planning of NBS for pollution control in European agricultural regions.

1. Introduction

The surplus of nutrients from agriculture has been recognized as one of the main reasons for European water bodies not achieving good ecological status according to the European Water Framework Directive 2000/60/EC (Vigiak et al., 2021). Nature-based Solutions (NBSs) can be a valuable option for intercepting and treating various streams of nutrient pollution from agriculture.

NBSs have already been used for manure treatment. Free water surface (FWS) constructed wetland (CW) systems have been documented since the early 1990s as a viable solution for swine wastewater treatment particularly in the US (Knight et al., 2000). However, the land requirement of extensive FWS appears less suited to European conditions, and few full scale FWS systems have been documented in the literature for European countries, mainly Belgium (e.g. Poach et al., 2004; Poach et al., 2007; Hunt et al., 2006; Meers et al., 2008; Mancuso et al., 2021). Innovative solutions have been studied in order to minimize the areal footprint of NBS for manure treatment, such as the use of subsurface flow wetlands (Kato et al., 2013; Zhang et al., 2017), highly adsorbent filling media such as zeolites (Borin et al., 2013), or aerated wetlands (Masi et al., 2017).

NBS may also help manage diffuse pollution due to excess fertilization. This is another case where use of FWS wetlands is well-known (Vymazal, 2007), and their performance in terms of nitrate removal has already been reviewed by Kadlec (2012) and, more recently, by Ioannidou and Stefanakis (2020). Another type of NBS suited for this goal are the so-called vegetated drainage ditches (VDD), (Kumwimba et al., 2018), i.e. agricultural drainage ditches properly vegetated and shaped to provide the same physical and biological processes occurring in FWS wetlands. A third type of NBS for diffuse pollution control are buffer strips for the interception of surface runoff water (BS-R) or groundwater (BS-G) (Stutter et al., 2019; Vidon et al., 2019); BS-R and BS-G have their own peculiarities, especially in terms of target pollutants and proper functioning conditions. The removal mechanisms and treatment performance of BS-R and BS-G have been reviewed by Zhang et al. (2010) and Hill (2018, 2019), respectively.

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Although water management policies increasingly support the use of NBSs, we still lack a coherent overview of their application in particular for nutrient pollution removal. Recently Mancuso et al. (2021) have examined which NBS can provide nutrient pollution control in agriculture, discussing the removal mechanisms of both wetlands and buffers strips in the same review. However, a quantitative review of both wetlands and buffer strips removal performance is still needed to properly guide future decision on NBS policy in agriculture. To this end, based on an extensive literature review, this work provides an overview of:

- (i) the range of climate, landscape and design variables under which selected categories of NBS have been implemented;
- (ii) their performances for nutrient pollution control, in terms of removal efficiency on concentrations and mass load removal per unit of surface;
- (iii) the relationships between landscape, climate, and design variables and treatment performance.

The insights gained with this overview may support the planning of NBS for nutrient pollution control at European scale. Our analysis focuses on the following types of NBS, visualizing their possible placement in the context of the streams of nutrient pollution within a typical agricultural catchment in Fig. 1:

1) CW for the management of manure
2) FWS wetlands for diffuse pollution
3) VDD,
4) BS-R and BS-G.

In the following sections, we describe the outcomes of the literature review, the dataset on NBS built from the information retrieved, and the results of the ensuing statistical analysis.

2. Materials and methods

2.1. Literature review: Data retrieval and preparation

A systematic literature review was conducted to identify, select and critically evaluate the variables, application limitations and performance levels of the various NBSs under investigation. Our methodology is in line with the approaches of other environmental science studies, and meets the requirements of comprehensiveness, transparency and replicability by other researchers (Mengist et al., 2020).

The literature search was carried out in the well-known references database SCOPUS (www.scopus.com) adopting the following search settings:

- Fields: Article, Abstract, Keywords;
- Document type: Article, Review, Book, Book Chapter (i.e. excluding Conference Paper);
- Language: English.

For each NBS type we defined a search string of relevant keywords, based on the recent literature reviews discussed in the introduction section and reported in Supplementary material (SM). The search identified $n = 1282$ peer reviewed articles of potential interest (NBS for manure treatment: $n = 285$; NBS for diffuse pollution control: $n = 997$), as detailed in the SM. A rapid expert judgment screening allowed a selection of articles consistent with the objectives of this research, reducing the peer review articles of potential interest to $n = 767$. Then we discarded all papers reporting mesocosm studies or anyway cases not sufficiently representative of real conditions as well as all the studies not referred to climatic conditions representative of European continent (e.g. cases reflecting a tropical climate).

We extracted the relevant information from each paper in order to create a consistent dataset. For NBS of type CW for manure management, we complemented the data from the literature with the Livestock Wastewater Management database (LWDB - Knight et al., 2000).

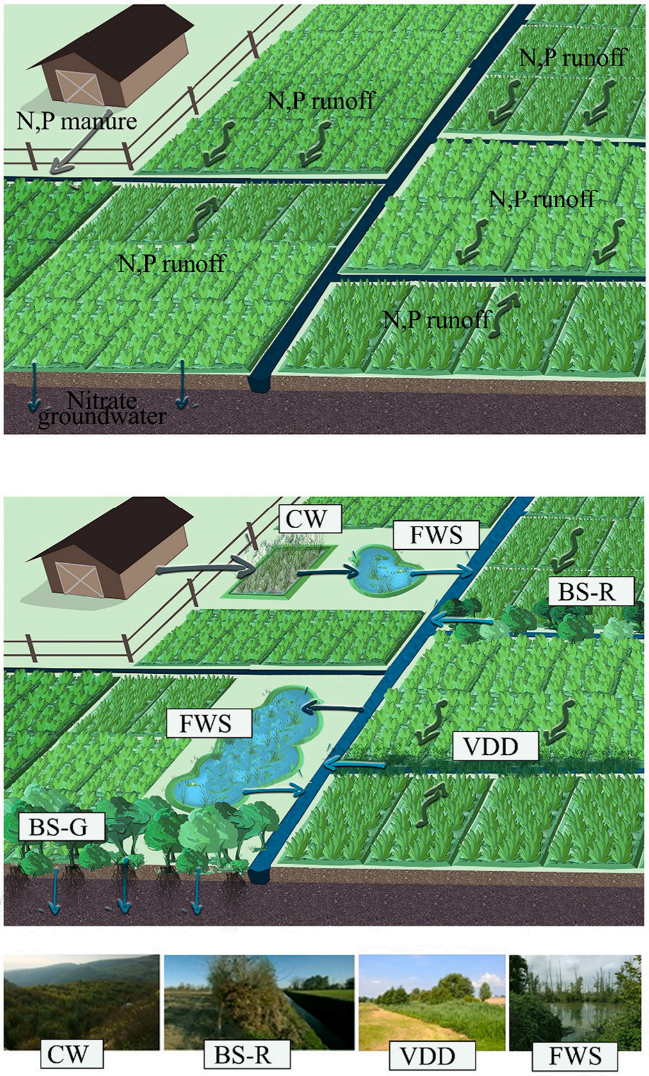

Fig. 1. Graphical representation of current nutrient pollution loads generated by agricultural regions, NBS applications for different type of agricultural pollution and full-scale examples of NBS applied to intercept nutrient pollution loads generated by agricultural regions. CW: constructed wetlands [picture: constructed wetland for swine wastewater treatment at SASA Srl farm (Roverè Veronese, Veneto Region, Italy; courtesy of IRIDRA Srl)]. FWS: constructed wetlands with free water surface [picture: free water surface wetland for diffuse pollution control (Salzano, Veneto Region, Italy; courtesy of Bruno Boz)]. VDD: vegetated drainage ditches [picture: vegetated drainage ditch (Czech Republic; courtesy of Jan Vymazal)]. BS-R: buffer strips for interception of surface runoff. BS-G: buffer strips for groundwater interception [picture: buffer strip for groundwater interception (Scandolara, Veneto Region, Italy; courtesy of Bruno Boz)].

When necessary, we resorted to external sources for the definition of missing landscape and climate variables (e.g. altitude, latitude, longitude, temperature, etc.); when not possible otherwise, missing information was filled through assumptions. All details on hypotheses, external data sources and assumptions are detailed in the SM.

Eventually, we developed a dataset (also provided as SM) covering:

- CW for manure treatment (see SM – Attachment 1) ($n = 129$ samples of which $n = 58$ samples from peer review literature and $n = 71$ samples from the LWDB);

- VDD and FWS wetlands for diffuse pollution (SM– Attachment 2) ($n = 29$ samples for VDD and $n = 73$ samples for FWS);
- BS-R and BS-G for diffuse pollution (SM – Attachment 3) ($n = 95$ samples for BS-R and $n = 118$ samples for BS-G).

2.2. Statistical analysis

The purpose of the statistical analyses was to investigate which climate, landscape, and design variables could be significant to explain the treatment performance of the various types of NBS. We investigated the following contaminants:

- total nitrogen (TN), and phosphorus (TP), total Kjeldhal Nitrogen (TKN), 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and total suspended solids (TSS) for CW;
- TN, TP, nitrates ($N\text{-}NO_3$), and phosphates ($P\text{-}PO_4$) for FWS wetlands and VDD;
- TP, $P\text{-}PO_4$, TN, $N\text{-}NO_3$, Sediments, TSS for BS-R;
- $N\text{-}NO_3$ for BS-G.

In the following, we limit our considerations to nitrogen and phosphorus, while the results of the analysis for other pollutants of interest are reported in the SM. The reader can refer to that for the complete results.

For each type of NBS, we extracted from the dataset the statistics of values assumed by the relevant climate, landscape and design variables, and for each contaminant the statistics of removal efficiencies in the various types of NBS. This information alone is important in order to evaluate the applicability and expected performance of the NBS. Furthermore, we investigated the relationship between climate, landscape and design of NBS and their performance, following a procedure similar to the one recently applied by Ilyas et al., 2021.

As a preliminary step, we applied Multiple Correspondence Analysis (MCA) in order to identify the most and least significant variables, thus reducing the problem complexity, while also checking whether the data spontaneously collected among meaningful clusters.

Then we used Multiple linear regression (MLR) analysis to evaluate the statistical significance of climate, landscape, and design variables in explaining the removal performance of the various NBS for each pollutant under investigation. To this end, we built MLR models relating the removal performance to the variables retained as significant from the MCA, and we evaluated their goodness of fit by referring to the coefficient of determination (R^2), adjusted R^2, and Root Mean Square Error (RMSE). Moreover, we confirmed the meaningfulness of the variables and coefficients of the MLR models by expert judgment, based on design practice and literature evidence. The results of the MCA are not presented here for conciseness but are provided in the SM along with additional details on the MLR analysis.

3. Results and discussion

3.1. NBS removal performance

Datasets were analysed to evaluate the removal performance of each pollutant under investigation with the different NBS analysed, that is constructed wetlands for manure treatment and NBS for diffuse pollution control. The performance, where possible, was expressed in two ways: (i) percentage removal, considering influent and effluent concentrations; (ii) mass load reduction by specific area per unit of time (e.g. grams of nitrogen removed per square meter of wetland per year). The main results for each dataset are presented and discussed here, by reporting the data in the form of box-whisker plots among the different NBS of interest, as shown in Fig. 2.

The datasets are validated and analysed comparing the results with the most relevant literature (Vymazal, 2007; Zhang et al., 2010; Kadlec, 2012; Hill, 2018; Ioannidou and Stefanakis, 2020). Rationales of literature selection for comparison, tabular values together with other graphical representations are reported in the SM, along with results for other pollutants (e.g. COD, BOD5, TSS, sediments).

Generally, our dataset is in agreement with previous reviews in the literature for all the NBS analysed. For wetlands for manure treatment, we find usually higher removal efficiencies than the values reviewed by Vymazal (2007): 58.1% and 1029.7 $g_N\ m^{-2}\ y^{-1}$, compared to 41.2–44.6% and 247–630 $g_N\ m^{-2}\ y^{-1}$ for TN; 54.4% and 114.6 $g_P\ m^{-2}\ y^{-1}$, compared to 41.1–59.5% and 45–72 $g_P\ m^{-2}\ y^{-1}$ for TP. The higher results registered for nutrient removal of wetland for manure can be explained by the much higher influent concentrations in the cases covered by our review (average 163.4 mg/l for TN and 41.3 mg/l for TP) as to those in Vymazal, 2007 (14.3–68.4 mg/l for TN, 4.2–10.5 mg/l for TP). Fig. 2 indicates also that the values in our dataset are in line with the literature also for FWS wetlands and VDDs for diffuse pollution control. The removal performance is lower than the mean values of Vymazal, 2007, which can be explained by the lower influent nutrient concentrations in our dataset (mean value of 10.6 mg/l for TN, 0.8 mg/l for TP). However, it is in line with values recently reported in a review by Ioannidou and Stefanakis (2020). Moreover, our average value for the specific removal of nitrates by FWS wetlands and VDD (140 $g_{N\text{-}NO3}\ m^{-2}\ y^{-1}$) is in agreement with the interquartile range of 7.3–182 $g_N\ m^{-2} y^{-1}$ in Kadlec, 2012.

For BS-R, our dataset agrees with the review of Zhang et al. (2010): median removal for BS-R resulted equal to 72% and 74% for TN and TP, respectively, in agreement with the interquartile range from Zhang et al. (2010), equal to 55–85% for TN and 45–85% for TP. For BS-G, our dataset shows good agreement with data in Hill (2018): nitrate removal for BS-G (median 58%) is in line with the range of values reviewed by Hill (2018), equal to 43–99% under optimal functioning conditions for BS-G.

A higher efficiency (both in percentage and in terms of areal load removal) is expected for NBS dealing with more concentrated pollution (wetlands for manure and BS-R) in comparison with those addressing more diluted pollution (FWS wetlands and VDD for diffuse pollution) or groundwater (BS-G).

3.2. Role of landscape, climate, and design variables in NBS for nutrient pollution control

3.2.1. Statistical variability

The statistical variability of the main landscape, climate, and design variables from the datasets is reported in Table 1.

A first important aspect to compare in terms of design variables is the different types of pollutant sources, and therefore of the influent pollutant characteristics, that the investigated NBS face. The level of input nutrients concentrations treated by the various NBS is shown in Fig. 3. Indeed, when dealing with wastewater generated by manure, wetlands receive influent nutrient concentrations (median values 147.8 mg L^{-1} and 34.1 mg L^{-1}, respectively for TN and TP) higher than the ones faced by FWS wetlands and VDDs intercepting agricultural runoff (median values 7.9 mg L^{-1} and 0.2 mg L^{-1}, respectively for TN and TP). This can be considered the main aspect justifying the higher nutrient removal performance of wetland for manure in comparison to FWS and VDD for diffuse pollution, as observed in Fig. 2. Regarding buffers strips, BS-R intercepts mainly the sediments and their attached pollutants (median values 26.9 mg L^{-1} and 4.4 mg L^{-1}, respectively for TN and TP), which are more dependent on stochastic variability of rain events. On the other hand, BS-G targets to remove nitrates diluted in the groundwater (median value 7.7 mg L^{-1} for N-NO3), leading to a lower removal performance in comparison to BS-R (see Fig. 2) but more stable in time (less risk to an ineffective pollutant removal due a particularly intense rain event). It is also interesting to note from Fig. 3 the lower pollutant influent concentration intercepted by FWS and VDD than those of BS-R. This is consistent with the fact that BS-Rs are generally located close to the site where runoff is generated, whereas wetlands and VDD receive

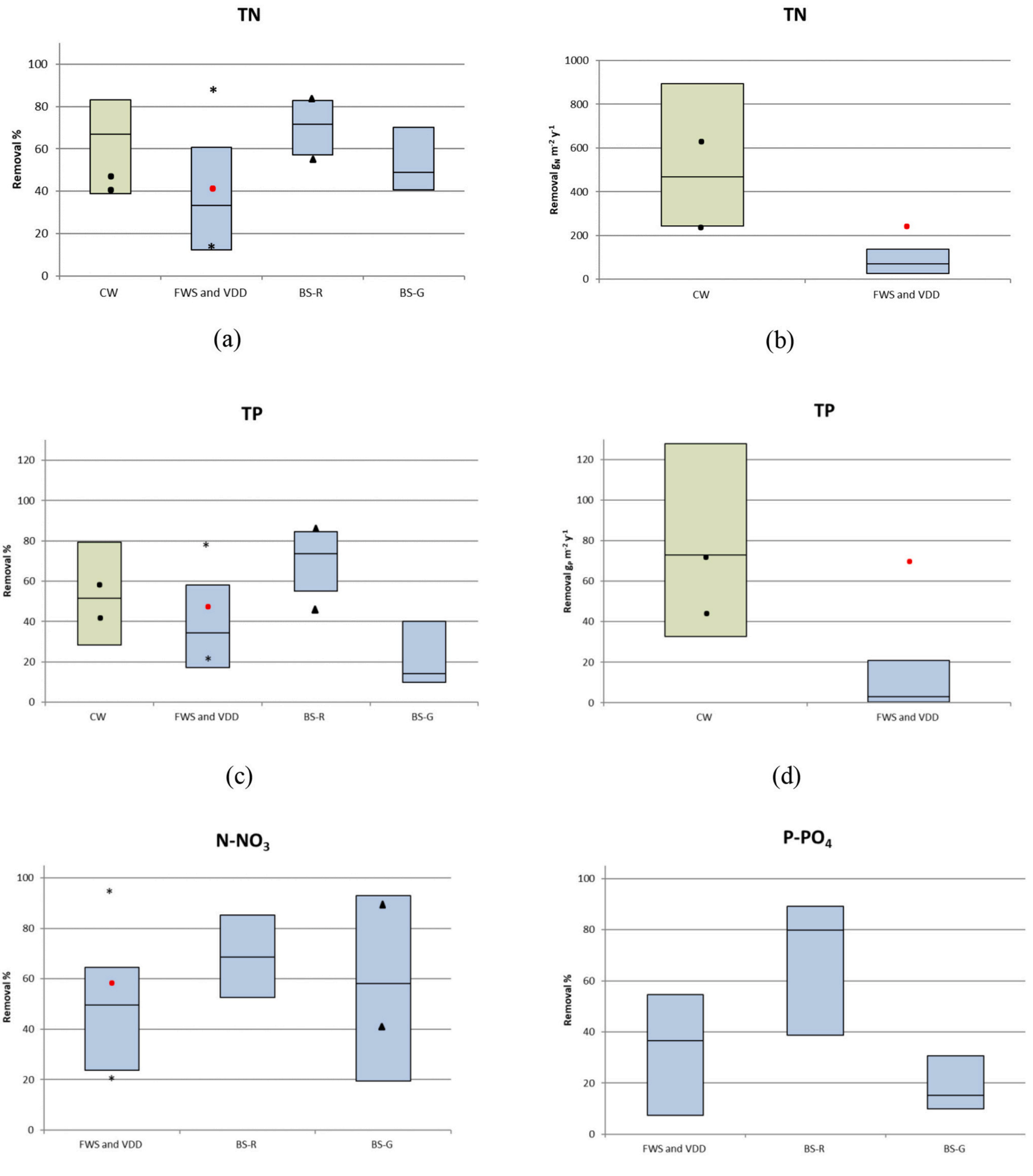

Fig. 2. Box-whiskers plots for nutrient removal performance of the different NBSs under investigation (in green wetlands for manure treatment; in blue NBSs for diffuse pollution): (a) percentage TN removal rate; (b) specific area TN load reduction; (c) percentage TP removal rate; (d) specific area TP load reduction; (e) percentage N-NO_3 removal rate; (f) percentage P-PO_4 removal rate. Range of value from Vymazal (2007) are reported to compare the results of wetland for manure (black dots; TN: 41.2–44.6% and 247–630 g_N $m^{-2}y^{-1}$; TP: 41.1–59.5% and 45–72 g_P $m^{-2}y^{-1}$). Results of wetland and VDD for diffuse pollution control are compared with average value of FWS as revised by Vymazal (2007) (red dots; TN: 41.2% and 247 g_N $m^{-2}y^{-1}$; TP: 48.8% and 70 g_P $m^{-2}y^{-1}$; N-NO_3: 60.7%) and range of values from Ioannidou and Stefanakis (2020) (black asterisks; TN: 14–90%; N-NO_3: 22–99%). Range of values from Zhang et al. (2010) and Hill (2018) are used to compare, respectively, the results for BS-R and BS-G (black triangles; TN for BS-R: 1st quartile 55%, 3rd quartile 85%; TP for BS-R: 1st quartile 45%, 3rd quartile 85%; N-NO_3 for BS-G: 43–99%). CW: constructed wetland; VDD: vegetated drainage ditch; FWS: free water surface (wetland); BS-R: buffer strips for runoff interception; BS-G: buffer strips for groundwater interception. N° of samples for box-whiskers plots: wetland for manure, 35 (a), 30 (b), 48 (c), 37 (d); FWSs and VDDs for diffuse pollution, 73 (a), 59 (b), 43 (c), 32 (d), 53 (e), 17 (f); BS-R, 51 (a), 47 (c), 51 (e), 36 (f); BS-G, 17 (a), 16 (c), 111 (e), 23 (f). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

– Statistical analysis of the most relevant landscape, climate, and design variables for wetlands for manure-driven wastewater, wetlands and vegetated drainage ditches for diffuse pollution, and buffer strips for diffuse pollution. HRT: hydraulic retention time; HLR: hydraulic loading rate; VDD: vegetated drainage ditch; FWS: free water surface (wetland); BS-R: buffer strips for runoff interception; BS-G: buffer strips for groundwater interception.

		Manure treatment		Diffuse pollution control							
		CW		FWS		VDD		BS-R		BS-G	
	Unit	Mean ± Std	25°-75° Perc.	Mean ± Std	25°-75° Perc.	Mean ± Std	25°-75° Perc.	Mean ± Std	25°-75° Perc.	Mean ± Std	25°-75° Perc.
Landscape											
Altitude	m slm	191 ± 248	46–246	120 ± 215	15–183	120 ± 215	15–183	284.3 ± 213.1	84.5–369.0	173.4 ± 251.7	35.0–191.0
Surface slope	%							6.1 ± 3.8%	3.0–8.5%	4.0 ± 4.2%	1.0–5.2%
Mean Water table depth	M									1.9 ± 2.0	0.8–2.5
Climate											
Average annual Temp.	°C	12.4 ± 4.3	8.8–15.9	11.4 ± 3.8	8.1–15.1	11.4 ± 3.8	8.1–15.1	11.2 ± 3.6	8.4–13.3	11.2 ± 3.6	8.4–13.3
Average annual n° of months with $T < 6$ °C	–	5.1 ± 2.0	5.0–6.3	4.9 ± 2.3	3.0–7.0	4.9 ± 2.3	3.0–7.0	5.6± 1.8	5.0–7.0	5.6 ± 1.8	5.0–7.0
Potential annual ET	mm y^{-1}	1264 ± 318	1087–1484	1145 ± 328	809–1300	1145 ± 328	809–1300	1163 ± 224	1016–1368	1163 ± 224	1016–1368
Average annual precipitation	mm y^{-1}			875 ± 334	624–1049	875 ± 334	624–1049	967 ± 242	787–1164	967 ± 242	787–1164
Design											
Area	Ha	0.7 ± 4.2	0.03–0.26	9.15 ± 35.10	0.02–0.80	0.13 ± 0.20	0.03–0.19				
Width	M			17.5 ± 25.2	3.0–19.3	4.3 ± 3.0	2.0–6.6	12.5 ± 10.9	5.0–15.7	25.7 ± 36.1	7.0–30.6
Aspect ratio	–			6.8 ± 5.9	5.0–5.0	127.0 ± 162.0	13.3–138.0				
Average depth	M	0.4 ± 0.3	0.2–0.6	0.5 ± 0.3	0.3–0.6	0.5 ± 0.3	0.3–0.6				
Wetland to watershed area ratio	–			1.2 ± 1.8%	0.1–1.2%	1.2 ± 1.8%	0.1–1.2%				
HRT	D	27.1 ± 30.6	7.9–32.8	13.1 ± 19.6	2.0–16.9	13.1 ± 19.6	2.0–16.9				
HLR	cm d^{-1}	3.9 ± 10.6	0.5–2.4	77.1 ± 140.9	6.9–88.0	77.1 ± 140.9	6.9–88.0				
TN loading rate	ton_N y^{-1} ha^{-1}	29.5 ± 62.2	2.9–14.7	7.7 ± 10.1	0.9–12.1	7.7 ± 10.1	0.9–12.1				
TN Input conc.	mg L^{-1}	263.4 ± 291.2	89.6–299.0	10.6 ± 12.1	4.1–12.9	10.6 ± 12.1	4.1–12.9	31.4 ± 24.8	11.1–62.1		
TP loading rate	ton_P y^{-1} ha^{-1}	2.2 ± 2.3	0.6–3.5	0.54 ± 0.98	0.02–0.63	0.54 ± 0.98	0.02–0.63				
TP Input conc.	mg L^{-1}	41.3 ± 30.5	19.6–59.1	0.82 ± 1.87	0.15–0.43	0.82 ± 1.87	0.15–0.43	8.0 ± 11.6	1.4–10.3		
$N\text{-}NO_3$ Input conc.	mg L^{-1}									12.0 ± 18.2	3.4–12.0

agricultural runoff already diluted with surface water of agricultural drainage ditches or small streams.

Among the design variables of wetlands for manure treatment, the hydraulic retention time (HRT) has a median value of 15.4 days. This is rather high in comparison to treatment wetlands for domestic wastewater and results from a high number of cases of extensive free water systems (FWS) for manure treatment included in the dataset, particularly from the US. Table 1 also provides useful indication of ranges of variability for other design variables of interest for NBS for manure treatment: wetland average depth (interquartile range 0.2–0.6 m), hydraulic loading rate (interquartile range 0.5–2.4 cm d^{-1}), total nitrogen loading rate (interquartile range 2.9–14.7 ton_N y^{-1} ha^{-1}), and total phosphorous loading rate (interquartile range 0.6–3.5 ton_P y^{-1} ha^{-1}).

With the regard of FWS wetlands and VDDs for diffuse pollution control, despite different aspect-ratio (i.e., length to width ratio), planning can be guided by a number of common design variables, for which the dataset provides useful range of variability in Table 1: average depth (0.3–0.6 m, 25th - 75th percentiles), hydraulic loading rate (6.9–88.0 m cm d^{-1}, 25th - 75th percentiles), total nitrogen loading rate (0.9–12.6 ton_N y^{-1} ha^{-1}, 25th - 75th percentiles), and total phosphorous loading rate (0.02–0.63 ton_P y^{-1} ha^{-1}). Therefore, key design variables such as nitrogen, phosphorous, and hydraulic loading rates differs significantly between wetlands applied for manure rather than agricultural pollution control, as visualised Fig. 4, variability that should be properly considered in NBS planning phase.

Another important design variable for wetlands and VDDs for diffuse pollution control is the wetland-to-watershed area ratio (WWAR: Kadlec and Wallace, 2009). The WWAR can be very useful for a preliminary evaluation of the areas needed to implement effective NBS of this type. The typical range of WWAR is between 0.1% and 1.2% (25th - 75th percentiles, respectively), in agreement with the range reported by Kadlec and Wallace (2009). Regarding buffer strips, width is the key design variable, as known from previous research studies (Stutter et al., 2019; Vidon et al., 2019). Table 1 suggests a clear range of values for an effective application (25th - 75th percentiles): 5.0–15.7 m for BS-R and 7.0–30.6m for BS-G.

Finally, it is important to highlight that the range of removal performance discussed in section 3.1 should be considered linked to the specific variability of landscape and climate variables reported in Table 1. In particular, landscape characteristics are important for the effectiveness of buffer strips: BS-R are included in a specific range of surface slopes (3.0–8.5%, 25th - 75th percentiles), while BS-G require

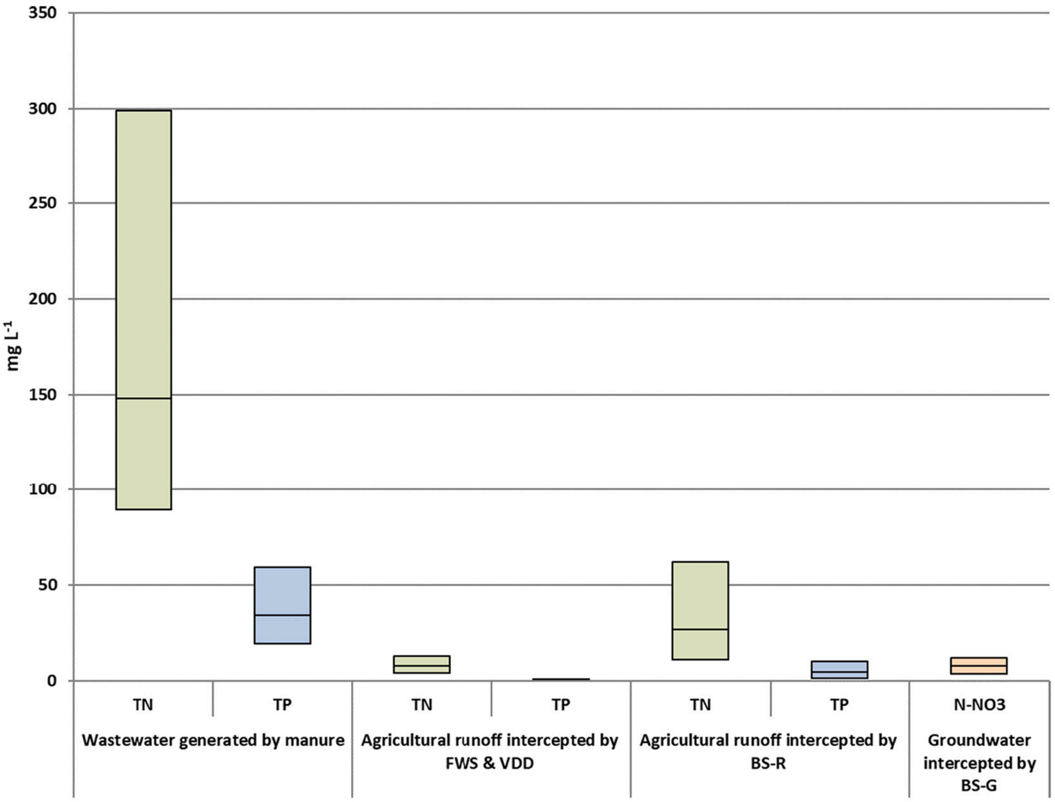

Fig. 3. Box-whiskers plots for influent nutrient concentrations intercepted by the different NBSs under investigation (in green TN concentration; in blue TP concentration; in orange N-NO_3 concentration). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
VDD: vegetated drainage ditch; FWS: free water surface (wetland); BS-R: buffer strips for runoff interception; BS-G: buffer strips for groundwater interception.
N° of samples for box-whiskers plots: wastewater generated by manure, 34 (TN), 43 (TP); Agricultural runoff intercepted by FWSs and VDDs, 55 (TN), 38 (TP); BS-R, 51 (TN), 48 (TP); BS-G, 110 (N-NO_3).

shallow water table depths (0.8–2.5 m, 25th - 75th percentiles), in agreement with literature evidence (Stutter et al., 2019; Vidon et al., 2019).

3.2.2. *Statistically significant variables for removal efficiencies*

This section presents the results of the MLR. Table 2 summarises the main results in terms of significance of landscape, climate, and design variables on NBS treatment performance, based on the MLR. All details on MLR statistical performance are detailed in the SM.

Regarding wetlands for manure treatment, both positive and negative dependence of the removal efficiency on the explanatory variables of the linear regression models for TN and TP retain a physical meaning and are in accordance with the literature (see Kadlec and Wallace, 2009). In particular, it can be noted that (see Table 2):

— the negative coefficients of water inflow (for TN) and phosphorus loading (for TP) can be explained as they imply a shorter hydraulic retention time of the system, all the rest being equal;

— the negative coefficients of the Boolean variable of presence of mixed wastewater and runoff can be explained with the lower expected concentration, hampering the biological removal processes in wetlands due to worsening performance of bacteria (Kadlec and Wallace, 2009; Vymazal, 2007);

— the negative coefficient of the Boolean variable of presence of manure from poultry farms is expected, since poultry is more difficult to treat than pig manure, most probably due to the extremely high ammonia concentrations which are typical for this waste. Indeed, fewer CW applications for poultry manure treatment have been found in the literature– see SM– Attachment 1);

— the negative coefficient of the Boolean variable of use of the wetland as a tertiary treatment (i.e. after a secondary treatment stage, either NBS or conventional wastewater treatment plant) is consistent with the lower expected influent concentrations, for the same reasons explained above;

— the positive coefficient of the Boolean variable of presence of porous media filling is also justified, as it is a proxy of the use of additional media to improve performance, such as a hybrid CW with also subsurface flow systems;

— the negative coefficient of the Boolean variable of presence of emergent vegetation only in wetlands is justified, since, especially in FWS, a greater biodiversity is expected to improve the plant nitrogen uptake of the NBS;

— the positive coefficient of NBS area is also expected as P is mainly removed by sorption processes (adsorption, absorption, plant uptake) in wetlands (Kadlec and Wallace, 2009; Vymazal, 2007), therefore, a larger NBS area means more adsorption sites and plants for uptake, and therefore, greater possibility of removing P, all other things being equal.

Also in the case of FWS wetlands and VDD, the dependencies on the variable of the selected linear regression for TN removal (Table 2) are in accordance with literature on constructed wetlands (see Kadlec and Wallace, 2009). In particular, it can be noted that:

— the positive effect – i.e. higher TN removal % – with higher precipitation is significant, since it means that a greater load is treated by the wetland system;

— the negative effect – i.e. lower TN removal % – with higher global aridity index and higher evapotranspiration is also consistent, since greater water losses by evapotranspiration lead to higher effluent concentrations (due to water budget) and, therefore, lower removal

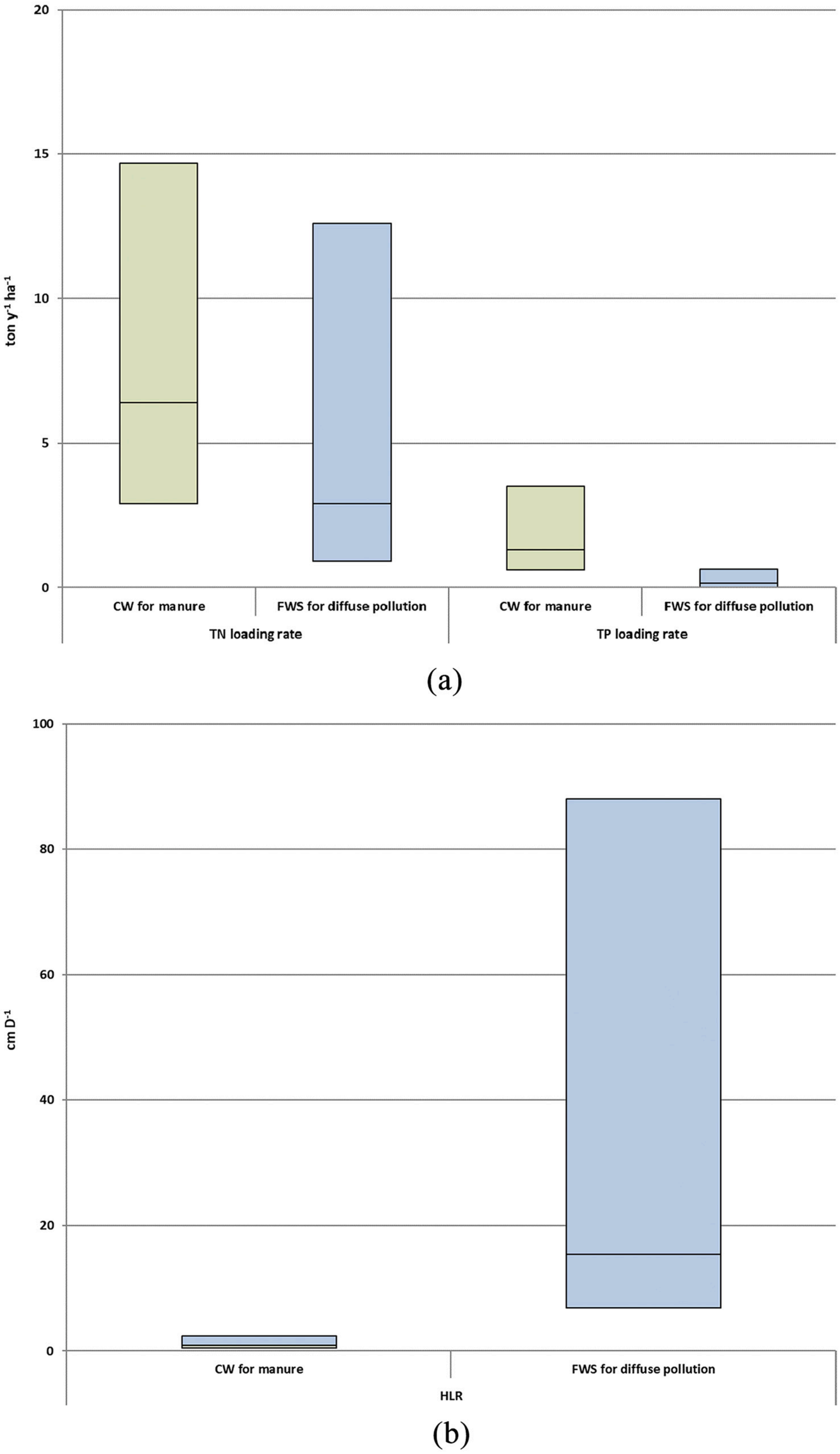

Fig. 4. Box-whiskers plots for the dimensional design variables of the different wetlands under investigation (in green wetlands for manure treatment; in blue FWSs for diffuse pollution): (a) TN and TP loading rate; (b) HLR. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
N° of samples for box-whiskers plots: wetland for manure, 30 (TN loading rate; a), 34 (TP loading rate; a), 37 (b); FWSs for diffuse pollution, 59 (TN loading rate; a), 33 (TP loading rate; a), 57 (b).

performance in % between in and out.

In terms of nitrate removal by FWS and VDD, the parameters of the selected linear regression (see Table 2) also agree with expert-based judgment and known literature (Kadlec and Wallace, 2009), in particular:

— the negative effect – i.e. lower N-NO_3 removal % – with a higher number of months with low temperature is consistent, since it is well-known that nitrogen removal in CWs is principally driven by bacteria sensitive to temperature variation (Kadlec and Wallace, 2009; Vymazal, 2007);

Table 2

– Results of the multiple linear regression analysis for investigated NBS. *** $p < 0.01$, high significance; ** $p < 0.05$, medium significance, * $p < 0.1$, significance. +, positive correlation with percentage removal. -, negative correlation with percentage removal. VDD: vegetated drainage ditch; FWS: free water surface (wetland); BS-R: buffer strips for runoff interception.

				Wetland for manure		VDDs and wetlands for diffuse pollution			BS-Rs for diffuse pollution
Selected parameters	Category	Type	Unit	TN	TP	TN	N-NO3	TP	TP
Average annual temperature (T)	Climate	Cardinal	°C						+***
Average annual precipitation (P)	Climate	Cardinal	cm y^{-1}	+**		+***			-***
Annual average nb. of months with mean temperature < 6 ° C	Climate	Cardinal	n° months y^{-1}				-***		
(maximum monthly precipitation – minimum monthly precipitation) / (mean monthly precipitation)	Climate	Cardinal	–				-*		
Annual Potential Evapotranspiration (PET)	Climate	Cardinal	mm y^{-1}			-**		-**	
Global aridity index (PET/P)	Climate	Cardinal	–			-***	-***		+***
Presence of clayey soil	Landscape	Binary	–						+**
Presence of runoff mixed with influent wastewater	Landscape	Binary	–	-***					
Wastewater originating from poultry farms	Landscape	Binary	–	-***					
The NBS is a vegetated drainage ditch	Design	Binary	–				+***		
Presence of emergent vegetation only	Design	Binary	–	-***	-***			+***	
Use of substrates additional to soil to enhance the performance (e.g. gravel, sand, zeolites, woodchip)	Design	Binary	–					+***	
The NBS is a wetland for tertiary treatment after primary and secondary lagoons	Design	Binary	–	-***	-***				
The NBS is a hybrid constructed wetland mixing surface and subsurface flow systems	Design	Binary	–	+**					
The NBS is a buffer strip of herbaceous vegetation	Design	Binary	–						+***
Area	Design	Cardinal	Ha		+***				
Width	Design	Cardinal	m						+***
Aspect Ratio	Design	Cardinal	–					+***	
Specific water inflow	Design	Cardinal	1000 $m^3 y^{-1} ha^{-1}$	-***	+***				
TN loading rate	Design	Cardinal	tN y^{-1} ha^{-1}						
N-NO3 loading rate	Design	Cardinal	tN y^{-1} ha^{-1}				-*		
TP loading rate	Design	Cardinal	tP y^{-1} ha^{-1}		-**				
Best fit linear model intercept	-	Cardinal	-	+***	+***	+***	+***	-***	-***

— a negative effect – i.e. lower $N\text{-}NO_3$ removal % – is also expected with a less uniform monthly precipitation pattern, since it can be correlated to a less uniform water flow entering the wetland and, moreover, less uniform hydraulic retention times, worsening the treatment performance;

— the negative effect – i.e. lower $N\text{-}NO_3$ removal % – with a higher nitrate loading rate can also be explained from a biological perspective, indeed, a higher nitrate load could encounter a carbon deficit for denitrification (Kadlec and Wallace, 2009); since the source of C in agricultural runoff is usually low and rather diluted, C deficit can hinder denitrification rates;

— the negative effect – i.e. lower $N\text{-}NO_3$ removal % – with a higher global aridity index is also reasonable for the same considerations made for TN removal;

— the positive effect – i.e. higher $N\text{-}NO_3$ removal % – if the NBS is a VDD instead of a FWS is less justified by literature, which shows comparable removal efficiencies (e.g. Vymazal and Březinová, 2018). Analysing in detail the dataset used for fitting, it is clear that the difference between VDDs and FWS is affected by a lower number of samples of VDDs and is mainly driven by the single case of Robertson and Merkley (2009), in which, probably, the use of a particular substrate (woodchips – carbon source for denitrification) boosted the nitrate removal. Since the use of a particular substrate is not the common design approach of a VDD, it is suggested to not consider a general greater denitrification performance of VDDs in comparison to FWS.

Regarding TP removal of FWS and VDD, the selected linear regression (see Table 2) highlight variables that are strongly in line with evidence from literature (Kadlec and Wallace, 2009; Vymazal, 2007), in particular:

— the negative effect – i.e. lower TP removal % – with a higher global aridity index is also reasonable for the same considerations made for TN removal;

— the positive effect – i.e. higher TP removal % – with a higher aspect-ratio is also reasonable, as it means running wetlands and VDDs more proximal to a plug-flow reactor, minimizing preferential paths;

— the positive effect – i.e. higher TP removal % – due to the presence of plants and additional substrates is also in line with the general understanding of P removal processes in wetlands, mainly driven by sorption by either plant uptake or adsorption on substrate (Kadlec and Wallace, 2009; Vymazal, 2007).

The case of buffer strips deserves some more elaboration. In fact, in spite of a representative number of cases in the dataset, robust indications on BS-R performance did not clearly emerge from linear regression analyses, reflecting the current high uncertainty on their removal performance and the removal mechanisms reported in literature (Vidon et al., 2019; Stutter et al., 2019). Indeed, also previous attempt at regression analyses often showed low fitting performance (e.g. Mayer et al., 2007). However, Zhang et al. (2010) present a more successful analysis and identify vegetation, slope, and width as key explanatory variables. The lack of an apparent relationship between removal and the explanatory variables that we used can be partly explained by the fact that, often, the cases of BS-R included in our dataset are already in optimal functioning conditions. For example, the optimal value of slope suggested by Zhang et al. (2010) is <10% and the 3rd quartile of our dataset is 8.5% (see Table 1), meaning that the samples were probably not sufficient to capture the detrimental effect of too high slopes with a linear regression analysis.

The only regression analysis with results in line with expert expectation and in line with literature evidence (e.g. Vidon et al., 2019) is for TP removal from BS-R, in particular (see Table 2):

— the positive effect – i.e. higher TP removal % – when clay is present is consistent with a higher P sorption capacity of clay particles;

— the positive effect – i.e. higher TP removal % – with higher temperatures and drier conditions (higher global aridity indexes) can be justified by less humid conditions, which favour a higher infiltration capacity of the soil and, therefore, greater infiltration of intercepted runoff (Vidon et al., 2019);

— the negative effect – i.e. lower TP removal % – with higher annual precipitation can be explained by a higher annual load to be intercepted, decreasing the buffer strip capacity to intercept the annual load;

— the positive effect – i.e. higher TP removal % – with a larger width is also in line with literature evidence (larger contact surface for TP interception) and in line with several literature studies (e.g. Zhang et al., 2010);

— the positive effect – i.e. higher TP removal % – in presence of herbaceous vegetation is also in line with the recent literature review (Vidon et al., 2019) since the higher density of shrubs helps to slow down the runoff, favouring infiltration and limiting preferential paths that can occur if only trees are planted.

Because of the lack of an adequate sample size for other contaminants, the analysis of BS-G was conducted on N-NO_3 only, which is the main target of buffer strips for groundwater interception (Vidon et al., 2019; Stutter et al., 2019; Hill, 2019). Despite a relatively large dataset (n° 107 samples), the regressions are able to explain only a small part of the variability of the abatement efficiency (see detailed results in SM). This can be explained by the fact that buffer strips for groundwater interception included in our dataset function under optimal conditions, as also reported by Gold et al. (2001). This is clear for the key variable for BS-G positioning (the optimal water table depth suggested by Dosskey and Qiu (2011) is than 2 m, and the 3rd quartile of our dataset is 2.5 m (Table 1), i.e. the samples were probably not sufficient to capture the detrimental effect of too deep water tables. Similar considerations can also be made for the width: Hill (2018) reviewed several studies and found that usually a width of <20 m for a BS-G placed where the water table is shallow is sufficient to reach 90% of nitrate removal efficiency. The median width of our dataset is 12 m, with a 3rd quartile of 31 m (Table 1). The fact that typical design variables (such as width and vegetation) prove not relevant emerges also in other similar studies, such as Mayer et al. (2007).

Finally, all the MLR for each NBS and pollutant have highlighted a high significance of the linear intercept (see Table 2). As detailed in the SM, the explained variance is usually not very high, suggesting that removal efficiency is essentially well represented as a constant value with some variability partly explained by the set of landscape, climate, and design variables discussed here.

4. Conclusions

To the best of our knowledge, this work is the first consistent literature review of two families of NBS, which are often addressed separately: wetlands and buffer strips.

In the planning of NBS, the pollution removal capacity per unit area, expressed as removed mass over a given time period, may be more meaningful than the percentage removal between influent and effluent concentrations. The order of magnitude of the removed mass is strictly related to the physical and biogeochemical processes that every specific NBS can naturally deploy. Unfortunately, quantifications of mass removal capacity have been more difficult to collect for buffer strips, hampering a proper comparison of the two NBS families for nutrient pollution control. In any case, the different NBS are not alternative, but have different fields of application, depending on where they can be located within an agricultural catchment. Buffer strips for surface runoff interception (BS-R) are usually located in the upstream parts of the catchments, while buffer strips for groundwater interception (BS-G) or extensive free water surface (FWS) wetlands are located downstream. Wetlands for manure treatment are located near point sources and not necessarily connected to the drainage network directly. For an agricultural watershed with various sources of pollution, the best option is probably a mix of all the NBS types discussed here. The data presented here concerning nutrient removal performance of the various NBS, as well as the range of landscape, climate and design variables under which these are implemented, provide a quantitative basis for a first sizing of solutions at a broad planning stage. We have shown that the performance depends primarily on design variables, but is influenced by landscape and climate to some extent. At the stage of detailed design, specific mathematical models should be used in order to simulate and optimize the performance of NBS (e.g. Canet-Martí et al., 2022), when justified by the scale and complexity of the problem.

At the same time, the statistical range of performances summarized in this work should not be considered as a fixed limit, but rather as reflecting the practice currently documented in the literature. Each of the NBS discussed here has the potential to be enhanced by innovative design techniques or management practices. For instance, aerated wetlands have shown promisingly higher nutrient removal performance for manure treatment (Masi et al., 2017). Diffuse pollution control of wetlands and VDDs can be improved by using carbon-rich materials to enhance denitrification (e.g. Robertson and Merkley, 2009; Liu et al., 2015), or P-sorbent materials that could also permit nutrient recovery (Altamira-Algarra et al., 2022). Minor geometrical and structural modifications as with low-grade weirs (Kröger et al., 2014; Baker et al., 2016) or two-stage ditches (Davis et al., 2015; Hodaj et al., 2017) could allow VDDs to have operational conditions more similar to FWS, leading to an enhancement of nutrient removal performance. Similar benefits have been suggested by reshaping the riparian zone where the buffer strips are placed, for instance by improving the direct interception of tree roots with groundwater (e.g., Gumiero and Boz, 2017), or including a permeable reactive barrier (e.g., Addy et al., 2016) and edge-of-field wetlands (e.g., Díaz et al., 2012; Zak et al., 2019). With the spreading of NBS at full scale and with the improvement of their performance following innovation and experimentation, the performance indicated by the statistics of the cases analysed in the literature are likely to improve.

Last but not least, properly designed multifunctional NBS for nutrient pollution control in agricultural regions may deliver a wider range of ecosystem services. Other pollutants can be removed by the same NBS, such as carbon loads (COD, BOD5) and sediments (TSS), for which statistical analyses of the NBS performance are reported in SM, or pesticides (Vymazal and Březinová, 2015; Tournebize et al., 2017, Kumwimba et al., 2018; Arora et al., 2010). NBS in agricultural regions can also contribute to flood control (Gumiero and Boz, 2017; Zak et al., 2019; Salazar et al., 2012; Acreman and Holden, 2013; Lane et al., 2018), landscape amenity (Borin et al., 2010; Russi et al., 2013), biodiversity support (Gibbs, 2000; Herzon and Helenius, 2008; Ma, 2008; McCracken et al., 2012; Strand and Weisner, 2013; Stutter et al., 2019), and production of plant biomass for use either as a carbon stock for climate change mitigation (Mitsch et al., 2013; de Klein and van der Werf, 2014; Maucieri et al., 2017; Cole et al., 2020) or as a renewable energy source (Avellán and Gremillion, 2019; Ferrarini et al., 2017). Therefore, planning of NBS for nutrient pollution control should incorporate all the relevant ecosystem services that a NBS can bring to agricultural catchments.

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Credit author statement

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Pistocchi A.: Supervision, Conceptualization, Methodology, Project administration, Funding acquisition, Writing - original draft, Writing - Review & Editing.

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Data availability

Data will be made available on request.

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