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The role of riparian buffers in protecting stream water quality and habitat integrity: thresholds for freshwater management

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Abstract

Freshwater ecosystems face multiple stressors from agriculture, dispersed urbanization, and forestry plantations (eucalyptus, coniferous), which degrade water quality and habitat integrity. To assess the effectiveness of riparian strips as ecological buffers, we selected 168 sites in Galicia (NW Iberian Peninsula). We applied a methodological approach to identify impacts at different spatial scales (basin, riparian and reach), along multiple pressure intensification gradients. Generalized Additive Models (GAMs) were fitted to compare different models including basin and riparian predictors alone, and combined models to predict water quality and habitat integrity variables. The combined models showed high significant predictive capacity for water quality, while performance was lower for habitat integrity variables. Relevant quantitative ecological thresholds concerning basin and riparian management practises were also identified: agriculture cover exceeding 15% and urban higher than 6% increased nitrogen and phosphorus exports to streams, while extensive agricultural over 8% seem to partially limit these inputs. Moreover, wider native riparian forest (> 7 m) generally showed lower nutrient concentrations and better habitat conditions compared to those with exotic riparian trees presence. However, higher tree density and steeper riparian slopes increased nitrogen inputs to streams while simultaneously benefiting in-stream habitat structure. We conclude that riparian forests can act as effective ecological buffers mitigating multiple pressures impact to streams, although basin-scale management remains essential. These results provide fundamental support for the ecological protection of rivers, as establishing limitations for basin scale activities and defining appropriate riparian characteristics are critical to maintaining good water quality and habitat integrity.

1. Introduction

River networks and their adjacent floodplains provide multiple benefits to society, including supporting (e.g., fertile soil formation), regulating (e.g., water regulation and waste treatment), provisioning (e.g., fish and other animals), and cultural ecosystem services as nature observation (Petsch et al. 2023). The global decline in the ecosystem services provided by freshwaters is linked to the spread and intensification of anthropogenic pressures, including pollution, channel alteration, and the introduction of alien species, many of which have been exacerbated by climate change (Grizzetti et al. 2017; Palt et al. 2022; Pereira et al. 2024; Jorda-Capdevila et al. 2019). These pressures may lead to water quality and stream habitat degradation, with negative consequences for downstream water use, human well-being, aquatic and terrestrial biodiversity and ecosystem functioning (Dodds et al. 2013; Peters and Meybeck 2000).

Among the major threats to freshwater ecosystems, pollution is one of the most critical challenges of the 21st century (Gleick 2003). Urban pollution, via wastewater treatment plants (WWTPs) effluents and runoff, delivers organic matter, nutrients, sediments and other pollutants (e.g., metals, pesticides), often with high ecotoxicological risks (Martí et al. 2004; Taebi and Droste 2004; Ginebreda et al. 2010; Cojoc et al. 2024). Similarly, agricultural pollution, especially via intensive agricultural fields, remains a major source of nitrogen, organic matter, and sediments to surrounding streams (Petzoldt & Uhlmann 2006;

European Environment Agency 2025). However, grass or woody vegetation patches complementary with extensive agricultural uses can improve water quality and habitat integrity (Vondracek et al. 2005). Finally, forestry management practices (e.g., road construction, fertilization, ploughing, and harvesting) can introduce large quantities of sediment and nutrients; increasing turbidity, siltation, salinization, and eutrophication risk in adjacent freshwater ecosystems (Nisbet 2001; Wang et al. 2020; Palt et al. 2022). A remarkable forestry impact is the introduction of alien species for wood, biofuel and pulp production (Tomé et al. 2021; Sertutxa et al. 2024).

In the Iberian Peninsula, *Eucalyptus spp.* is generally preferred over native species due to shorter rotations periods (12–15 vs. 60–100 years; Sertutxa et al. 2024), with their cultivation often requiring pre-planting fertilization and subsoiling (Bouso 2022). Compared to native species, eucalypt can alter soil properties and decrease water and nutrient availability (Pohjonen and Pukkala 1990). Moreover, the replacement of native forests by a single tree monoculture simplifies tree structure and composition, potentially altering the structure and functioning of recipient ecosystems, and thus affecting terrestrial ecosystems regional biodiversity (Alday et al. 2017; Castro-Díez 2017). In fact, organic matter inputs to rivers from Eucalyptus seem to extend to the entire aquatic food web, with potential negative effects on periphyton and on shredder invertebrates (García and Pardo 2012; González-Paz et al. 2023). Despite evidence of Eucalyptus impacts on streams, their relative significance compared to urban or agricultural pollution is still poorly understood, particularly from a holistic perspective on water quality and habitat integrity.

Within the EU freshwater protection framework, the presence of well-preserved riparian buffers is recognized as essential components for the biodiversity and for the integrity of aquatic ecosystems (Pardo et al. 2012; Schürings et al. 2024). Native riparian buffers mitigate agroforestry impacts on water chemistry, communities, and ecosystem processes, because they are potential buffer zones, especially for retaining nitrogen and sediment inputs (Nisbet 2001; Ferreira et al. 2015; Grizzetti et al. 2017, Pinay et al. 2018; Lupon et al. 2026). Alongside riparian conservation, basin-scale management and diffuse pollution mitigation are essential for achieving the EU's goal of good ecological status in surface waters, a principle upheld from the Water Framework Directive (WFD) 2000/60/EC (EU 2000) to the European Nature Restoration Law (Regulation EU 2024/1991). Although multiple studies have linked pressures to ecological status, the interactions among land use and riparian buffers with water quality and habitat integrity remain unclear (Feld et al. 2018; Palt et al. 2022). Studies searching for management thresholds have focused primarily on nutrient pollution (only nitrogen and phosphorus) and specific reach-scale variables such as fine sediments, channel shade, water temperature, or large woody debris stocks. However, they often lack a combined, multiple-scale approach for their study, despite the need for coordinated riparian and basin-scale management efforts (Feld et al. 2018).

The primary objective of this study is to develop and apply an innovative methodological framework for establishing multiple-scale relationships between agroforestry and urban pressures and their impacts on river systems, while evaluating the degree to which riparian ecosystems contribute to mitigating such

impacts. This approach could also provide management criteria at both riparian and basin scales aimed at protecting water quality and habitat integrity in streams and rivers.

2. Methodology

2.1 Study sites

The study was conducted in the Galicia-Costa (predominantly) and Miño-Sil hydrologic districts (NW Iberian Peninsula; Fig. 1). The region has a temperate humid climate with high relative humidity, high precipitation levels (1000–2500 mm yr^{-1}; AEMET 2017), and mild temperatures (mean annual temperature of 13.3ºC; Martínez et al. 1999). Streams are typically short, steep, and small to medium-sized, flowing over schist and granite substrates that produce acidic, sandy loam soils (Macías and de Anta 2008).

Natural forest vegetation in the uplands includes deciduous Atlantic oak forests and coniferous species, essentially *Pinus pinaster* (41.5% and 29.4% of the total forestry area, respectively; de la Mata et al. 2024; IFCG 2024), while deciduous forests of *Betula alba* L., *Quercus robur* L., and *Alnus glutinosa* L. dominate the riparian zones. These are often accompanied by species such as *Frangula alnus* Mill., *Fraxinus excelsior*, *Laurus nobilis*, and *Corylus avellana* (Cillero et al. 1999). However, farming and forestry have been intensive on productive soils since the 20th century, while remote mountainous areas have been marginalized for cultivation (Lomba et al. 2022). Currently, most forested areas are plantations of exotic conifers or eucalypts (Alday et al. 2017), with eucalypts covering 30% of the Galician forestry area (438,156 ha; IFCG 2024). Moreover, farmland abandonment facilitated the expansion of *Pinus radiata* D. Don (Alday et al. 2017) and invasive *Acacia* species (González-Muñoz 2012).

To assess the effects of human activities within river basins, as well as their interactions with riparian forest characteristics, on water quality and habitat integrity, we selected 168 sites across small- to medium-sized rivers (Strahler stream order: 2–6; Fig. 1), and spanning an altitudinal gradient of 4–850 m a.s.l. The sites covered the range of land uses and pressures more representative within the Galician landscape, and included agricultural and silvicultural (eucalypt, pine) gradients, point sources (WWTPs, n = 6; industrial areas, n = 5; mining, n = 1), and upstream, non-dammed sections. Reference sites (n = 8) having absence of significant pressures within their basins and riparian areas were also included (Pardo et al. 2012). At each site, we characterised basin land uses, pollution, riparian variables (native and exotic), water quality, and habitat integrity.

2.2. Land use characterization

Basin (n = 14) and pollution (n = 6) variables (Table S1) were quantified using QGIS (3.44). Basins were delineated using the hydrological network of Institute for Territorial Studies of Galicia (IET) and the 2nd Coverage Digital Elevation Model (2015–2021) from the CNIG/IGN, with a 2-m grid spacing (MDT02). The model was corrected (*r.fill.dem* tool), and flow accumulation and sub-basins were derived (*r.watershed* and *r.water.outlet)* by Strahler order. Polygons were smoothed and characterized by area,

perimeter, slope, and channel length. Land-use composition was assessed by overlaying the sub-basins with the Agroforestry Land Use Map of Galicia (MUAG) database (based on SIOSE_AR and PNOA 2020 orthophotography), complemented with crop declarations from the Register of Agricultural Holdings of Galicia (REAGA), Discharge Control Plan (PCV) from Augas de Galicia, the Galician Continuous Forest Inventory (IFCG), the Wetlands Inventory and river polygons from the IET. Riparian buffers (30 m each side) were delineated to assess cumulative land use upstream.

2.3. River and riparian characterization

Sites sampling was performed always during summer (years 2022, 2023 and 2025), at low discharge levels. Rivers and surrounding riparian zones were characterised following Kuglerová et al. (2020) and Pardo et al. (2014), obtaining several riparian (native and exotic; n = 14), water quality (n = 19) and habitat integrity (n = 23) variables (Table S1).

Water quality included both physicochemical and chemical parameters. Hand-held sensors were used to measure water temperature (°C), barometric pressure (hPa), dissolved oxygen concentration (mg L^{-1}) and saturation (%) (HQ30D Portable Dissolved Oxygen Meter), electrical conductivity (µS cm^{-1}; Orion 3-Star ThermoScientific), turbidity (NTU, Hach 2100Q IS) and pH (Hach Sension+ PH1). Additionally, water samples (100 mL) were filtered (Whatman GF/F 0.7µm filters) stored at 4°C in the dark, transported to the laboratory, and frozen at -18 ºC for nutrient analysis. NO_3^-, NO_2^-, PO_4^{3-}, NH_4^+ and dissolved organic carbon (DOC) were analyzed by continuous flow analyzer (Auto-Analyser AA3) following ISO methods (13395, 15681-2, 11732). Major cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) were determined by mass spectrometry, and anions (Cl^-, SO_4^{2-}) by ICP (inductively coupled plasma) colorimetry. All water analyses were performed at Scientific and Technological Support Center for Research (University of Vigo).

To measure stream habitat integrity, we selected a 50 m reach at each site and measure several variables related to channel geomorphology, physical characterization and benthic organic matter. Channel wetted width and depth were measured in three transects along the reach, while bank height, bank width, and water depth were measured along 10 transects. Substrate composition (Kuglerová et al. 2020) was visually estimated from the complete reach, using 20 random 1x1m squares. Large woody debris and vegetated dikes were measured *in situ*. Native and exotic benthic coarse particulate organic matter (BCPOM; >5 mm) were collected from benthic samples that were taken using a semi-quantitative multihabitat sampling of 2.5 m^2 (i.e., the 20-kick method, Pardo et al. 2014).

Finally, shade was measured using digital photography and the Canopy Cover Index via the Gap Light Analysis Mobile App (GLAMA). Three pictures (right, centre and left) were taken every 15 m and 1 m above the water level along each 50 m reach. Following Kuglerová et al. (2020), we also assessed structural parameters of riparian zones and stream channels. In four 10x10 m plots (two per bank), we recorded tree species, distance to stream, and tree diameter at the breast height. Adjacent land cover use and continuity with riparian areas were evaluated as native versus exotic cover percentages within 20 m on each side of the stream bank.

2.4. Statistical analysis

To reduce dimensionality and avoid multicollinearity among the 77 variables measured, we selected the most relevant variables based on their influential power and independency using Pearson correlation tests. Accordingly, we performed 2 Pearson correlation matrices (one for explanatory and one for response variables; Figure S1 and S2), and variable selection was further complemented by expert knowledge and literature criteria to ensure ecological relevance (Zuur et al, 2010). Based on the results we selected 18 explanatory variables and 12 response variables for further analysis (Table 1).

Table 1
Descriptive table of name, description and unit for every explanatory (basin, pollution, native, exotic and riparian) and response (water quality and habitat integrity) variables selected for GAM models.

Type	Variable	Name	Units
Basin	Ext_agric_pct	Extensive agriculture percentage	%
Basin	Agric_pct	Total agriculture percentage	%
Basin	Urban_pct	Urban land cover percentage	%
Basin	Euc_pct	Eucalypt percentage	%
Basin	Conif_pct	Coniferous forest percentage	%
Basin	Nat_veg_pct	Natural vegetation percentage	%
Basin	Catchment_area	Catchment area	km^2
Pollution	Discharge_flow	Discharge (effluent) flow	$m^3\ s^{-1}$
Pollution	PE	Population equivalent	h-e
Pollution	LSU	Livestock units	-
Native	Native_dist_max	Native riparian strip width (< 10m)	m
Native	Native_continuity	Native riparian continuity (> 20m)	%
Native	Native_stems	Native tree stem count	-
Exotic	Exotic_dist_max	Exotic riparian strip width (< 10m)	m
Exotic	Exotic_continuity	Exotic riparian continuity (> 20m)	%
Exotic	Exotic_stems	Exotic tree stem count	-
Riparian	Riparian_slope	Mean riparian slope	%
Riparian	Riparian_shade	Mean riparian shading	%
Water quality	NO3_N	Nitrate-nitrogen	$mg\ L^{-1}$
Water quality	PO4_P	Phosphate-phosphorus	$mg\ L^{-1}$
Water quality	DIN	Dissolved Inorganic Nitrogen	$mg\ L^{-1}$
Water quality	EC	Electrical conductivity	$\mu S\ cm^{-1}$
Water quality	DOC	Dissolved Organic Carbon	$mg\ L^{-1}$
Water quality	Turbidity	Turbidity	NTU
Water quality	Water_temp	Water temperature	ºC

Type	Variable	Name	Units
Habitat integrity	Fines_pct	Fines (silt and sand) substrate percentage	%
Habitat integrity	LWD	Large woody debris volume	m^3
Habitat integrity	Bank_height	Bank mean height	cm
Habitat integrity	BCPOM_native	Benthic coarse particulate native organic matter	g
Habitat integrity	BCPOM_exotic	Benthic coarse particulate exotic organic matter	g

We used Generalized Additive Models (GAMs; Hastie and Tibshirani 1990; Wood 2006) to relate water quality and habitat integrity (i.e., response variables) to basin land uses, pollution, and riparian (native and exotic) variables (i.e., explanatory variables). GAMs were selected for their flexibility in handling non-linear responses without requiring a predefined functional form (Wood 2006), making them well-suited for ecological data (Large et al. 2013).

GAM models were fitted for each response variable (n = 12) using the *mgcv* package in R (R version 4.5.3). The error distribution and link function were chosen for each response variable based on its characteristics. For continuous positive variables (NO_3^-, PO_4^{3-}, DIN, EC, DOC, turbidity, bank height), we used a Gamma distribution with log-link; for zero-inflated variables (fines percentage, LWD, native and exotic BCPOM), we used a Tweedie distribution with log-link (Dunn & Smyth 2005); and for normally distributed variables (water temperature), we used a Gaussian distribution with identity link. In all models, smoothing parameters were estimated by Restricted Maximum Likelihood (REML), which provides better stability and reduces the risk of overfitting compared to other methods (Marra & Wood 2011).

For each response variable, GAMs were built for five accumulative scenarios that included, as explanatory variables, variables related to basin and pollution, native or exotic riparian forest (Table 2). For each model, we retained only significant variables. Variable selection was performed using the internal function selection, which adds an extra penalty to effectively shrink and then exclude non-significant terms ($p > 0.05$) from the model (Varanka & Hjort 2017; Zuur et al. 2010). Further, variables with VIF > 5 were sequentially removed due to multicollinearity (Akinwande et al. 2015).

Table 2
Overview of the five scenarios, type and number of variables used in generalized additive model (GAM) development.

Scenario	Type	Variables	N
1	Basin model	Basin + Pollution	10
2	Native riparian model	Native + Riparian	5
3	Exotic riparian model	Exotic + Riparian	5
4	Riparian model	Native + Exotic + Riparian	8
5	Global model	Basin + Pollution + Native + Exotic + Riparian	18

Model performance was compared using AIC (Akaike 1974), and the percentage of deviance explained was used as a measure of goodness-of-fit. Relative predictor contributions were estimated by comparing the deviance explained by the full model against nested models excluding each term (Pedersen et al. 2019), and significant predictors were visualized using partial effects plots, showing smooth functions with 95% confidence intervals, with covariates held at mean or median values (Wood 2006).

Thresholds were identified as predictor values where the smooth function crossed zero (i.e., partial effect changes sign), following established ecological approaches (Large et al. 2013; Sonderegger et al. 2009; Pedersen et al. 2019). Where confidence intervals overlapped zero, thresholds were interpreted cautiously (Marra & Wood 2011). Multiple thresholds were recorded but not conclusively interpreted. Partial effects for all GAM models are shown in Figures S3–S15.

All statistical analyses were conducted using R version 4.5.3 (R Development Core Team 2026).

3. Results

3.1 Water quality and habitat integrity

Water quality showed broad ranges across streams (Table 3). NO_3^- concentrations ranged from 0.001 to 6.14 mg L^{-1}, comparable to DIN, while PO_4^{3-} was much lower (0.0001 to 2.86 mg L^{-1}). DOC, EC and turbidity also exhibited wide ranges, with maximum values of 89.43 mg L^{-1}, 293.90 µS cm^{-1} and 146 NTU, respectively. The range in summer water temperature was comprised between 8.59 and 25.05 ºC.

Table 3
Summary statistics (minimum, median, mean, and maximum) and units for reach-scale response variables of water quality and habitat integrity.

Variables	Units	Minimum	Median	Mean	Maximum
NO3_N	$mg\ L^{-1}$	0.001	0.59	0.88	6.14
PO4_P	$mg\ L^{-1}$	0.0001	0.01	0.03	2.86
DIN	$mg\ L^{-1}$	0.007	0.72	0.95	6.17
EC	$\mu S\ cm^{-1}$	19.14	77.83	81.00	293.90
DOC	$mg\ L^{-1}$	0.24	1.61	2.33	89.43
Turbidity	NTU	0.59	2.57	5.44	146.00
Water_temp	ºC	8.59	16.98	16.97	25.05
Fines_pct	%	0.00	12.25	21.46	100.00
LWD	m^3	0.00	0.20	5.91	152.83
Bank_height	cm	23.95	95.17	97.89	289.30
BCPOM_native	g	0.00	22.00	29.51	225.94
BCPOM_exotic	g	0.00	0.00	5.20	184.55

Similarly, habitat integrity variables also spanned several orders of magnitude (Table 3). Fine sediments had a median value of 12.25% and LWD showed a highly skewed distribution. Bank height was symmetric around 95 cm while native and exotic BCPOM showed contrasting medians of 22.00 g and 0.00 g, respectively, despite having similar ranges.

3.2 Scenarios and relative contribution

The global model, including basin and riparian variables performed best for all response variables except bank height, which retained only riparian variables (Table 4). In addition, some marginally significant predictors ($p < 0.10$) during residuals diagnostic were retained or removed based on AIC.

Table 4
Akaike's Information Criterion (AIC) values for every reach-scale variable and scenario. The best-performing scenario for each variable is shown in bold.

Response	Basin	Native	Exotic	Riparian	Global
NO3_N	118.49	198.25	182.87	153.80	**95.89**
PO4_P	-1089.58	-1155.56	-1127.83	-1157.68	**-1167.95**
DIN	147.25	244.68	216.72	189.81	**124.21**
EC	1588.98	1618.72	1621.50	1616.46	**1537.85**
DOC	449.34	402.05	402.05	393.20	**376.33**
Turbidity	743.50	792.18	786.61	761.53	**720.98**
Water_temp	680.49	662.03	642.53	642.53	**616.30**
Fines_pct	1310.98	1336.72	1323.38	1323.38	**1295.90**
LWD	700.99	729.21	711.98	711.98	**688.85**
Bank_height	1580.33	1576.69	1572.59	**1571.31**	1582.05
BCPOM_native	1443.14	1427.02	1418.42	1418.42	**1408.59**
BCPOM_exotic	685.89	707.10	717.04	675.12	**621.67**

Consequently, the relative contribution of basin- and riparian-scale variables with the total deviance explained is presented in Fig. 2. Across all response variables, NO_3^- model had the highest deviance explained (79.1%). Subsequently, six GAM models achieved deviance explained from 65.2% to 72.8%: PO_4^{3-}, DIN, EC, DOC, turbidity and exotic BCPOM. The lowest performance was found for fines percentage, water temperature, LWD, bank height and native BCPOM (27.3%-48.2%).

Moreover, riparian variables emerged as the main contributors (> 55%) of PO_4^{3-}, DOC, water temperature, bank height and both BCPOM (native and exotic) model (Fig. 2). In contrast, basin variables primarily explained (> 55%) fine sediments, LWD, and DIN. Finally, turbidity, EC, and NO_3^- were influenced by both basin-scale and riparian-scale variables (between 45%-55%).

Extensive agriculture was the most frequent retained basin variable (75% of the models) while agriculture and urban uses appeared in half of the models with importance ranges of 0.10–0.31 and 0.01–0.20, respectively (Fig. 3). Eucalypt percentage was selected in four models with importance values of 0.02–0.23, while coniferous appeared in two models with values of 0.07 and 0.13. Notably, natural vegetation percentage was excluded due to collinearity, and catchment area was retained only in the DIN model (importance = 0.12). Regarding pollution variables, only population equivalent was retained for one single model (DOC).

Among riparian variables, native stems and riparian shade were the most recurrent predictors, appearing in 10 and 9 models, respectively (Fig. 3). Native stems showed importance values ranging of 0.13–0.40, while riparian shade ranged of 0.01–0.47. Exotic stems appeared in half of the models, with a maximum importance of 0.16, while riparian slope was retained in 8 models with importance values of 0.06–0.36. Finally, the least common variables in both native and exotic groups were maximum distance and continuity, except for native maximum distance, which appeared in five models with importance values of 0.01–0.23.

3.3 Effects and thresholds

Basin-scale variables showed strong relationships with several response variables (Fig. 4). Extensive agriculture generally reduced most responses, with values above 4.1% reduced turbidity, whereas over 7.8% reduced EC, fine sediments, water temperature, and native BCPOM, and showed multiple effects on NO_3^- and LWD, DOC and DIN. Total agriculture, with a threshold range of 12.0-19.4%, increased NO_3^-, DIN, EC, fine sediment, and turbidity, while reducing exotic BCPOM. Besides, urban cover over 6% increased EC and turbidity, decreased native BPOM, and increased exotic BCPOM, with additional effects on PO_4^{3-}. Eucalypt (17.8–30.1%) increased fine sediment and LWD, although reduced DOC. Meanwhile, coniferous cover (10.0%) reduced LWD and increased water temperature. Finally, a log-transformed catchment area > 1.6 was associated with increased DIN.

Among the riparian predictors, native distance greater than 6.9 m were associated with reduced PO_4^{3-} and EC (Fig. 4). The number of native stems was one of the most influential predictors. Specifically, values between 16.1 and 19.2 (corresponding to a density of 0.40 and 0.48 stems m^{-2}) were associated with increases in NO_3^-, DIN, EC, LWD, and bank height; while above 18.4 decreased fine sediments and both native and exotic BCPOM. In contrast, exotic variables showed contrasting patterns. Exotic stems over a consistent threshold of 2.1, reduced NO_3^-, PO_4^{3-}, DIN, and EC, while increased exotic BCPOM, and exotic continuity had a relevant effect on exotic BCPOM (> 16.2%). Finally, riparian slope values over 10.8%-14.4% decreased PO_4^{3-} and DOC alongside increased NO_3^-, DIN, and turbidity, with additional multiple effects on water temperature and bank height. On the other side, riparian shade was associated with reduced fine sediment and turbidity (56.7% and 46.8%). Besides, shade also showed multiple and unclear effects on PO_4^{3-}, EC, DOC, water temperature, bank height and native BCPOM.

4. Discussion

The beneficial role of riparian forests as ecological buffers and the need for effective riparian management have been highlighted by Feld et al. (2018), who proposed separating basin- and riparian-scale factors. Our non-parametric approach, based on field data from a representative network of Galician streams and including riparian-scale variables, reinforces this idea through the relative importance in the GAM models, which ranged from 38% to 90% on water quality and 36%-100% on habitat integrity responses. Basin- and riparian-scale variables predicted several water quality

parameters satisfactorily, while habitat integrity models performed less well. Furthermore, the identification of quantitative thresholds represents a novel application of this framework. First, the observed nonlinear responses suggest that small changes in land use or riparian characteristics could trigger ecological shifts with significant consequences for water quality and stream habitat integrity. Besides, the consistency of these tipping points across response variables suggest that they might be applied to water management frameworks. Finally, as an exploratory first step connecting basin and riparian variables with water quality and habitat integrity, our approach did not include cross-validation. However, to develop predictive models and incorporate these thresholds into management, a cross-validation study should be required.

Our multiple scale approach allowed to predict water quality parameters (NO_3^- and DIN, PO_4^{3-}, EC, DOC and turbidity) fairy well (deviance explained: 65.2%-79.1%), matching or exceeding previous studies that use similar models to predict DOC (Stanley et al. 2012), nutrients (Tso et al. 2023; Rothwell et al. 2010), EC (Olson and Hawkins 2012; McManus et al. 2020) and turbidity (Venkateswarlu and Anmala 2024). Water temperature showed the worst deviance explained (48.2%) among water quality parameters. In contrast, models for habitat integrity (percentage of fine sediments, LWD, bank height, and native BCPOM) variables performed poorly overall (deviance explained: 27.3%-35.7%). This may be explained by the importance of local and in-stream dynamics on morphological predictions, which are not fully captured by basin- and riparian-scales. Nonetheless, even for these variables, our approach offers a novel perspective compared to other temperature prediction approaches (Piotrowski et al. 2015) or channel morphology studies (Kaufmann & Faustini 2012). For instance, the better performance of exotic over native BCPOM likely reflects the lower nutritional quality and slower decomposition of eucalyptus litter (López et al. 2001; García & Pardo 2012), leading to greater benthic accumulation, along with summer peak inputs (Molinero and Pozo, 2004) which may enhance predictability.

Basin-scale variables explained substantial variance in DIN, EC, fine sediment and LWD levels. For those parameters, variables related to diffuse agricultural sources and forestry emerged as the most influential pressures. For instance, levels of DIN (including NO_3^-) and EC increased when agriculture areal cover exceeded 15%, linking agricultural practices to elevated nitrogen (N) loads and increased EC (Lassaletta et al. 2009; Zhang et al. 2023). Similar thresholds and trends were observed for fine sediments, reinforcing the idea that agriculture promote soil erosion, habitat simplification, and surface water degradation (Lamba et al. 2015; Ladrera et al. 2019; Wiltshire et al. 2025). Interestingly, our results also showed that stream N concentrations increase even in those basins where agriculture is mostly extensive, partially questioning the effectiveness of this management strategy. Yet our results suggest that promoting extensive agriculture might be a good management practice for reducing EC, turbidity, and fine sediments levels, as we observed a consist reduction when this land use covered at least 7.8% of the basin. The presence of grass or pasture crops in extensive lands tends to reduce erosion and sediment transport (Vondracek et al. 2005; Pierce et al. 2012). Moreover, riparian trees along field margins on extensive agriculture uses facilitates LWD inputs into the channel (Angradi et al. 2004; Galia

et al. 2022). Overall, these findings suggest that effective management may require both limiting agricultural cover (under 15%) and implementing instead lands with extensive agricultural practices.

As agriculture, forestry also impacted water quality and habitat integrity. Eucalypt cover reduced DOC, while increased both fine sediments and LWD. Fine sediments increases are probably due to timber harvesting (particularly when conducted near riparian zones), which can significantly impact stream sediment loads (Santiago et al. 2011; Lamba et al. 2015, Rodrigues et al. 2018). Moreover, eucalyptus cover was associated with increased LWD on streams due to clear-felling management (Burrows et al. 2011; Kuglerová et al. 2020), while coniferous cover with branches removal practices (Diez et al. 2001) reduced LWD. In forested streams, reducing eucalyptus under 20% and coniferous cover (< 10%) at the basin scale will help decrease sediment loads, as plantation management practices may have a greater influence than species composition (Diez et al. 2001).

Interestingly, and contrary to other studies (Mainstone & Parr 2002), basin characteristics did not drive variations in PO_4^{3-} or organic matter, possibly due to the short-slope river morphology or increased plant uptake during summer, which may limit PO_4^{3-} accumulation even in enriched rivers. Among land use variables, diffuse urban pollution was the main driver of PO_4^{3-} concentrations, suggesting that urban runoff can be as or even more important as point-sources (sewage and WWTPs) or agriculture for nutrient pollution (Jarvie et al. 2006; Pereda et al. 2021; Nie et al. 2018). Urban land use also affects other water quality (EC) and habitat integrity (turbidity, BCPOM) variables, most of which increasing above a threshold of 6% of urban areal cover. Interestingly, native and exotic BCPOM exhibited opposite responses to urban influence, likely due to the greater presence of exotic species in highly human-disturbed urban streams (Pennington et al. 2010).

The results further support the role of riparian zones as control points within basins. Specifically, we observed four riparian characteristics that are key for water quality and habitat integrity: riparian width, riparian tree density, riparian species and riparian slope. First, wider native forests (at least 7 m) can retain nutrients, showing reductions in PO_4^{3-} and EC values, consistent with the recommendation of 15 m of riparian forest from Brumberg et al., 2021. Beyond 20 m, the exotic continuity over 16% of the area further increased exotic CBPOM and reduced bank height due to the expansion of exotic trees into stream margins which reduce bank stability (Simon & Collison 2002; Santiago et al. 2011), and may contribute to sediment inputs (Rodrigues et al. 2018). Overall, wider native strips (> 7 m) without exotic tree continuity appeared to protect both water quality and habitat integrity parameters.

Contrary to potential nutrient mitigation, lower-density forests were associated with reductions in DIN and EC, consistent with the reduced nutrient uptake and denitrification efficiency of dense and thin riparian buffers (Mander et al. 1997; Mayer et al. 2007). Lower-density forests also maintained considerable native litter inputs while reducing LWD, a key habitat factor influenced by riparian forests that promotes heterogeneity (McIlroy et al. 2008). This pattern could be explained by riparian soils acting as potential DIN sources, contrasting with the typical nitrogen sink behaviour reported in more humid

zones (Lupon et al. 2026). In contrast, high tree density (over 0.5 stems/m^2) potentially mitigated water temperature, confirming the cooling effects, especially in summer maximum values (Bowler et al. 2012); and due to vegetation roots and cover, enhances soil strength reducing sediment fluxes and streambank erosion (Simon and Collison 2002). Even in low densities, exotic riparian trees (e.g., eucalyptus, coniferous and acacia) was linked to reductions in DIN and DOC, which may be explained by the low nitrogen and phosphorus content of eucalyptus litter (the primary pathway for nutrient return to the soil from the forest canopy; Molinero and Pozo 2004), while simultaneously increasing exotic CBPOM inputs.

Among riparian characteristics, slope appeared as one of the most important on water quality. Steeper slopes increased DIN and turbidity via runoff effects while promoting lower water temperatures, consistent with longitudinal thermal gradients (Garner et al. 2014). In contrast, lowland reaches allowed greater autotrophic production and soil accumulation, promoting particulate PO_4^{3-} (Mainstone & Parr 2002; Bowes et al. 2003) and DOC (Mei et al. 2014; Lee et al. 2019). Finally, riparian shade despite becoming the most influential predictor for several water quality and habitat integrity variables, showed effects that were frequently complex or incomplete, without clear thresholds. Particularly, for DOC this aligns with Stanley et al. (2012), as irradiance acts through multiple opposing mechanisms. Furthermore, higher riparian shade reduced sediment fluxes, supporting the riparian forest on reducing bank erosion (Simon & Collison 2002).

Conclusions and implications for landscape management

5. Conclusions and implications for landscape management
This study aimed to examine the effects of different basin land uses (agroforestry and urban) on water quality and habitat integrity while, at the same time, evaluate the mitigation capacity of riparian buffers, comparing native and exotic species. Our results showed that managing riparian forest through their composition and structural attributes is critically important; however, basin-scale management still needs to be considered. In addition, the non-parametric GAM methodology allowed for more flexible relationships between river system variables and provided scientific support for defining critical thresholds across basin and riparian scales for freshwater management.

In our Galician context, wider native riparian forests (> 7 m) can act as ecological buffers against nutrient inputs, in contrast to the presence of exotic species (e.g. Eucalypt), which had a detectable impact on in-stream habitat. Moreover, higher riparian densities exports nitrogen compounds to the stream and benefits habitat integrity. Leachable nutrients and water temperature were influenced by steeper slopes. While agricultural (> 15%) or urban (> 6%) land uses resulted in poorer water quality and habitat integrity, extensive agricultural practices (> 8% cover) with riparian buffer margins can partially limit these impacts.

Accordingly, management decisions should prioritize limiting basin land uses and conserving and restoring wider natural riparian areas to mitigate anthropogenic pressures near streams. A mosaic

landscape, combined with expanding the current hydraulic public domain and ensuring legal maintenance, would improve both water quality and habitat integrity in streams.

Declarations

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data and code availability

The statistical analyses were carried out using the R packages cited in Materials and Methods. Custom codes developed for the analyses are available from the corresponding author upon reasonable request. The authors do not have permission to share data because correspond to Augas de Galicia and the Xunta de Galicia autonomous government.

CRediT authorship contribution statement

Mateo Soto-Tielas: Conceptualization, Formal analysis, Investigation, Methodology, Writing – review and editing, Visualization; **Noé Ferreira-Rodríguez**: Visualization, Writing – review and editing; **Anna Lupón**: Supervision, Visualization, Writing – review and editing; **Isabel Pardo**: Conceptualization, Funding acquisition, Investigation, Supervision, Visualization, Writing – review and editing.

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Figures

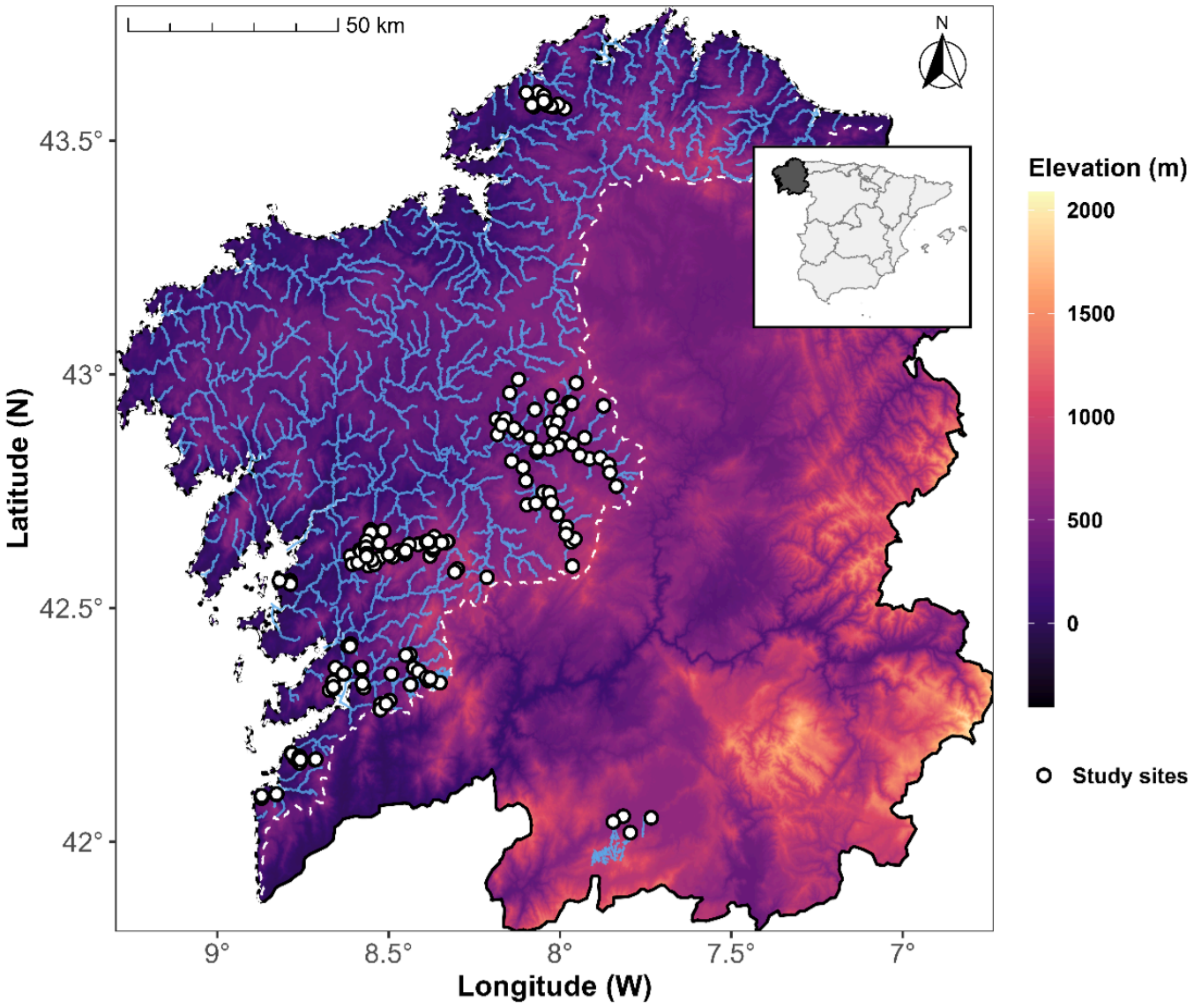


Figure 1

Location of the 168 sampling sites (white dots) located in small-medium rivers in Galicia (NW Iberian Peninsula). The Galicia-Costa River network is represented by blue lines, and the dashed white line indicates the division between Galicia-Costa and Miño-Sil River hydrologic districts.

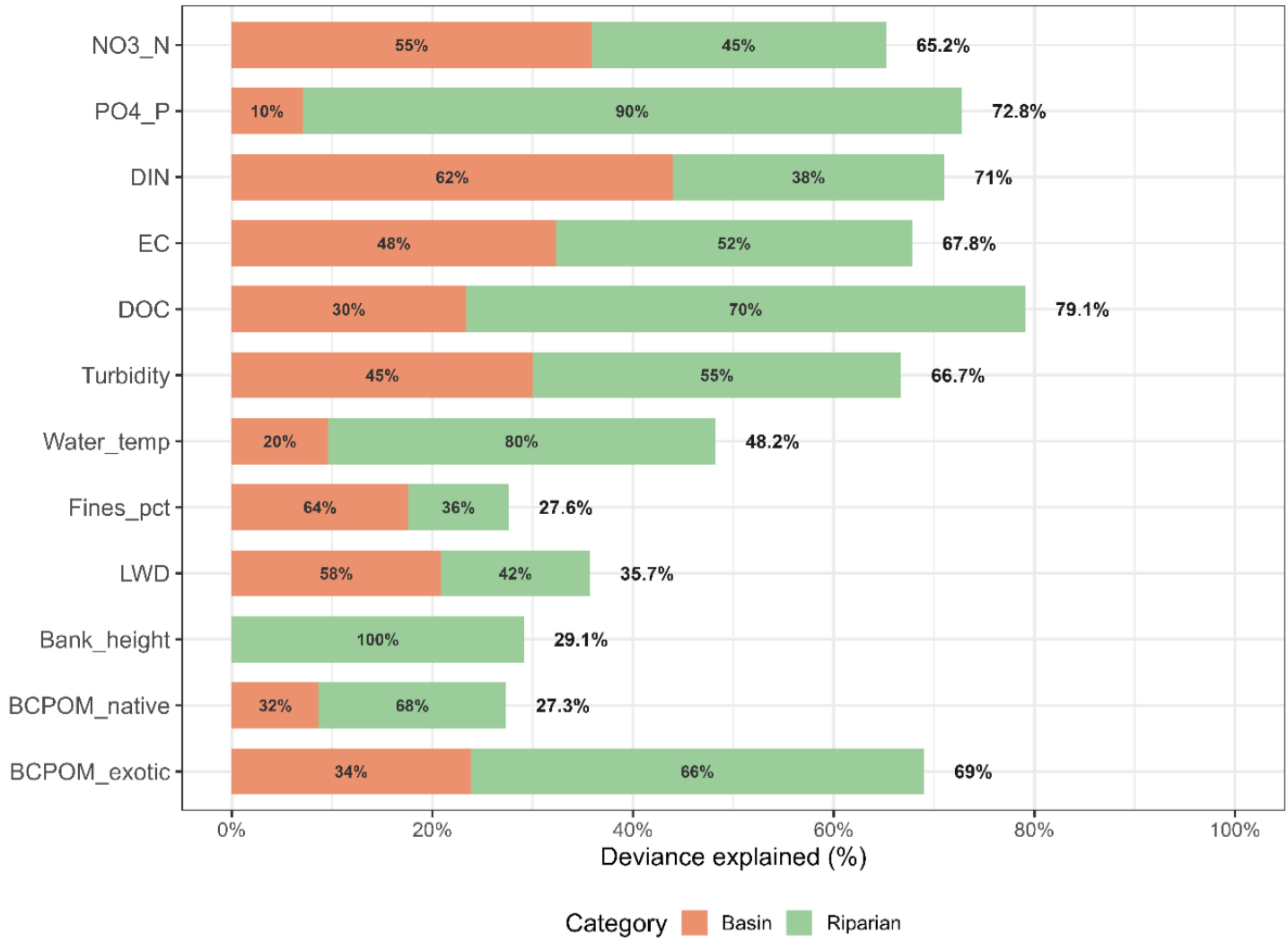


Figure 2

Relative contribution (%) of basin (orange) and riparian (green) variables, and total deviance explained (in bold) for the best GAM scenario selected by the lower AIC showed in Table 2.

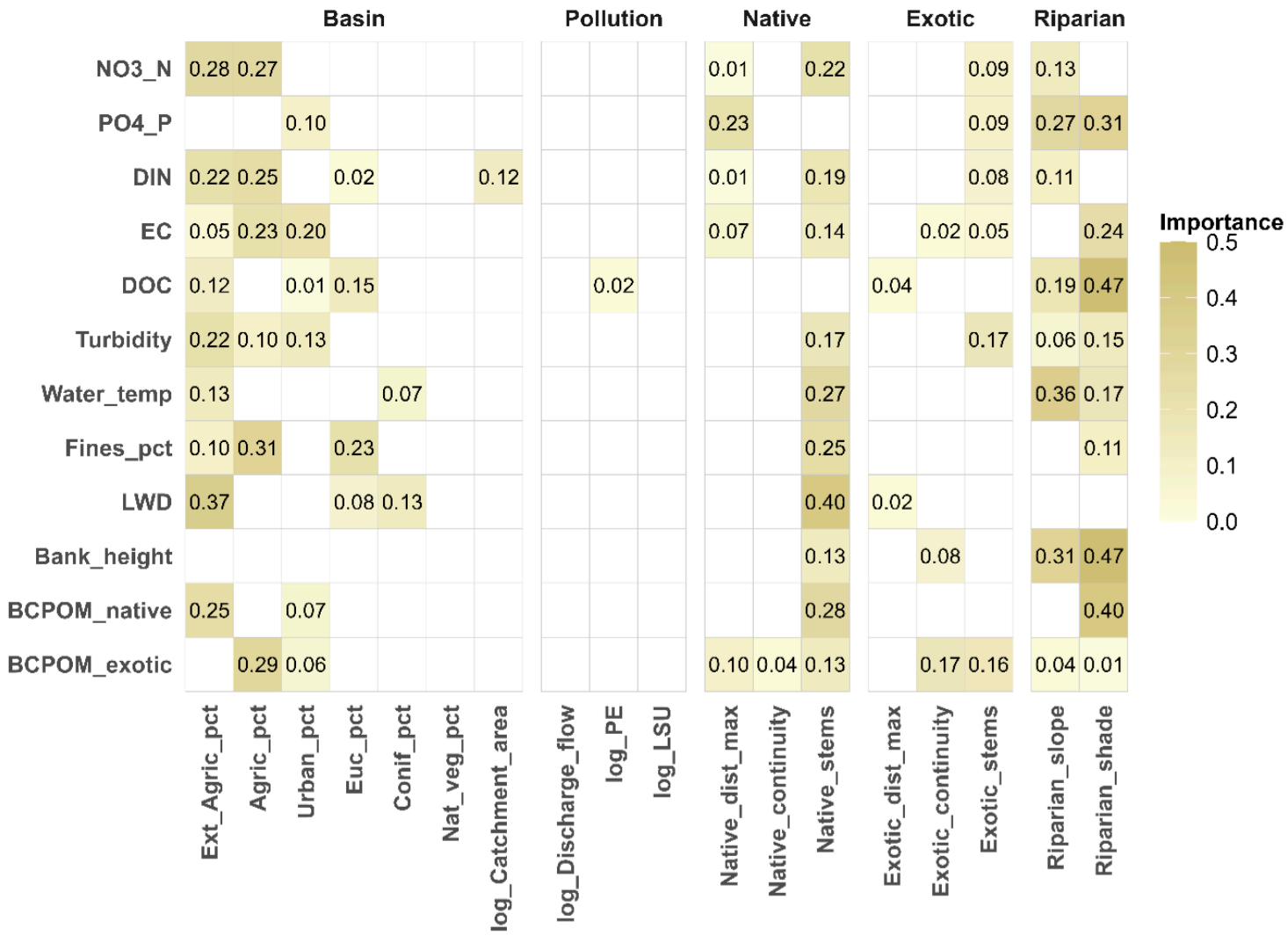


Figure 3

Heatmap of the relative importance (0 to 1) of each explanatory variable in the best suited GAMs for each response variable. Explicative variables were grouped in basin, pollution, native, exotic and riparian variables.

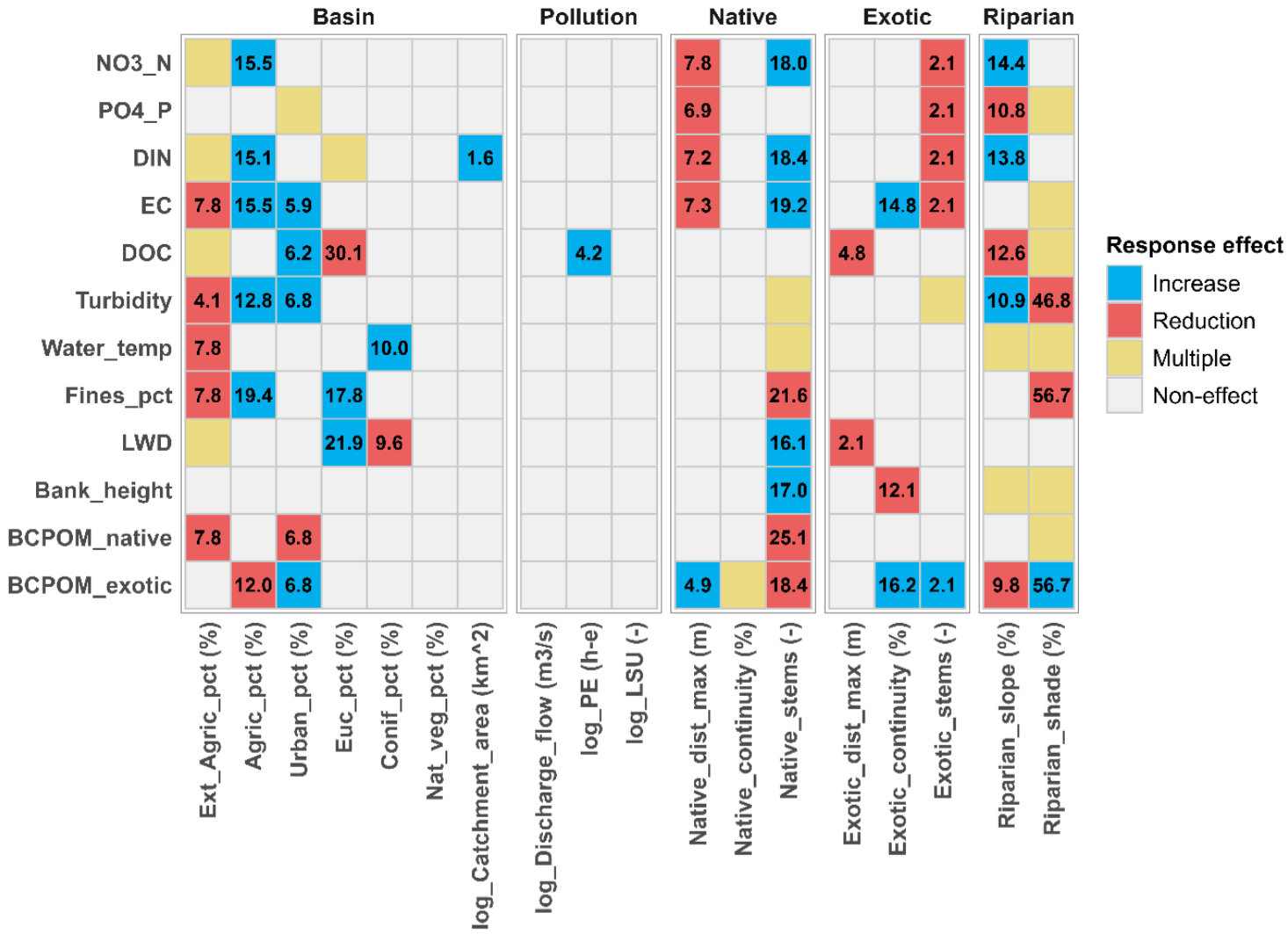


Figure 4

Heatmap of the response effect of each explanatory variable (increase in blue, reduction in red, multiple effects in yellow, and non-effect in grey) with the corresponding significant thresholds (number in bold) and units (Table 1) in the best suited GAMs. Explanatory variables were grouped in basin, pollution, native, exotic and riparian variables.

Supplementary Files

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- SupplementarySotoTielas2026EnvironmentalManagement.docx