Hydrobiologia
https://doi.org/10.1007/s10750-025-05946-7

POND BIODIVERSITY AND FUNCTIONS

Vegetated buffer strips show variable capacity to reduce nutrient loading and sediment influx in ponds in two European countries

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Received: 6 March 2025 / Revised: 16 June 2025 / Accepted: 27 June 2025

Abstract Eutrophication is a pervasive threat to freshwater ecosystems, and while the implementation of vegetated terrestrial buffer strips is increasingly promoted as a measure to reduce nutrient runoff into riverine systems, little is known on their effectiveness in protecting ponds in agricultural landscapes. We investigated the effect of buffer strip width on pond nutrient concentrations (TN, TP), the concentration of total suspended solids (TSS) and phytoplankton biomass (CHLa) using data from 34 ponds located on agricultural land in Belgium and Germany. We found a strong negative relation between buffer strip width and the concentrations of TN, TP and TSS in the German set of ponds. While even small buffer strips (5 m) can already be effective, our results also show that larger buffer strips are considerably more effective. In contrast, we did not find an association between buffer strip width and the concentrations of TN, TP and TSS in the Belgian ponds. This could be linked to differences in landscape characteristics, historical eutrophication and pond hydroperiod between both countries. In addition, we did not find evidence for an effect of buffer strips on phytoplankton biomass, which is likely reflecting the fact that, even with buffer strips, nutrient concentrations remained very high in the studied ponds.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10750-025-05946-7.

Guest editors: Lena Fehlinger, Robert A. Briers, María Cuenca-Cambronero, Sandro Lanfranco & Dani Boix / Ponds for Biodiversity, Climate and People.

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Published online: 30 July 2025

Keywords Pond conservation · Eutrophication · Management measures · Nitrogen · Phosphorus · Suspended solids

Introduction

Small standing waterbodies such as ponds are abundant ecosystems in virtually all geographical regions on Earth (Downing et al., 2006). They deliver multiple vital ecosystem services (Downing, 2010; Biggs et al., 2017) and are recognized for their strong contribution to biodiversity (Williams et al., 2004; De Bie et al., 2007), often supporting multiple rare, endemic and threatened species (Biggs et al., 2000; Nicolet et al., 2004). Ponds are also key elements of blue landscape connectivity, serving as stepping stones for the dispersal of species (Fortuna et al., 2006; Céréghino et al., 2008). A vast number of ponds is located in intensively managed agricultural areas. Small ponds are especially vulnerable to the impact of surrounding land use (Declerck et al., 2006; Novikmec et al., 2016) due to their relatively small size and shallow depth, their high perimeter-to-volume ratio and the fact that they are often located in local depressions in the landscape (Gołdyn et al., 2015; Reverey et al., 2016).

It has been shown that agriculture in close proximity of ponds can enhance nutrient load (Moss et al., 2013; Musseau et al., 2022), sediment runoff (Robotham et al., 2021) and pesticide contamination (Lorenz et al., 2022; Almeida et al., 2023). Nutrient enrichment strongly affects the structure and the functioning of pond ecosystems (Scheffer & Jeppesen, 1998; Moss, 2008; Wurtsbaugh et al., 2019) and ultimately leads to the loss of aquatic biodiversity by promoting excessive algae and periphyton growth and the loss of submerged aquatic vegetation (Egertson et al., 2004; Phillips et al., 2016). Sediment influx coming from land erosion represent another threat to ponds due to increases in water turbidity and pond filling up leading to terrestrialization (Sayer & Greaves, 2020; Swartz & Miller, 2021).

The fact that small ponds respond strongly to land use in their close proximity and that they characteristically have small catchment areas (Davies et al., 2008) suggests that measures at relatively small spatial scale are likely effective in reducing adverse external influences of land use. One such measure is the creation of vegetated terrestrial buffer strips that reduce the inflow of pollutants from the surrounding terrestrial environment into the ponds (Englund et al., 2021). Buffer strips are commonly defined as an area of land separating agricultural land from valued aquatic or terrestrial habitats (Gene et al., 2019; Prosser et al., 2020). Previous studies on the effect of vegetated terrestrial buffer strips show that they can reduce diffuse pollution in streams (Stutter et al., 2012; Poole et al., 2013; Aguiar Jr. et al., 2015; Cole et al., 2020; Vormeier et al., 2023) through a range of physical, hydrological, chemical and biological processes (Vought et al., 1995; Tabacchi et al., 2000; Dosskey et al., 2010; Knight et al., 2010; Cole et al., 2020; Calvo et al., 2024). Fueled by the evidence for their effectiveness, the establishment of buffer strips around freshwater systems is increasingly implemented in management programs and policies directed at safeguarding freshwater biodiversity. In Germany, buffer strips are governed by multiple layers of legislation. The paragraph 38 of the German Water Resources Act (BGBl, 2009) mandates a minimum 5 m buffer strip along surface water bodies to protect against nutrient and pesticide runoff. Each federal state has the flexibility to adapt this requirement to local contexts, but the state of Brandenburg abides to it (paragraph 77a of GVBl., 2012). These provisions align with the National Action Plan on the Sustainable Use of Plant Protection Products (BMEL, 2013), which focuses on reducing pesticide-related risks. The Fertilizer Ordinance (paragraph 13a, BGBl, 2020) further restricts fertilizer application near surface waters, generally requiring a distance of 5 to 10 m, which may extend up to 30 m on sloped terrain. In Flanders (Belgium), buffer strip regulations addressing fertilizers and pesticides are also grounded in several key legislative texts. The Flemish Decree on Integrated Water Policy (article 9 to 10 of Belgisch Staatsblad, 2003) requires unfertilized zones of at least 5 m, and up to 10 m along surface water bodies in ecologically sensitive or sloped areas, to prevent nutrient runoff. The Flemish Manure Decree (Belgisch Staatsblad, 2006) sets further restrictions on the use, timing and quantity of nitrogen and phosphorus fertilizers. Complementing these, the Royal Decree on the Sustainable Use of Plant Protection Products and Additives (article 5 to 9 of Belgisch Staatsblad, 2013) regulates pesticide use, mandating untreated buffer zones along surface waters of typically 1 to 3 m, but up to 30 m depending on product toxicity. In both Belgium and Germany, these requirements align with broader EU directives such as the

Water Framework Directive (European Union, 2000), the EU Nitrates Directive (European Union, 1991) and the EU Common Agricultural Policy (CAP) (European Union, 2021). The CAP conditions subsidy eligibility on environmental compliance through GAEC (Good Agricultural and Environmental Conditions) standards. However, those legislations noticeably refer to surface waters in general but the types of water bodies are not explicitly mentioned, leaving it unclear whether ponds and small water bodies would be included or not.

So far, the majority of the studies on buffer strips has been conducted on riverine systems and at relatively large spatial scales (e.g., catchments), whereas studies including ponds rather focused on how they could be used in combination with "classical" vegetated buffer strips to filter agricultural runoff (Uusi-Kämppä et al., 2000; Wang et al., 2005; Zak et al., 2018). Studies generally observe a positive relation between buffer strip width and the reduction of nutrient and pesticide inflow from surrounding agricultural land (reviewed in Prosser et al., 2020). Although these earlier findings are promising, important knowledge gaps remain with regard to the effectiveness of buffer strips to safeguard the ecological state and biodiversity of small standing water bodies such as ponds. Filling that knowledge gap is crucial to formulate relevant policy recommendations that aim to reconcile nature conservation and agriculture.

The aim of the present study is to assess the effect of buffer strips on the nutrient concentration (total nitrogen, total phosphorus), the concentration of total suspended solids and the phytoplankton biomass in ponds. We expect (1) a negative relationship between buffer strip width and the concentrations of total nitrogen, total phosphorus, total suspended solids and the phytoplankton biomass, but also that (2) even small buffer strips result in substantially lower concentrations of total nitrogen, total phosphorus, total suspended solids and phytoplankton biomass in the water column.

Material and methods

Pond selection and study area

We surveyed a set of 34 small (63 to 6561 m^2, median size of 569 m^2) and shallow (depth ranging from 9 to 250 cm, median depth of 57 cm) ponds located in different regions in Belgium and Germany (Fig. 1, Table 1). Twelve ponds were located in Flanders (Northern Belgium), and twenty-two ponds were located in the state of Brandenburg (North-Eastern Germany). All selected ponds had at least 80% coverage with intensive land use (cropland and grassland) in their 100 m perimeter and differed with respect to their median buffer strip width (ranging from 0 to 17 m in Belgium and from 0 to 53 m in Germany). The smaller size of the buffer strips in Belgium might

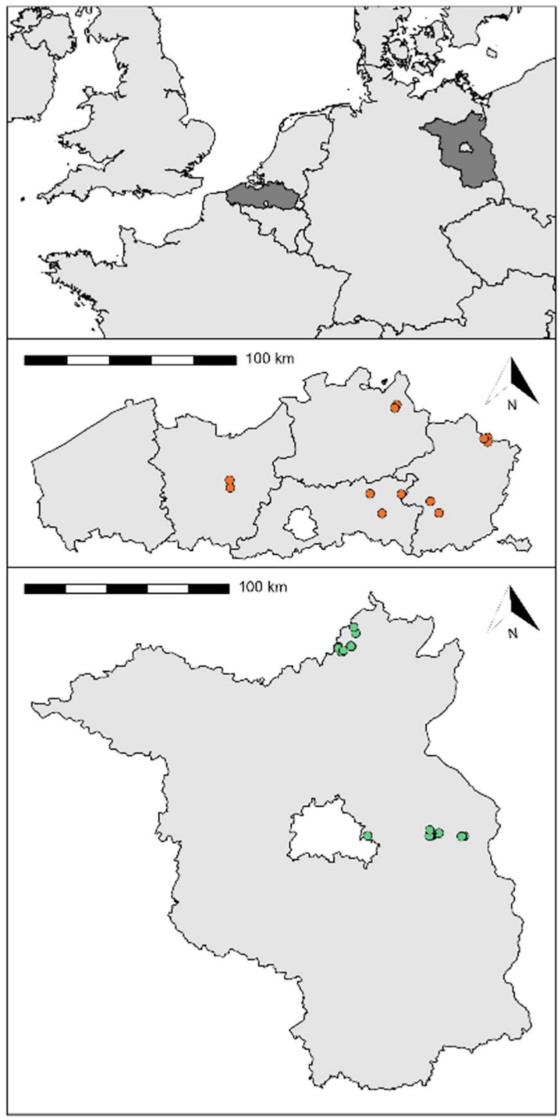

Fig. 1 Overview map of the study area (upper panel) and the location of the ponds in the two study regions. Middle panel is Flanders (Belgium), and the lower panel is Brandenburg (Germany)

Table 1 Summary of key pond characteristics including median buffer strip width, TN (mg/L), TP (mg/L), TSS (mg/L) and CHLa (ug/L) concentrations, pond hydroperiod, mean depth (m), area (m^2) and vegetation coverage

Pond number	Country	X	Y	Buffer width	TN	TP	TSS	CHLa	Hydroperiod	Depth	Area	Submerged	Floating	Emersed
1	Germany	52.467556	14.135844	24	2.80	0.463	3.28	23.43	Temporary	52	420	4	2	4
2	Germany	52.467556	14.135844	21	1.80	0.390	13.90	177.73	Temporary	41	3030	4	1	1
3	Germany	52.467556	14.135844	0	4.40	3.060	2.15	33.23	Temporary	38	598	3	3	2
4	Germany	52.467556	14.135844	0	5.10	1.607	13.77	31.53	Temporary	19	146	2	2	4
5	Germany	52.463358	14.36257	40	2.70	0.289	2.84	11.83	Temporary	24	2169	1	3	1
6	Germany	52.463358	14.36257	20	3.30	1.296	15.50	85.43	Temporary	25	1233	2	1	2
7	Germany	52.463358	14.36257	16	1.70	0.263	5.08	8.70	Temporary	75	453	2	1	2
8	Germany	52.463358	14.36257	15	2.30	0.234	6.07	11.30	Temporary	59	3014	1	1	1
9	Germany	53.340751	13.589403	6.5	4.00	0.376	30.00	136.30	Permanent	67	499	2	1	2
10	Germany	53.340751	13.589403	15	3.60	0.842	68.00	488.07	Temporary	38	187	1	1	1
11	Germany	53.340751	13.589403	17	2.10	0.755	8.29	40.83	Temporary	52	2109	3	1	4
12	Germany	53.340751	13.589403	0	10.10	0.966	15.65	13.73	Permanent	76	128	1	1	1
13	Germany	53.340751	13.589403	4.5	3.90	1.393	5.83	17.77	Permanent	117	390	4	1	1
14	Germany	53.340751	13.589403	0	24.50	3.924	208.50	20.90	Temporary	9	6561	1	1	1
15	Germany	53.340751	13.589403	13	1.60	0.769	8.60	50.23	Temporary	44	63	1	1	1
16	Germany	53.340751	13.589403	16	1.50	0.462	6.10	74.23	Permanent	250	1260	1	4	1
17	Germany	53.340751	13.589403	23	2.60	2.092	2.21	105.57	Permanent	91	731	1	1	1
18	Germany	52.481325	13.671731	33	2.90	0.099	4.08	13.23	Temporary	12	437	1	1	4
19	Germany	52.467556	14.135844	53	3.30	0.318	5.27	22.97	Temporary	24	2262	3	1	2
20	Germany	52.467556	14.135844	28	1.60	0.204	4.18	10.43	Permanent	57	648	4	2	4
21	Germany	52.467556	14.135844	51	2.20	0.382	8.70	34.30	Temporary	16	1460	1	1	1
22	Germany	53.340751	13.589403	23	2.50	0.378	6.93	73.00	Permanent	135	2041	3	1	1
23	Belgium	51.339916	5.011208	0	3.00	0.893	45.95	280.70	Temporary	29	4250	3	4	1
24	Belgium	51.339916	5.011208	0	2.60	0.494	2.02	28.13	Permanent	57	336	2	1	1
25	Belgium	51.013425	3.89254	0	1.90	0.347	11.75	57.91	Permanent	84	702	2	1	1
26	Belgium	51.013425	3.89254	5	1.20	0.073	NA	1.90	Permanent	105	540	4	1	2
27	Belgium	50.919333	4.9701	5	1.60	0.686	22.77	34.35	Permanent	66	650	1	1	3
28	Belgium	50.919333	4.9701	6	13.70	0.072	40.70	33.77	Permanent	78	169	1	1	1
29	Belgium	50.919333	4.9701	0	2.20	0.094	19.93	86.72	Permanent	95	250	1	1	1
30	Belgium	50.905695	5.258256	3.5	1.10	3.069	19.13	195.03	Permanent	40	105	4	1	3
31	Belgium	50.905695	5.258256	0	5.30	0.184	9.96	20.42	Permanent	73	440	2	2	1
32	Belgium	51.194813	5.621579	17	2.50	0.794	24.74	0.02	Permanent	75	928	1	1	1

Table 1 (continued)

Pond number	Country	X	Y	Buffer width	TN	TP	TSS	CHLa	Hydroperiod	Depth	Area	Submerged	Floating	Emersed
33	Belgium	51.194813	5.621579	12	1.60	0.293	27.03	21.00	Permanent	84	380	1	1	3
34	Belgium	51.194813	5.621579	12	2.00	0.102	30.23	189.17	Temporary	44	108	2	1	1

The coverage of submerged, free-floating and emersed vegetation is represented as categories where 1 = 0–25%, 2 = 25–50%, 3 = 50–75% and 4 = 75–100%. The coordinates of the ponds refer to the region in which they are located. The exact location cannot be disclosed due to landowner privacy concerns

be linked to the smaller size of the agricultural fields, reducing the available space. The ponds can be categorized as eutrophic to hypertrophic (see Table 1 for details on pond characteristics).

From the 34 investigated ponds, 19 ponds periodically dry out during summer (2 in Belgium and 17 in Germany), while 15 ponds hold water permanently (10 in Belgium and 5 in Germany). None of the ponds was hydrologically connected to other water bodies.

Data collection

We sampled all 34 ponds in late spring 2021 (May–June) and measured four key variables associated with eutrophication: total nitrogen concentration (TN), total phosphorus concentration (TP), total suspended solids concentration (TSS) and phytoplankton biomass as chlorophyll a. In each pond, we collected depth-integrated water samples in the open water zone at different locations using a tube sampler (length 1.5 m; diameter 75 mm), avoiding contact with vegetation and the bottom substrate during sampling. Samples for the analysis of nutrients (TN and TP) and TSS were stored cool in dark conditions in the field. In vivo chlorophyll a concentration (CHLa) was used as proxy for phytoplankton biomass and was directly measured as the mean of three measurements taken in a row in a black bucket containing the depth-integrated water samples, using a handheld fluorometer (AquaFluor, Turner Designs and Algaetorch, bbe-moldaenke in Belgium and Germany, respectively). The concentration of total suspended solids (TSS) was determined gravimetrically in the laboratory by filtering a known volume of pond water on a pre-weighted glass fiber filter (Whatman GF/F, diam. 47 mm). Nutrient samples were either kept in the fridge at 4 °C for a few days (in Germany) or frozen at −20 °C (in Belgium) until further processing in the laboratory. Total nitrogen concentrations were determined with NDIR after combustion (TOC/TN analyzer) (DIN EN 1484 (DEV, H3) Water analysis—Guidelines for the determination of total organic carbon (TOC) and dissolved organic carbon (DOC); total (TN) NDIR after combustion EN 12260 (DEV, H 34) Water quality—Determination of nitrogen—Determination of bound nitrogen (TNb), following oxidation to nitrogen oxides). Total phosphorus concentrations were determined by using the potassium peroxydisulfate method (Murphy & Riley, 1962; Solórzano &

Sharp, 1980; Worsfold et al., 2016) using a photometer device (CARY 1E from Varian). The proportion of the pond surface area covered by floating, submersed and emersed macrophytes was estimated visually in the field. Pond hydroperiod was assessed based on expert knowledge and based on visual observation during field visits (from April to November 2021, roughly every month and a half).

The quantification of buffer strip width

We defined a buffer strip as the vegetated and non-cultivated area located between the edge of the pond and the agricultural fields surrounding it. As water levels can vary considerably throughout the year, the edge of the pond was delimited by the shoreline that is inundated at maximum water level in the winter period.

We used satellite images of the year 2021 available on Google Earth Pro to measure the width of the buffer strip along eight cardinal lines (crossing at the pond's centroid) starting from the pond´s edge to the start of the agricultural field. Obtained data were subsequently verified based on in situ field observations collected in 2021. Measurements along the eight cardinal lines were summarized for each pond by the median to obtain one value of buffer strip width for each pond. The median value was the best descriptor because buffer strip width was sometimes irregular. Using the minimum buffer width would have yielded similar patterns given its high correlation with median buffer width (Pearson correlation coefficient of 0.95). The vegetation within the buffer strips was mostly composed of reed, grasses and ligneous vegetation.

Statistical analysis

We used multiple Bayesian generalized linear models (GLMs) to separately assess the effect of buffer strip width on the concentration of TN, TP, TSS and CHLa. GLMs were based on a Gamma distribution and a log-link function because the response variables represent nonnegative continuous quantities (McCullagh & Nelder, 1989; Bolker, 2008). The models included country-specific intercepts and slopes to account for baseline differences in physical and chemical variables and differential effects of buffer strip width between both countries, respectively. In addition, we performed a sensitivity analysis by adding the volume of the pond (approximation by multiplying the area by the depth) as covariate. The addition of the volume did not change the effects of buffer strip width on the response variables (see SI 2, Figure S2 for details).

The main goal of our statistical analysis was to estimate the regression coefficients for the effect of buffer strip widths on the considered variables for each country (Belgium and Germany) and to evaluate the statistical support for the association being negative. We then assessed the biological relevance of these findings by calculating the percentage decrease in the concentrations of TN, TP, TSS and CHLa with increasing buffer strip width. Using empirical data that included buffer widths ranging from 0 to 53 m, we generated posterior predictions for TN, TP, TSS and CHLa along a grid of buffer width values. For each buffer width and posterior iteration, we calculated the percentage decrease relative to the model-predicted concentration at a buffer width of 0 m.

We fitted the Gamma GLMs through the "brms" package v.2.16.3 (Bürkner, 2017) in R v.4.0.3 (R Core Team 2021), which performs Bayesian inference by means of a dynamic Hamiltonian Monte Carlo algorithm (Carpenter et al., 2017). We used a vague zero-centered Normal(0,3) prior for the regression parameters (the intercept and the effect of median buffer strip width, country and their interaction) and a vague Gamma(0.1,0.1) prior for the shape parameter of the Gamma distribution (McElreath, 2020). We ran separate models for each of the four outcome variables (concentrations of total nitrogen, total phosphorus, total suspended solids and phytoplankton biomass). For each model, we ran eight chains with 5,000 iterations each, of which the first 2,500 were discarded as warm-up. MCMC convergence test, goodness-of-fit and prior sensitivity analyses yielded satisfactory results (see SI 3, and Figure S3, S4, S5 for details).

Results

We found high posterior probabilities for a negative relationship between median buffer strip width and the concentrations of TN, TP and TSS in the set of ponds that were sampled in Germany (99.78%, 99.80% and 99.95%, respectively) (Fig. 2). In contrast, the results for Belgium are characterized by high uncertainty and we did not find statistical support for

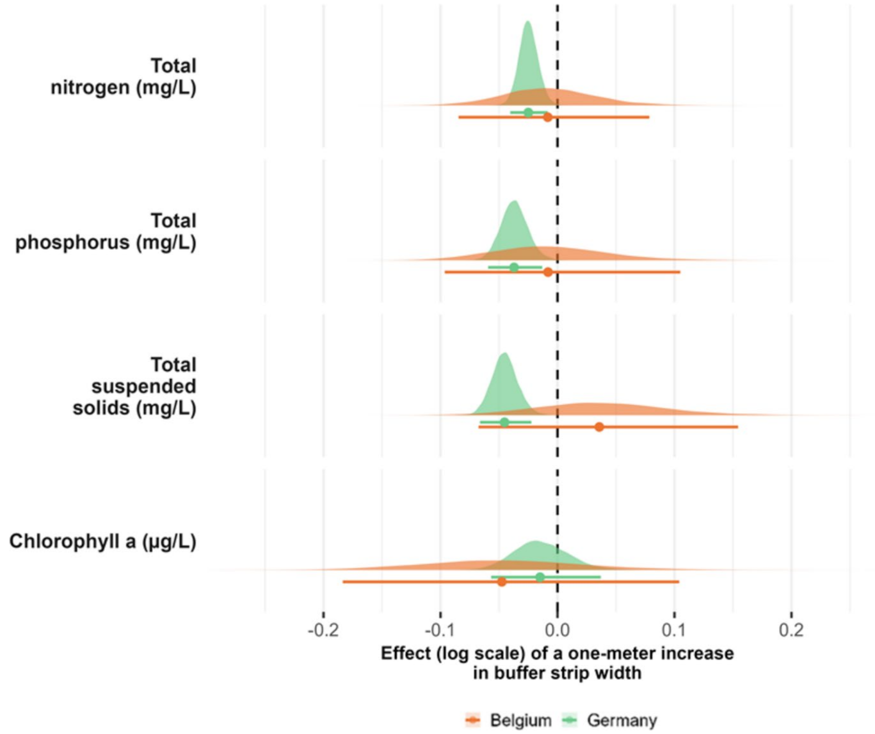

Fig. 2 Regression coefficients reflecting the effect sizes of a one-meter increase in buffer strip width on the concentration of TN, TP, TSS and CHLa, four variables that are linked to the productivity of ponds. Green and orange shaded areas show the full posterior distribution of the coefficients for German and Belgian ponds, respectively, while the dots show the posterior means and horizontal lines the 95% credible intervals. The vertical dashed line represents the line of no effect

a negative relationship between buffer strip width and the concentrations of TN, TP and TSS in the set of investigated ponds in Belgium (58.28%, 56.69% and 24.98%, respectively) (Fig. 2). In addition, we did not find strong support for a relation between buffer strip width and CHLa in the set of investigated ponds from both countries (posterior probability of a negative effect of 75.26% in Germany and 72.96% in Belgium; Fig. 2). Table 2 summarizes the predicted reductions in TN, TP and TSS concentrations for buffer widths of 5, 10, 50 and 100 m compared to ponds without buffer strips in the German context. Large increases in buffer strip widths are associated with even stronger differences in concentration, but the relative change with increasing buffer strip width becomes less profound (Figs. 3, 4).

Discussion

Our study provides empirical evidence for the capacity of buffer strips to reduce concentrations of nutrients and total suspended solids in small ponds surrounded by agricultural land, while also revealing a differential buffer strip effect between Germany and Belgium. While we observed a consistent negative relation between buffer strip width and the concentration of total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS) in ponds located in Germany, we did not find clear evidence for such relations for ponds in Belgium. In Germany, relatively small buffer strips (5 m width) already seem to result in lower concentrations of nutrients and suspended solids, but their effectiveness increases considerably with increasing width. In contrast to our expectations, we did not observe a relation between buffer strip width and phytoplankton biomass in the set of investigated ponds in both countries.

Based on our models, German ponds surrounded by a buffer strip of 5 m are predicted to have 12% (TN), 17% (TP) and 20% (TSS) lower concentrations of key drivers of pond productivity compared to ponds without buffer strip. This finding is in line with earlier studies that show positive effects of buffer strips on reducing agricultural runoff of nitrogen, phosphorus and suspended solids into surface waters (Zhang et al., 2010; Sweeney & Newbold, 2014; Prosser et al., 2020; Lyu et al., 2021). Earlier investigations have shown that buffer strips are highly effective in trapping organic or sediment-bound forms of

Table 2 – Predicted reductions in total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) concentrations (both in mg/L and as percentage reductions) for buffer strips of 5, 10, 50, and 100 m compared to ponds without buffer strips in the German context. Values include 95% credible intervals (CrI) for each estimate

	TN				TP				TSS			
Buffer width (m)	Reduction (mg/L)	95% CrI	Reduction (%)	95% CrI	Reduction (mg/L)	95% CrI	Reduction (%)	95% CrI	Reduction (mg/L)	95% CrI	Reduction (%)	95% CrI
5	−0.75	−0.21, −1.56	12	5, 18	−0.3	−0.10, −0.63	17	9, 24	−8.38	−2.11, −20.51	20	9, 29
10	−1.4	−0.44, −2.84	22	9, 33	−0.54	−0.19, −1.11	31	16, 42	−14.87	−4.03, −35.22	36	18, 50
50	−4.37	−1.72, −7.65	69	38, 86	−1.42	−0.66, −2.49	83	60, 94	−35.08	−13.74, −71.14	87	62, 97
100	−5.58	−2.75, −8.88	89	62, 98	−1.63	−0.90, −2.68	96	84, 100	−38.68	−18.12, −74.54	97	86, 100

nitrogen and phosphorus (Yang et al., 2015), which is likely due to their capacity to promote the deposition of large-sized particles (e.g., silt and sand) and the infiltration of small-sized particles (e.g., clay) into the soil by slowing down the flow of agricultural runoff (Dillaha & Inamdar, 1997; Mankin et al., 2007; Gharabaghi et al. 2006). Therefore, the observed lower concentrations of TN and TP in ponds surrounded by buffer strips in our study likely result from a higher retention of suspended solids (TSS). Although buffer strips have proved highly effective at trapping sediment-bound nutrients, they are much less effective at trapping water-soluble forms of nitrogen and phosphorus such as nitrate and phosphate, requiring larger buffer widths to allow water infiltration into the soil (Yang et al., 2015). This could explain why we observe that larger buffer strips are still much more effective than smaller ones. However, since sediment-bound phosphate is the dominant form of phosphorus, representing 75–90% of the phosphate in agricultural runoff (Sharpley et al., 1993), buffer strips can trap most of the runoff phosphorus.

As a reasonable approximation, our results suggest that with each increase in buffer width of 5 m, TN, TP and TSS levels are reduced by an additional 10%. While the relationship between median buffer strip width and the reduction in nutrients and suspended solids for the German ponds deviates from a linear relationship and shows a pattern of diminishing returns, we observe that a roughly 10% reduction per 5 m median buffer strip width holds up to approximately 20 m for TN, 35 m for TP and almost 40 m for TSS. Similarly, Sirabahenda et al. (2020) showed that sediment retention rates in riparian buffer strips level off at widths above 50 m. Our results show a 50% reduction at a buffer strip width of approximately 30 m for TN and approximately 20 m for TP and TSS. Those buffer widths are considerably larger than those reported for streams in a meta-analysis by Lind et al. (2019) where a minimum of 75% reduction in nitrogen, phosphorus and sediments was found to occur at an average buffer strip width of 11 m (ranging from 0.7 to 30 m), 11 m (ranging from 4 to 18 m) and 8.8 m (ranging from 3.3 and 18 m), respectively. Those differences might be related to variations in catchment sizes. However, streams would be expected to require larger buffer strips than small waterbodies such as ponds, given their generally larger catchment sizes (Davies et al., 2008). Apart from that, both the

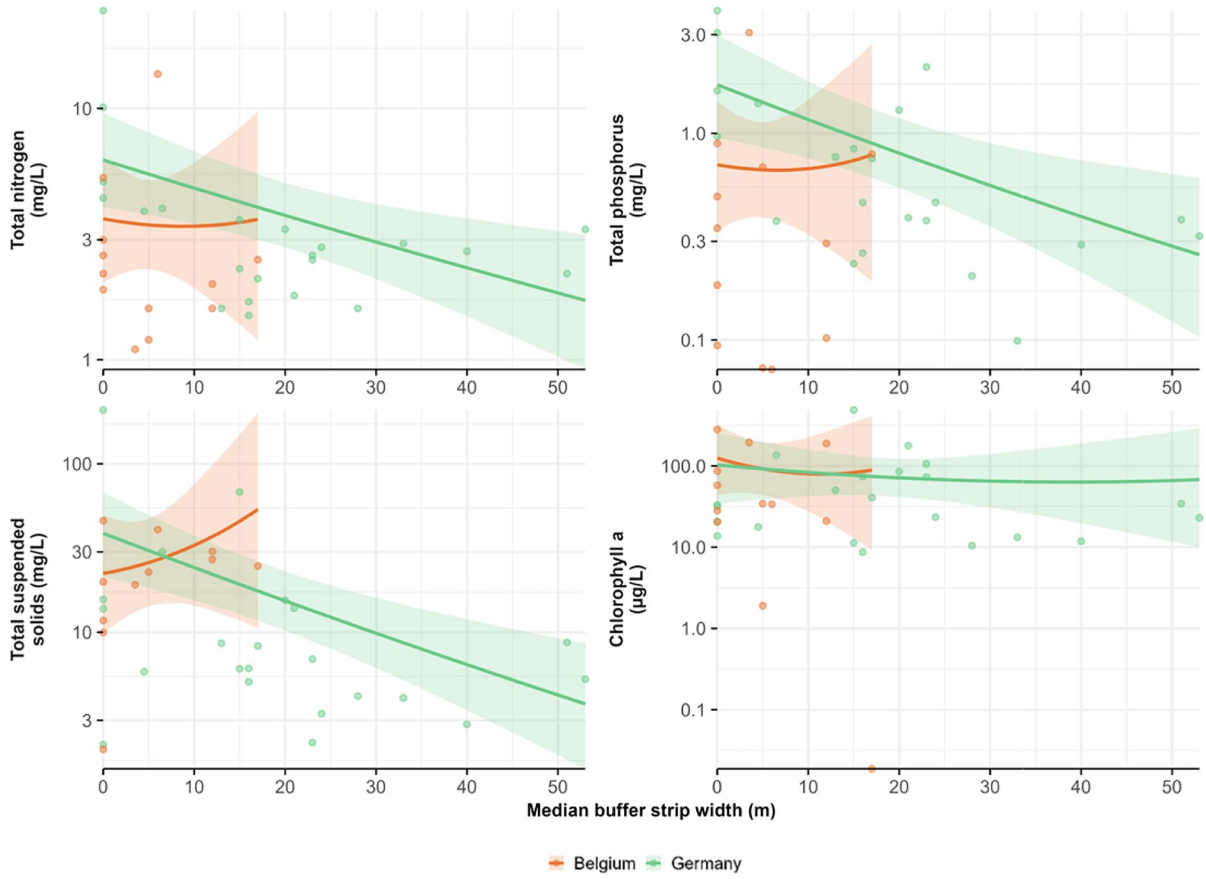

Fig. 3 TN, TP, TSS and CHLa concentration in relation to buffer strip width for Belgium (orange) and Germany (green) separately. The full lines indicate the posterior median relationship, while the shaded areas indicate 95% credible intervals. Original data points are shown as dots. A logarithmic scaling for the y-axis was used for clarity purposes

results of Lind et al. (2019) and those reported in our study show that significant reductions in phosphorus and sediment concentrations occur within similar buffer width ranges, whereas reductions in nitrogen concentrations may require larger buffer widths. Our findings show that the implementation of minimum 5-m-wide buffer strips along water bodies, as mandated by the Water Resources Act (BGBl, 2009) in Germany and the Flemish Decree on Integrated Water Policy (Belgisch Staatsblad, 2003) in Belgium, can already have a mitigating effect, but that larger buffer strips are needed to achieve strong reductions of agricultural runoff.

In contrast to our expectations, we did not observe a clear effect of buffer strips on ponds located in Belgium. In addition to the smaller sample size, this finding might result from several other aspects. First, the spatial and temporal organization of the agricultural landscape is to some extent different in Germany (Brandenburg) compared to Belgium (Flanders). While the landscape surrounding the set of German ponds has been characterized by large-scale, intensive crop farming for several decades, the landscape surrounding the set of Belgian ponds is more heterogeneous, with agriculture being applied at smaller spatial scales and with regular rotation between intensive cropland and grassland. The agricultural landscape surrounding the considered Belgian ponds also has more small landscape elements, such as hedges and small forest patches, which themselves can trap agricultural runoff (Fiener et al., 2011) and limit close to the ground aerial transport and deposition of soil and chemical particles (Raupach & Leys, 2000). Those landscape elements can therefore reduce the potential

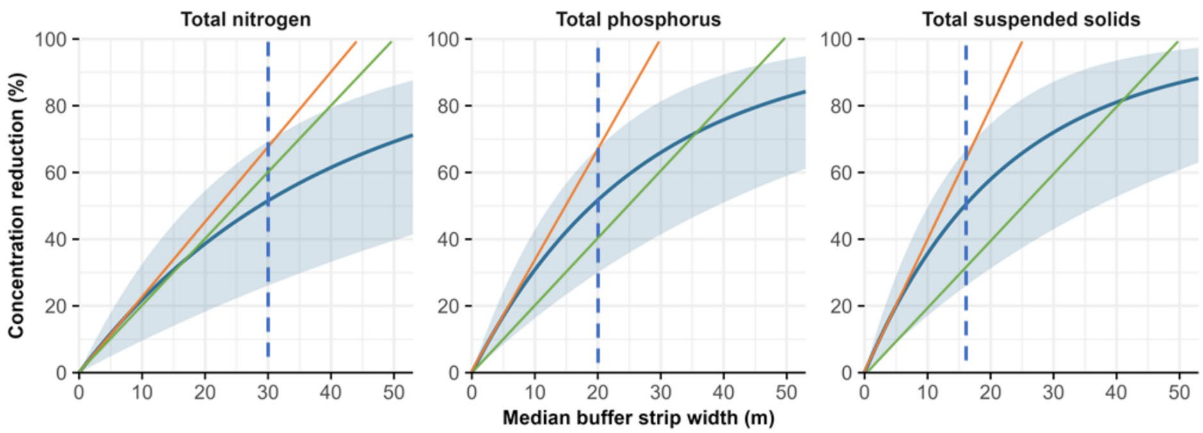

Fig. 4 Percentage reduction in TN, TP and TSS concentrations with increasing median buffer strip width in the investigated German ponds. The blue full line represents the posterior mean concentration reduction, while the shaded area represents corresponding 95% credible intervals. The dashed vertical blue line indicates the buffer width at which the concentrations of TN, TP and TSS are reduced by 50%. For ease of interpretation, we added two lines: The orange line shows a linear increase in reduction with increasing buffer strip width at the same rate as for the first 5 m (illustrating that there is a reduction from linearity at higher buffer strip widths) and the green line shows a 10% decrease in concentrations of the endpoint for every 5 m increase in buffer strip width (illustrating that, depending on the endpoint, increases in buffer strip width of up to 20 to 40 m result in a higher reduction than this 10% decrease in values per 5 m)

additional effect of buffer strips around ponds, making it less noticeable. The large-scale, long-term intensive crop farming around the ponds in Germany likely results in high agricultural runoff, which might explain the observed overall higher nutrient concentrations (TN and TP) in German ponds compared to Belgian ponds in our study and could strongly enhance the potential mitigating effect of buffer strips around ponds.

Second, differences in hydroperiod regimes between the investigated ponds in Belgium (10 permanent and 2 temporary ponds) and in Germany (5 permanent and 17 temporary ponds) may also explain the observed differential effect of buffer strips in both countries. Regular periodic pond drying can affect the potential effect of current buffer strips by reducing the importance of historical pond eutrophication due to (1) lowering internal N loading by promoting losses during the dry phase via mineralization, ammonia volatization and denitrification (Sahuquillo et al., 2012), and (2) reducing bioturbation-induced internal eutrophication (Vanni, 2002; Goeke et al., 2024) by preventing the establishment of dense fish populations (Snodgrass et al., 1996). Historical pond eutrophication is thus expected to be more important in permanent ponds compared to temporary ponds, especially in the presence of dense fish populations that promote internal eutrophication by sediment resuspension (Vanni, 2002; Goeke et al., 2024). Based on this, we expect a stronger relation between current buffer strip width and nutrient status in temporary ponds than in permanent ponds. Unfortunately, collinearity between landscape characteristics and between hydroperiod and country does not allow us to identify the exact mechanism behind the lacking association between buffer strip width and TN, TP and TSS in Belgium.

We did not observe a significant negative effect of buffer strip width on phytoplankton biomass in any of the sampled pond sets. This might be due to the fact that all investigated ponds in our study are highly eutrophic to hypertrophic. Nutrient concentrations in the studied ponds might thus still be high enough to sustain phytoplankton and in particular cyanobacteria blooms, which depend less on nutrient influx given the capacity of some cyanobacteria to fix nitrogen from the air (Scheffer & Jeppesen, 1998; Hargeby et al., 2004; Wurtsbaugh et al., 2019). This hypothesis is supported by the fact that we did not observe a correlation between phytoplankton biomass and nutrient concentrations (both TN and TP) (Figure S1). The large variation in CHLa concentrations between ponds (ranging from 0.02 to 280.7 µg/L in Belgium and from 8.7 to 488 µg/L in Germany) suggests that other factors than nutrients limit phytoplankton growth (e.g., (self-)shading, grazing or competition with macrophytes; (Søndergaard & Moss, 1998; Yeh et al., 2011; de Tezanos Pinto & O'Farrell, 2014). However, no relation was observed between submerged, free-floating or emersed macrophyte coverage and phytoplankton biomass (Figure S1). We note that the exceedingly high nutrient concentrations in the study ponds imply that a very strong reduction in nutrient loading would be required for these ponds to achieve high water quality standards. In the German context, our results predict 80% reduction in TP (from 1.7 to 0.3 mg/L) when buffer strips reach 50 m, which is the widest buffer width that was observed in the field. However, this substantial reduction might not suffice to maintain the good ecological status of those ponds, as illustrated by the absence of effect of buffer width on phytoplankton biomass. As a comparison, Poikane et al. (2019) showed that shallow alkaline European lakes (< 3 m deep) tend to shift from "good" to "moderate" ecological status (determined based on vegetation) at TP values between 0.058 and 0.078 mg/L. Based on our predictions, such concentrations would be reached at a buffer strip width of about 100 m. With that regard, the minimum width of 5 m buffer strips mandated by the German Water Resources Act is probably not a sufficient measure on its own to protect water bodies in highly intensive agricultural areas. In order to achieve the nutrient concentrations required for the maintenance of good ecological conditions, additional measures complementary to buffer strips might be needed, such as pond dredging and the reduction of fertilizer input to limit external nutrient loading.

While our results provide valuable insights on the effectiveness of buffer strips around small standing waterbodies, there are limitations. First, we focused only on buffer strips width, whereas their effectiveness also depends on factors like slope, soil composition (Prosser et al., 2020) and plant community (Aguiar et al., 2015; Prosser et al., 2020; Cole et al., 2020). Second, we assumed that TN and TP concentrations in pond water directly reflect nutrient runoff, but internal processes (e.g., nutrient uptake, legacy effects, sediment dynamics and fish presence) also influence nutrient concentrations (Bennion & Smith, 2000; Nowlin et al., 2005; Adámek & Maršálek, 2013; Lischeid et al., 2018). Despite these factors, our results clearly show a negative relationship between buffer strips width and nutrients and suspended solids concentrations in German ponds.

In conclusion, our study shows that implementing vegetated terrestrial buffer strips around small ponds located in agricultural areas can be an effective measure to mitigate the detrimental impact of agriculture on the nutrient status of ponds. However, our results also suggest that the effectiveness of buffer strips may depend on other factors, including pond hydroperiod, specific landscape characteristics and historical eutrophication. While even small buffer strips (5 m) proved effective in the German context, our result also show that larger buffer strips are considerably more effective. Importantly, the creation of buffer strips alone may not be sufficiently effective to restore the good ecological status of ponds, on which multiple ecosystem services depend (Biggs et al., 2017). Such systems likely need additional management interventions, such as nutrient removal by dredging. Further research could target best management practices for optimizing the effectiveness of buffer strips in runoff retention and further investigate the valuable ecosystem services that healthy ponds and buffer strips can provide to farmers such as increased pollination and biocontrol of pest insects through the promotion of biodiversity (Walton et al., 2021; Cuenca-Cambronero et al., 2023) and the control of soil erosion (Schütz et al., 2022).

Acknowledgements We thank Renee Van Dorst for her help during the field sampling and Mariana Meerhoff for the insightful discussions.

Author Contributions Louisa-Marie von Plüskow, Pieter Lemmens, Thomas Mehner and Luc De Meester conceived the ideas, designed the methodology and wrote the manuscript; Louisa-Marie von Plüskow, Pieter Lemmens, Louis-Marie Le Fer, Mareike Brehm-Benedix, Asja Vogt, Maria Auxiliadora Peso, Kiani Cuypers and Robby Wijns collected the data; and Louisa-Marie von Plüskow, Maxime Fajgenblat, Louis-Marie Le Fer and Pieter Lemmens analyzed the data. All authors contributed critically to the drafts and gave final approval for publication.

Funding Open Access funding enabled and organized by Projekt DEAL. This work was supported by the PONDERFUL project (Grant No. H2020-LC-CLA-2019–2), funded by the European Union (H2020).

Data Availability The underlying data will be made publicly available on the Dryad Digital Repository after acceptation of the manuscript.

Declarations

Conflict of interests The authors declare no conflict of interest.

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