Buffering in the riparian zone

Which attributes of forest buffers contribute to improving health of agricultural streams?

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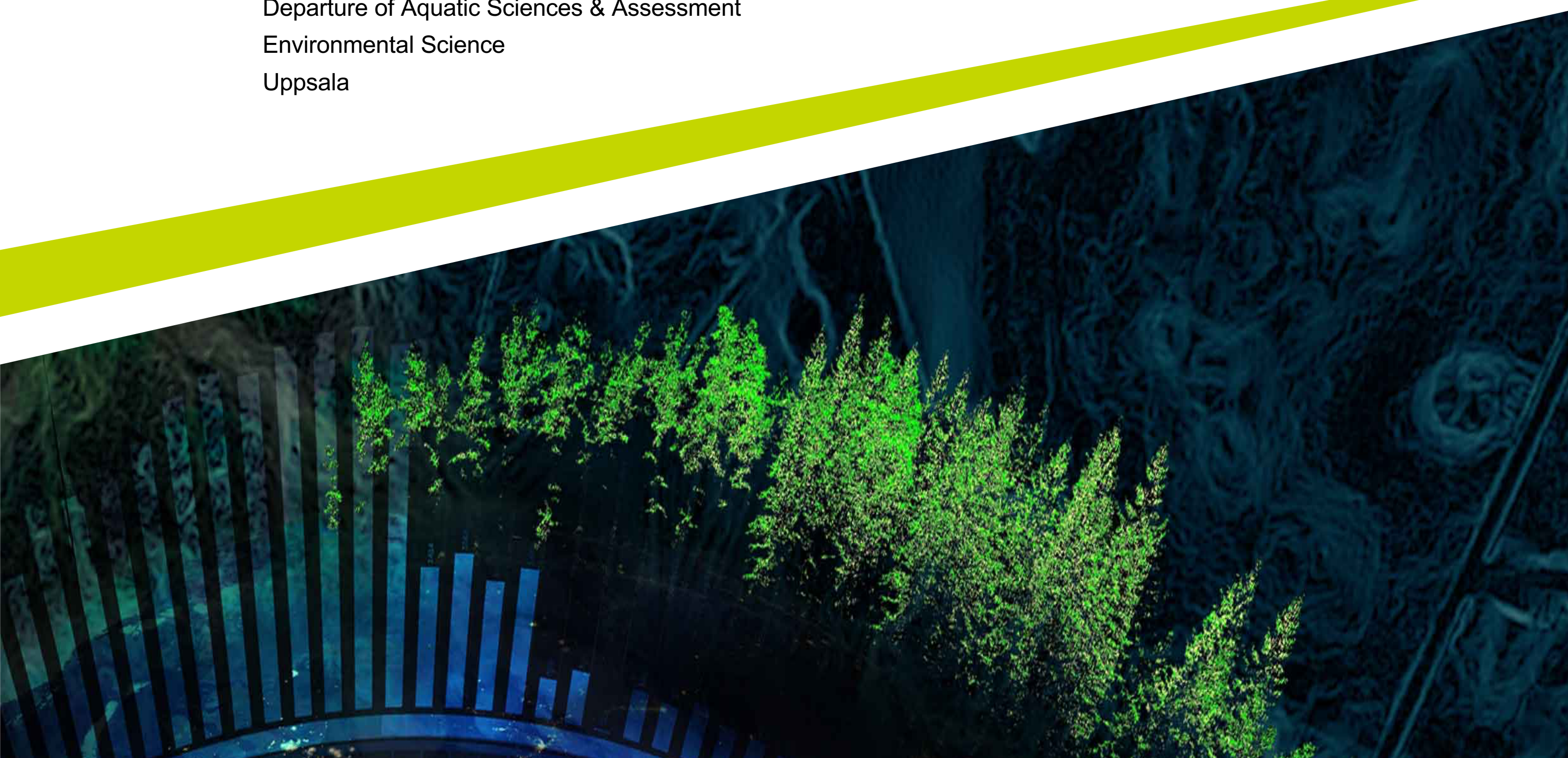

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Abstract

The current state of the world's freshwater is threatened because of human perturbations. It is important to protect our streams and waterways and solutions are required. One solution is the concept of forested riparian buffer zones which, if designed carefully, can buffer harmful substances and reduce impacts from agricultural land use, give shade and detritus, as well as significantly increasing the overall biodiversity among macroinvertebrates and diatoms in the water body.

In this study, a data analysis of riparian data from the streams in lake Ekoln basin was conducted in order to examine which attributes of a riparian buffer zone are most important for improving ecological condition in agricultural streams. Linear modelling with backwards model selection was used to assess the effects of six predictor variables on 15 response variables and their relationships were presented through tables and graphs.

I found that the simple presence of a forest buffer, regardless of any particular property, reduces the amounts of fine sediment and is associated with increased biodiversity of macroinvertebrates, and increased scores for the macroinvertebrate monitoring index EPT and diatom IPS. The results further revealed that some buffer properties were more likely to be associated with stream ecosystem improvements than others, both in terms of number of responses affected and the strength of those relationships (based on R^2).

Buffer width and buffer length had the highest average R^2 values out of all the six predictor variables, and was significantly correlated with six and three response variables respectively. Tree species richness was associated with five relationships to the response variables, and had most effect on diatom IPS, but had a low average R^2 value of 0,027. Tree cover density had only two relationships, but with very low R^2 (<0,0001).

Riparian condition index had the third highest average R^2 value and was strongly correlated with sediment and macroinvertebrates. But since riparian condition index is a multimetric variable, further investigation is needed for determining which attributes of the RCI that were the driving factors for sediment and macroinvertebrates.

Since all predictor variables showed relationships with at least two response variables, and reasonably no predictor variables act alone in contributing to an efficient buffer, it is important to highlight the combined importance of several variables. However, overall, these results indicate that focusing on aspects of buffer size (length and width) when designing forest buffers is important for maximizing stream ecosystem biodiversity.

Keywords: riparian buffer zones, water management, riparian condition, environment, sediment, biodiversity, Ekoln catchment area

Table of contents

List of tables

List of figures

Abbreviations

RCI	Riparian Condition Index
EPT	Ephemoptera, Plechoptera and Trichoptera
ASPT	Average Score Per Taxon
IPS	Indice de Pollution Spécifique

1. Introduction

All of Earth's rivers and streams are connected to the global hydrological cycle. Therefore, they are sensitive to climate change (Woodward et al. 2010). Streams, rivers and all types of waterbodies are, and have been, affected by anthropogenic activities for a long time, since human settlement often occurs in close proximity to sources of freshwater (Malmqvist and Rundle 2002). Many of these human activities have lead to the degradation of stream habitats and their ecological status (Burdon et al. 2020). In particular, because stream and rivers drain the landscape hydrologically; human impacts arising on land, will eventually reach the waterways. However, before excess runoff of, e.g. nutrients or pesticides, reaches the waterways, it has to pass through the border that is the *riparian zone*.

Riparian zones constitute the interface between terrestrial and aquatic ecosystems (Gregory et al. 1991). A riparian zone is the piece of land adjacent to a body of water and supports unique biodiversity of plants and animals (Naiman et al. 1993). Through a number of different processes, a well-functioning riparian zone may have the potential to protect waterways from sediment, pesticides, nutrient runoff and temperature increases, but this depends on the characteristics of the riparian zone, especially the vegetation type and density (Burdon et al. 2020).

Riparian zones are used to reduce the leakage of nutrients, e.g. nitrogen (N) and phosphorus (P), and fine inorganic sediment surface runoff (Bechtold et al. 2006). Riparian vegetation can buffer deposition of these substances due especially to vegetational root systems that stabilize the soil and slows the flow of water so that the substances will settle before reaching the stream. Inputs of fine inorganic sediment, mainly agricultural land uses and soil disturbances, has been linked to declines in biodiversity (Burdon et al. 2013). In order for a riparian zone to reduce this leakage, there needs to be enough vegetation that can absorb and uptake substances like soluble reactive phoshorus and nitrogen, and to stabilize riparian soils, thereby reducing fine inorganic sediments (Harding et al. 2009; Burdon et al. 2020). Though whether a longer length of riparian vegetation along the stream channel or enough width extending from the channel is more important is unclear (Lind et al. 2019).

Through riparian buffers, we could protect our waterways more efficiently - which they are in dire need of. There are thus good prospects for improving the status of streams and rivers by incorporating riparian replanting into frameworks regulating the management of freshwaters, such as the European Union's *Water Framework Directive*.

The European Water Framework Directive (WFD) is a framework that regulates the monitoring and management of freshwaters with the aim that all waterbodies in Europe shall reach "good status" by the year 2027 (European union 2023). It is therefore of interest and urgency to take action and enforce solutions that will improve the status of European waters. Hence, one solution could be riparian buffer zones. To implement riparian buffer zones, we first need to find out how to efficiently design them, and in particular identify which buffer attributes contribute most to positive effects on river health, such as what size a riparian buffer zone ought to be, and the density and species richness of the planted trees.

According to Lind et al. (2019) a buffer of 3-10 meters width from the stream channel can contribute with sediment filtration. Further, Lind (2019) and Schultz et al. (2009) concluded that the wider and more forested a riparian buffer zone is, the better it can protect the stream. A woody, forested riparian zone also means a more shaded stream channel. The shade is important in keeping temperatures in the stream lower, and can thus be a way to mitigate higher water temperatures from climate change (Johnson et al. 2016). This is why strips of riparian buffers already are in use by fisheries in order to keep maximum temperatures down and the fish populations thriving. (Broadmeadow et al. 2011). The forested aspect of a buffer zone also contributes to the structuring of instream habitats, in a way that they provide habitats for organisms like macroinvertebrates (aquatic insects and other invertebrates such as snails and worms) and diatoms (a key algal group which is a good quality resource for invertebrates to eat). Riparian vegetation also provides instream habitat with detritus like leaf litter and woody debris (Sargac et al. 2021; Bjelke et al. 2016). Since a riparian buffer takes away area from an agricultural landscape, it may be of interest for farmers to know how big of an area is needed for a riparian buffer zone.

Today, very few countries require uniform buffer strip widths. Countries that require uniform buffer strip widths are Germany and Switzerland with a width of 5 metres (Lind et al. 2019). Knowledge gaps about riparian buffer zones could make it impractical for land managers seeking to implement them – more consensus and clarity about the properties of riparian buffer zones are needed in order for managers and farmers to implement buffer zones as a way to protect water streams (Cole 2020). In Sweden, riparian buffers are not always looked on positively by land owners. Nevertheless, Hadjicharalambous (2021) has shown that farmers and agricultural companies are overall positive to riparian buffer zones of a size between 3-10 meters in width, although in order to designate more land use for this purpose, they wish for higher compensation.

With the purpose of identifying which attributes contribute to an effective riparian forest buffer, capable of improving the health of agricultural streams, this study analyzed the effects of different riparian buffer properties on streams in the lake Ekoln basin, part of lake Mälaren catchment, located in the county of Uppsala, Sweden. These streams had forested and unforested stream reaches. Twenty-eight variables from 10 buffered and unbuffered site-pairings, collected between the 2018-2019, were analyzed to determine the impact of riparian buffers on stream ecosystems.

Based on the scientific literature (Lind et al. 2019; Sargac et al. 2021; Bjelke et al. 2016; Johnson et al. 2016), I hypothesized (1) that buffered reaches have lower levels of nutrients, sediment, and lowered temperature than unbuffered reaches, and consequently higher diversity of aquatic organisms (macroinvertebrates and diatoms). Additionally, as the buffered riparian zones I studied vary in their properties such as width, length, Riparian Condition Index (RCI), and the type and density of trees, I hypothesized (2) that buffers that are wider and longer, and with more tree species, higher tree cover density, and a higher RCI score, will correlate with reduced phosphate, nitrogen and sediment, lower water temperatures, higher levels of dead wood, resulting in positive effects on diversity of macroinvertebrates and diatoms.

2. Method

This study is a data analysis of environmental data from lake Ekoln basin located around the city of Uppsala, Sweden. The data was analyzed using JMP (SAS Institute) using linear modelling, and I report here significant p-values as well as effect size values (R^2 values).

2.1 Field sites and study design

The dataset used in this study is part of the data that is collected within the CROSSLINK project, a European BiodivERsA research project which studied woody riparian buffers as a vital part in mitigating anthropogenic perturbations and enriching biodiversity and ecosystem service delivery in stream networks (www.riparianbuffers.com).

The CROSSLINK project included basins in four European countries: Belgium, Norway, Romania and Sweden. In this thesis, I analyzed data sampled from streams of the lake Ekoln basin which is part of lake Mälaren catchment situated in Sweden. The study sites were located on streams situated in agricultural areas of the catchment, and comprised 10 pairs of sites (defined as circa 100m long stream reaches) on 10 different streams, for 20 stream reaches in total (Figure 1). The surrounding landscape's character is a mosaic of land-use types that is dominated by forest and agriculture, as well as the urban areas of Uppsala city. (Ramberg 2020)

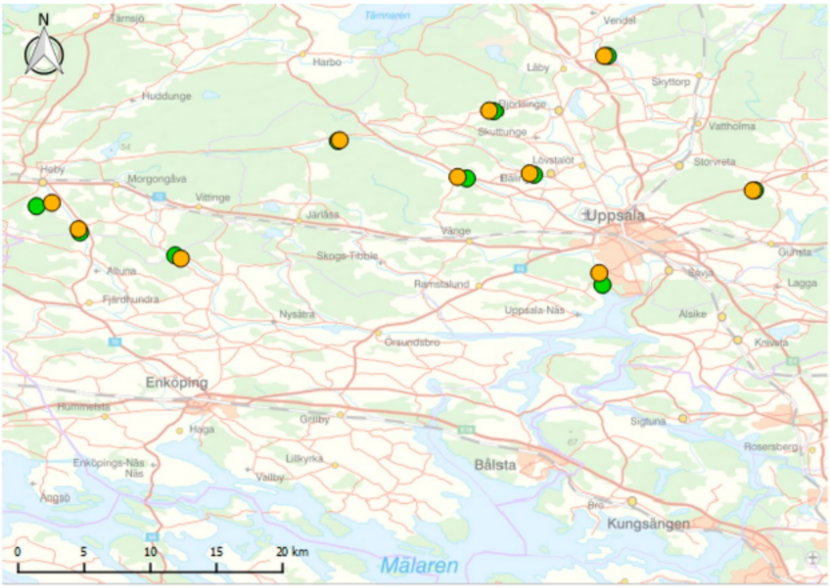

Figure 1. Position and schematic representation of streams and their paired reaches (orange dots—upstream unbuffered reaches; greendots—downstream forested buffered reaches). Modified from Sargac et al. (2021).

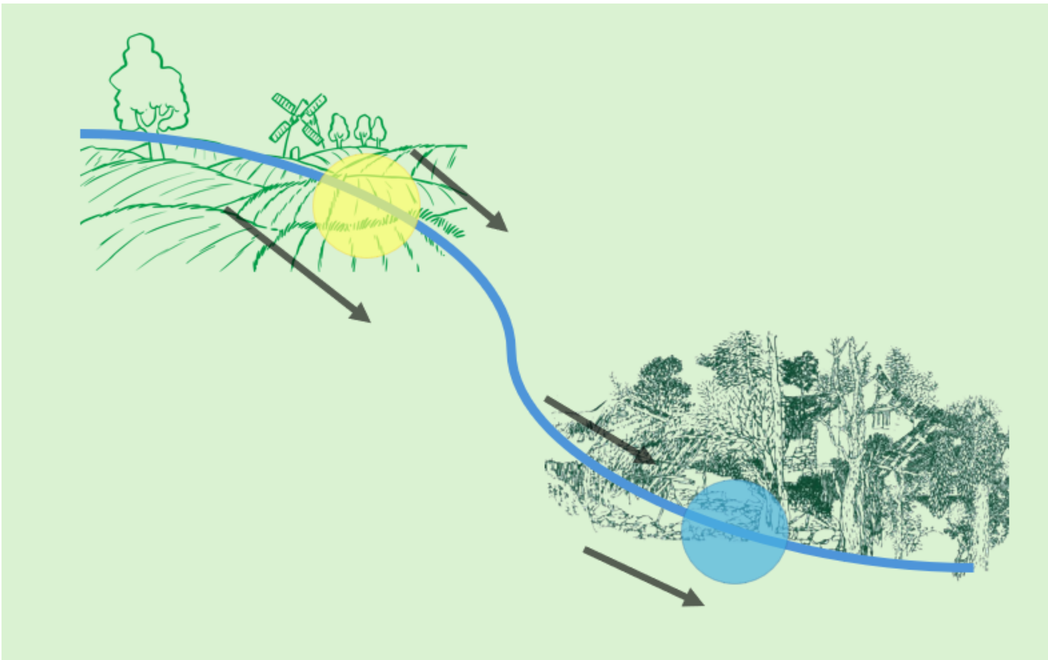

Figure 2. Picture showing how the paired stream reaches were situated with the unbuffered, unforested reach upstream (yellow dot) of the forested buffered site downstream (blue dot).

The stream pairs were selected so that an unbuffered reach that mostly had grassy or herbaceous vegetation with no or only a few isolated trees, was always situated upstream of a buffered site that flows through a patch of forest extending at least 50 m in width on both sides of the stream (Sargac et al. 2021; Figure 2).

2.2 Variables quantified

Burdon et al. (2020) provides full details of methodologies on how the response variables were sampled, while full details relating to predictor variables is available in Burdon et al. (2020), Witing et al. (2022) and van Pul (2018). Here I provide a summary of sampling methodologies in Table 1.

For all study sites, seven predictor variables (Table 1) relating to different riparian buffer properties were quantified. These comprised buffer presence – with or without, riparian condition index (RCI), width and length in metres, buffer size, tree cover density and tree species richness. Buffer size was later excluded since it was strongly correlated with buffer length and width (r >70%) which would violate assumptions of a regression analysis. Also I argue that advising landowners on buffer length and width is more practical than simply advising on overall buffer size per se, which makes designing riparian buffers easier.

Notably, the riparian condition index (RCI) has here been adapted for European conditions (Burdon et al. 2020). The RCI is an index developed in New Zealand by Harding et al. (2009) that assesses 11 attributes of riparian buffers and ranks them using a score of 1 to 5. Some examples of attributes assessed are buffer intactness, vegetation composition and bank stability (Burdon et al. 2020).

Table 1. Riparian buffer properties quantified at every site with a brief description of methodology. See the cited references for full details.

Predictor variable	Description	Methodology
Buffer presence	Binary variable indicating if the reach was in a buffered stream section or not	Sites were classed as buffered based on presence of an inatact forest buffer on both banks[1].
Buffer width (m)	Average buffer width from the bank to the forest edge, over the whole length of the buffer[2].	Quantified based on 10 measurements per reach from aerial photographs using the “measure” function in Google Earth[2].
Buffer length (m)	Buffer length longitudinally along the stream channel.	This variable was also quantified based off of aerial photographs using the “measure” function in Google Earth.
Riparian Condition Index (RCI)	Composite index of riparian quality, including information on bank	The riparian condition index is an index of the ecological quality of a riparian buffer zone that measures 13 variables and ranks

	integrity, tree height, diameter and more.	them a score between 1 (lowest) to 5 (highest)[1].
Buffer size (m^2)	The forest buffer size in square metres.	The forest buffer size was quantified in square metres and required on measurement per reach, using the “measure” function on aerial photographs in Google Earth[2].
Tree cover density	Measure of density of tree cover density in a band extending 50 m laterally x 100 m along each sampling reach.	Based on Copernicus[3] data derived *in situ* from a riparian habitat inventory.
Tree species richness	Number of species of trees.	Tree species were counted during inventories along the stream reaches, and identified with the app TreeSnap[1].

Referenses: [1]Burdon et al (2020), [2]van Pul (2018), [3]Witing et al. (2022)

At each site, 15 response variables were quantified. These can be divided into environmental, biodiversity and biomonitoring variables. The environmental variables included soluble reactive phosphorus (PO_4-P), total inorganic nitrogen (the sum of the ions NH_4-N, NO_2-N NO_3-N), sediment deposition, counts of dead wood, channel shading, absolute annual maximum temperature, annual mean daily maximum temperature and annual mean daily range temperature.

The biodiversity variables included macroinvertebrate and diatom richness richness and Shannon diversity. The Shannon diversity index takes into account not only the number of species living in a habitat, but also their relative abundance (Rain 2024).

The biomonitoring indices consisted of the ASPT index and EPT richness for macroinvertebrates and IPS index for diatoms (Table 2). For all indices, higher values are associated with greater presence of environmentally sensitive species which indicates good environmental conditions.

Table 2. Environmental, biodiversity and biomonitoring indices variables quantified every site with a brief description of methodology. See cited references for full details.

Response variable	Description	Sampling method
	Environmental	
Soluble reactive phosphorus	Concentration of inorganic P in the water	Samples collected in a bottle held just below the water

		surface, and analysed at SLU's certified laboratories[1].
Total inorganic nitrogren	Concentration of inorganic N in the water	Samples collected in a bottle held just below the water surface, and analysed at SLU's certified laboratories[1].
Sediment deposition	Quantity of sediment settling on the substrate over 3 days	Astroturf mats, serving as analogues for a patch of benthic macrophytes, were fixed to the stream bottom. After three days they were retrieved, and the deposition sediment was washed off and then dried in a muffle furnace (to burn off organic sediment), and then weighed to quantify deposition of inorganic sediment[1].
Shade	Channel shading at zenith during summer	Channel shading was measured at zenith during summer using the "CanopyApp"[1].
Dead wood counts	Number of logs larger than 10 cm in diameter, which is at least partly located in each plot.	Dead wood was counted by hand by walking along the stream reach[1].
Absolute annual maximum temperature (Cº)	The highest temperature measured in a year.	Temperatures were measured using a Manta +30 probe at five different times of the year[1].
Annual mean daily temperature (Cº)	The average temperature of the days in a year.	
Mean daily temperature range (Cº)	The mean daily temperature range shows how the temperature varies throughout the days. This is important since many organisms want stable temperatures.	
	Biodiversity	

Macroinvertebrate species richness	This variable counts the number of species among the macroinvertebrates.	The methods for collecting macroinvertebrates were Surber sampling and semi-quantitative kick-net sampling[1].
Macroinvertebrate Shannon diversity	Estimates species diversity within macroinvertebrates.	
Diatom species richness	The number of species within the diatoms.	Diatoms were sampled by brushing submerged stones, following the European protocol of this methodology[1].
Diatom Shannon diversity	Species diversity among the diatoms.	
	Biomonitoring indices	
Macroinvertebrate EPT richness	EPT stands for Ephemeroptera, Plecoptera and Trichoptera. These are orders of pollution sensitive species and therefore good indicators of pollution.	Sum of species counts for the three orders Ephemeroptera, Plecoptera and Trichoptera[2].
Macroinvertebrate ASPT	ASPT stands for Average Score Per Taxon	A taxon is assessed and scored according to their sensitivity to environmental degradation, then sensitivity scores are summed across all taxa, and divided by the number of taxa to give ASPT[3]. A higher ASPT means a higher number of sensitive species are present in the sample.
Diatom IPS	Diatoms were used as an indicator of water quality and the IPS index can describe their sensitivity to pollutants to evaluate the ecological condition of the water body.	Water samples were collected by brushing submerged stones, following the European protocol[4]. The IPS is similar in concept to ASPT, with higher scores indicating less polluted waters able to support more taxa[4].

References: [1]Burdon et al. (2020), [2]Weber (1973), [3]Armitage (1983), [4]Goma et al. (2005).

2.3 Data analysis

All data analysis was carried out using JMP Pro 17 (SAS Institute). During the fit model analysis, the raw data was transformed where necessary to satisfy assumptions of linear modelling (i.e. normality and constant variance) and then parameters of significance were determined. A random effect attribute was assigned to the “site block” category to account for the background variation among stream pairs in, for example, overall differences among the the pairs in characteristics such as width, depth, level of land use impact, ratio of stones to sediment, et cetera (Burdon et al 2020). The significant effects were visualized with the help of JMP’s graph builder tool, with regression plots including the regression line and a 95% confidence interval indicated with R^2 value for significant relationships – that is the effect size which measures the strength of the relationship between two variables.

3. Results

3.1 Environmental factors

The final model for soluble reactive phosphorus included buffer presence, length and tree richness (Table 3). Phosphate concentrations significantly declined with increasing buffer length (Figure 3). There was also a trend for increased phosphate concentrations with increasing tree richness (Table 3), but this effect was not significant at the 5% level (p = 0.065). No predictors were excluded from the final model for total inorganic nitrogen, i.e. total inorganic nitrogen was not significantly correlated with any of the buffer properties.

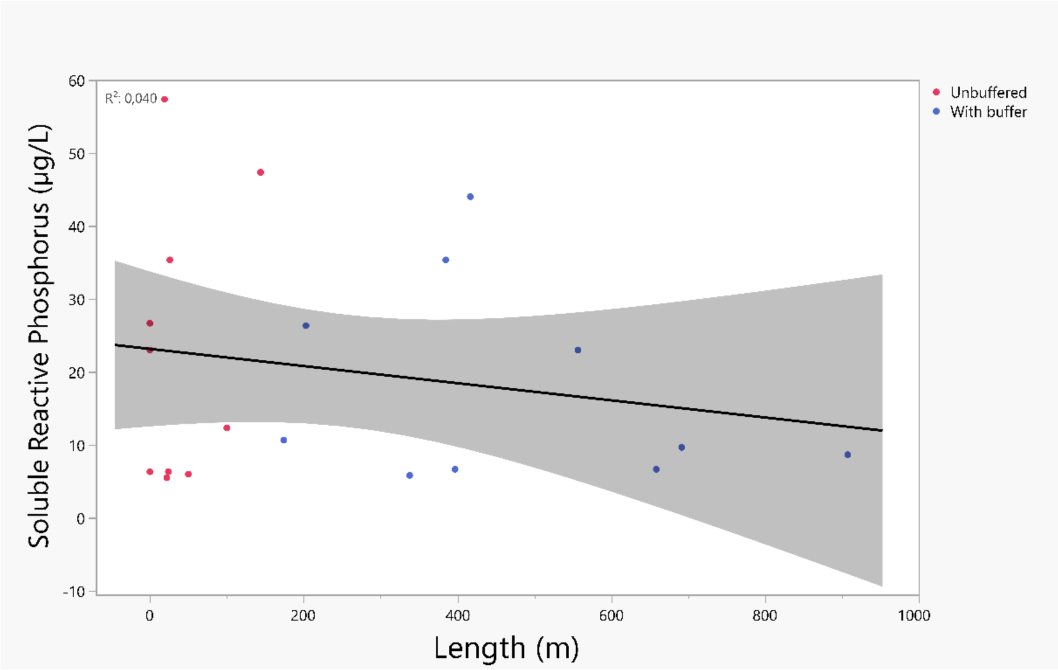

Figure 3. Linear regression modelling the relationship between buffer length and concentrations on soluble reactive phosphorus. R^2 value = 0,040. Grey area indicates 95% confidence interval around the regression line.

Table 3. Final linear models for abiotic environmental variables: significance levels (p-values) for buffer properties retained in the models following model reduction. ns = not significant. numbers in red = p < 0,05, numbers in yellow = p < 0,01, orange = p < 0.001

	Abiotic environmental variables							
	Response variable							
Buffer property	Soluble reactive phosphorus µg/L	Total Inorganic Nitrogen µg/L	Sediment	Dead Wood	Shade	Annual maximum temperature	Mean daily maximum temperature	Mean daily temperature range
	P value	P value	P value	P value	P value	P value	P value	P value
Buffer presence	ns	ns	0,1382	ns	ns			
Buffer length	0.0466	ns		<.0001	ns	0,2808		0.00872
Buffer width	ns	ns		0.0447	0.0003			0.02044
Tree cover density	ns	ns		ns	ns			
Tree species richness	0,0652	ns		ns	ns	0.0152	ns	0.01331
Riparian condition index	ns	ns	0,007	ns	ns			

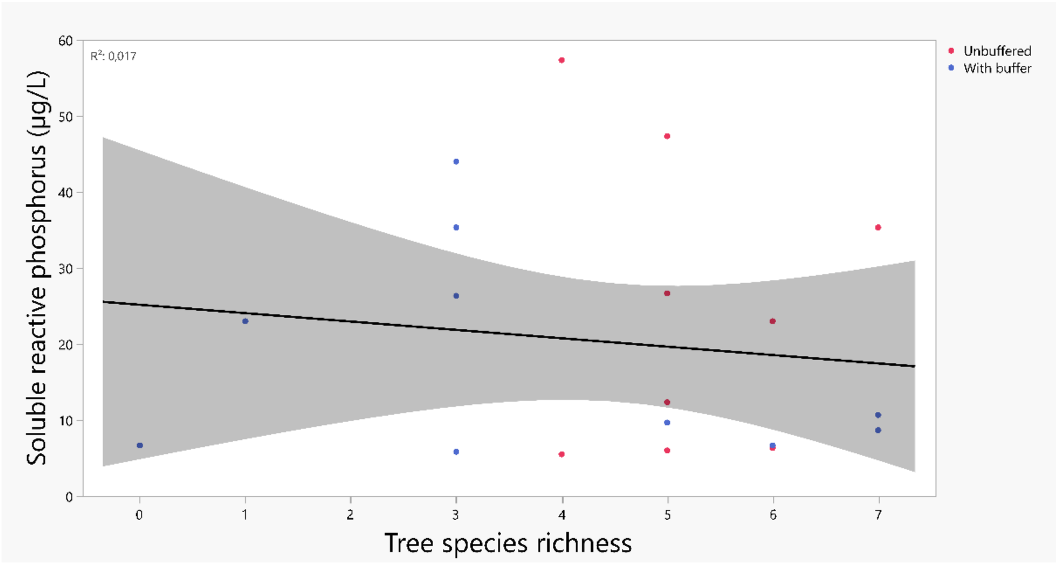

Figure 4. Linear regression modelling the relationship between tree species richness and soluble reactive phosphorus (µg/L). R^2 value = 0,017. Grey area indicates 95% confidence interval around the regression line.

There was a significant positive effect of buffer length on counts of dead wood found in the stream channel, but a weaker negative effect of buffer zone width (Table 2, Figure 5-6). Sediment was affected by buffer zone presence only (Table 1), with lower levels of sediment deposition in buffered stream sections (Figure 7). Shading increased with increasing buffer strip width (Table 1, Figure 9)

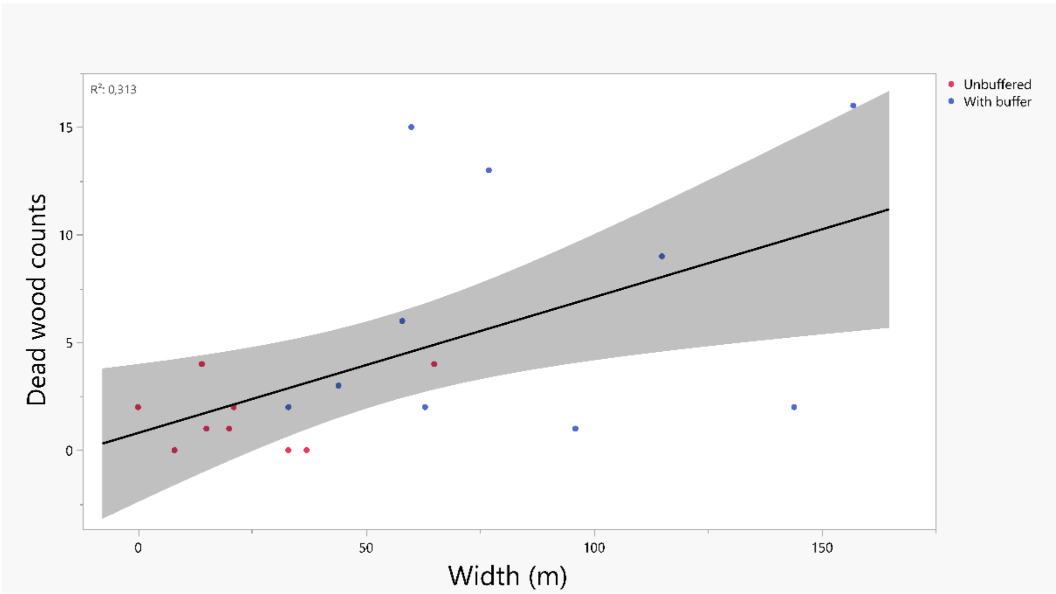

Figure 5. Linear regression modelling the relationship between buffer width and dead wood counts. R^2 value 0,313. Grey area indicates 95% confidence interval around the regression line.

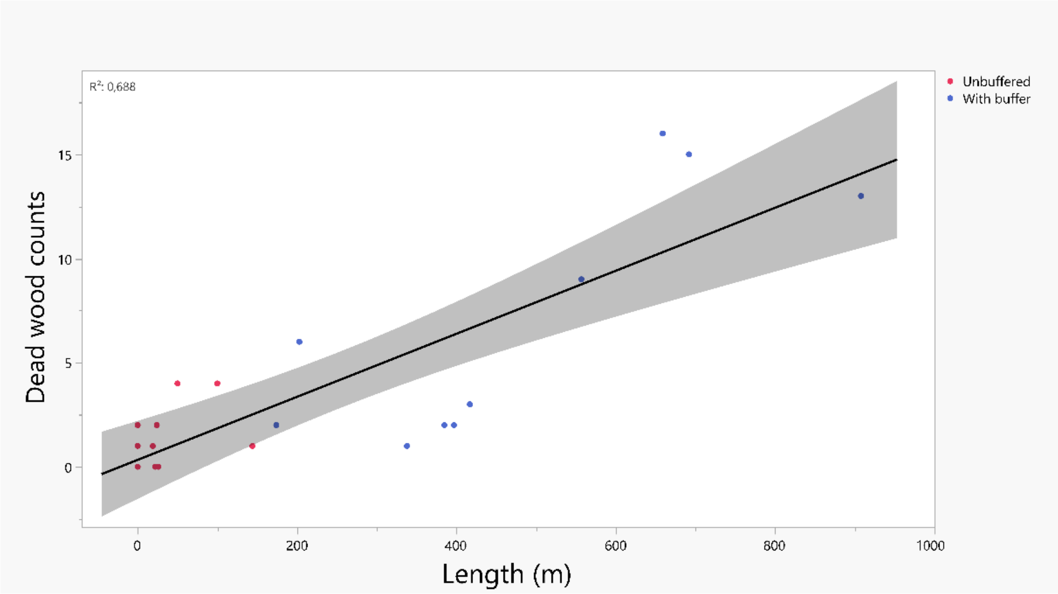

Figure 6. Linear regression modelling the relationship between buffer length and dead wood counts. R^2 value 0,688. Grey area indicates 95% confidence interval around the regression line.

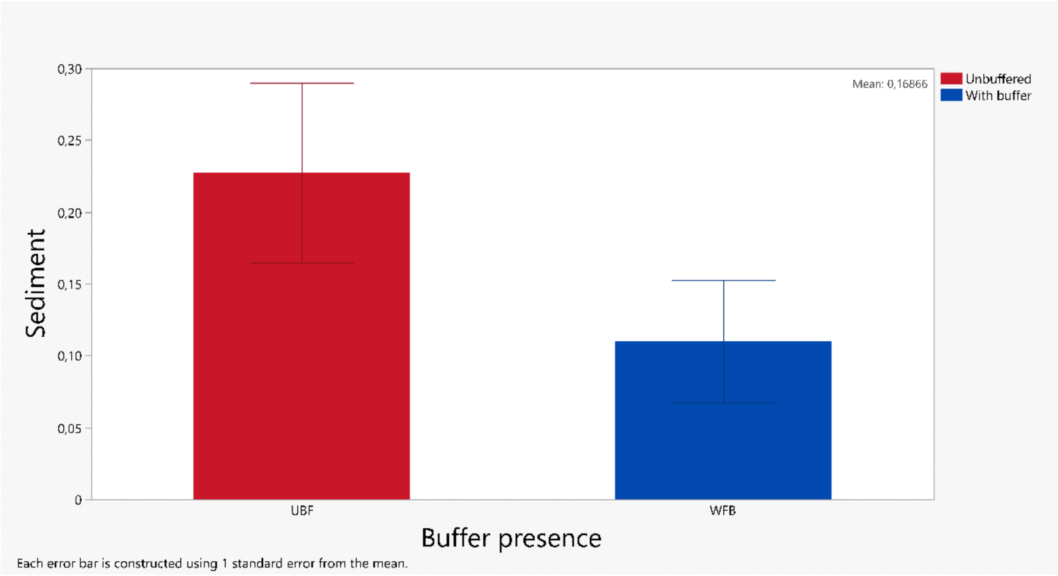

Figure 7. Relationship between buffer presence and mean (±1 SE) sediment deposition.

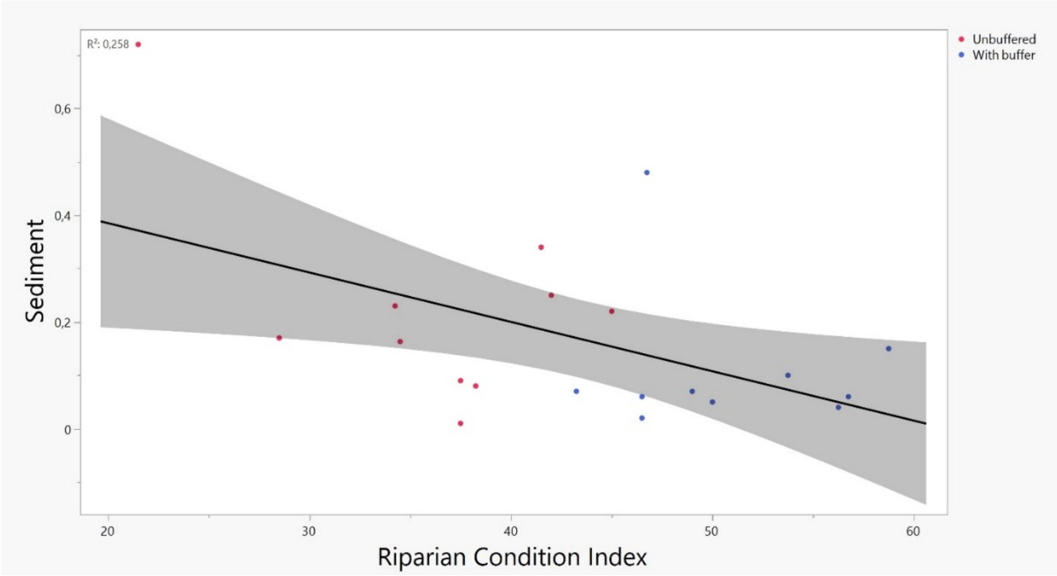

Figure 8. Linear regression modelling the relationship between riparian condition index and sediment. R^2 value = 0,258. Grey area indicates 95% confidence interval around the regression line.

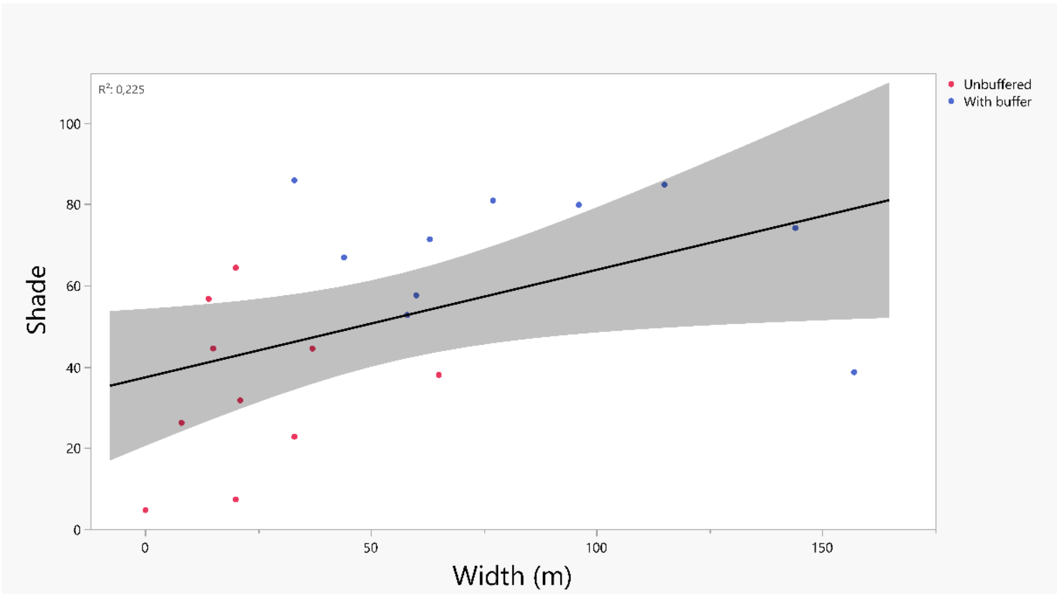

Figure 9. Linear regression modelling the relationship between buffer width and shade. R^2 value = 0,225. Grey area indicates 95% confidence interval around the regression line.

There was a significant relationship between absolute annual maximum temperature and tree species richness (Table 1). However, the R^2 was very weak and there was only a very weak decline in annual maxima with increasing tree species richness (Figure 10). Mean daily maximum temperature was not significantly affected by any buffer property (Table 1). Mean daily temperature range was affected by buffer length, width and tree species richness. Mean daily temperature range increased very slightly with increasing length and tree species richness, but decreased more strongly with increasing buffer width (Figure 11-13).

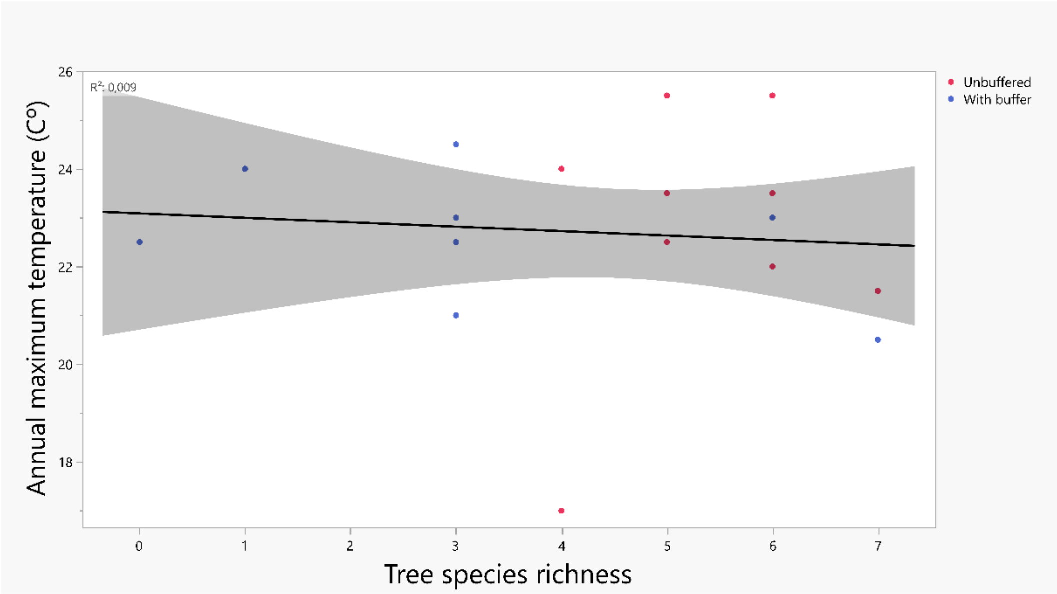

Figure 10. Linear regression modelling between tree species richness and absolute annual maximum temperature. R^2 value 0,009. Grey area indicates 95% confidence interval around the regression line.

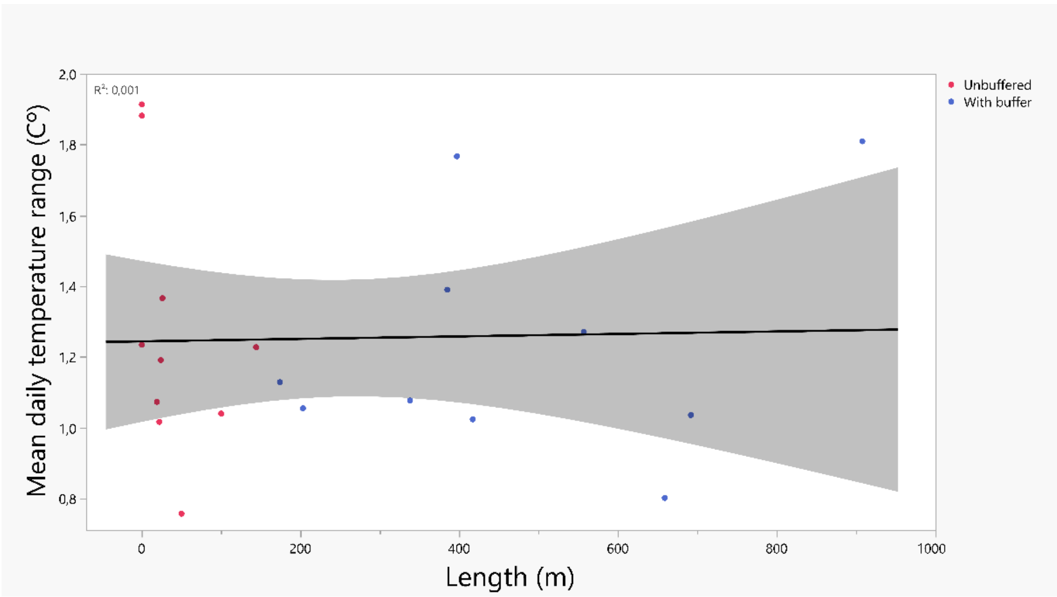

Figure 11. Linear regression modelling the relationship between buffer length and mean daily temperature range. R^2 value 0,001. Grey area indicates 95% confidence interval around the regression line.

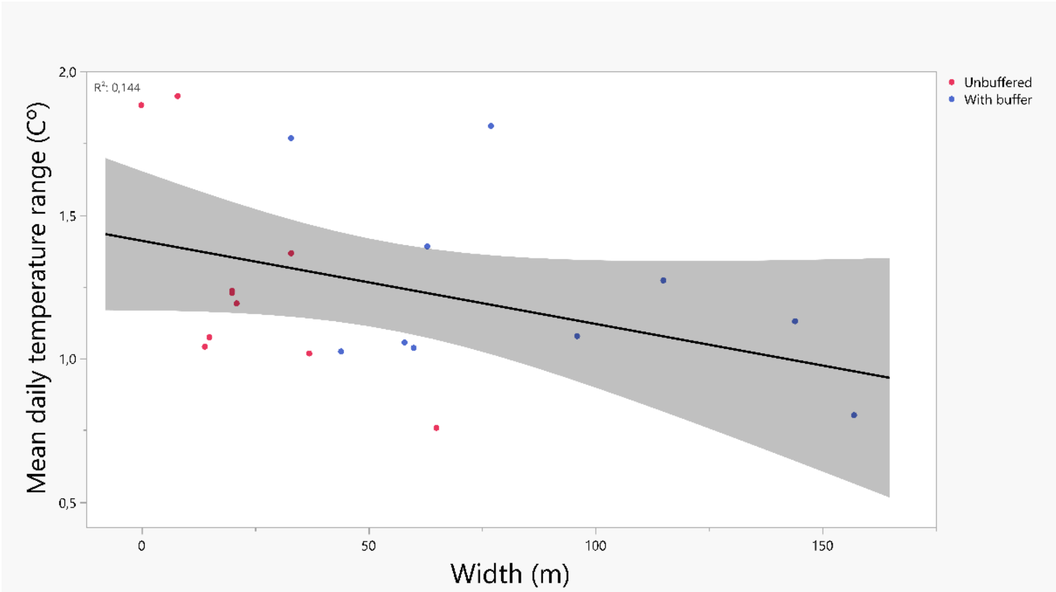

Figure 12. Linear regression modelling the relationship between buffer width and mean daily temperature range. R^2 value 0,144. Grey area indicates 95% confidence interval around the regression line.

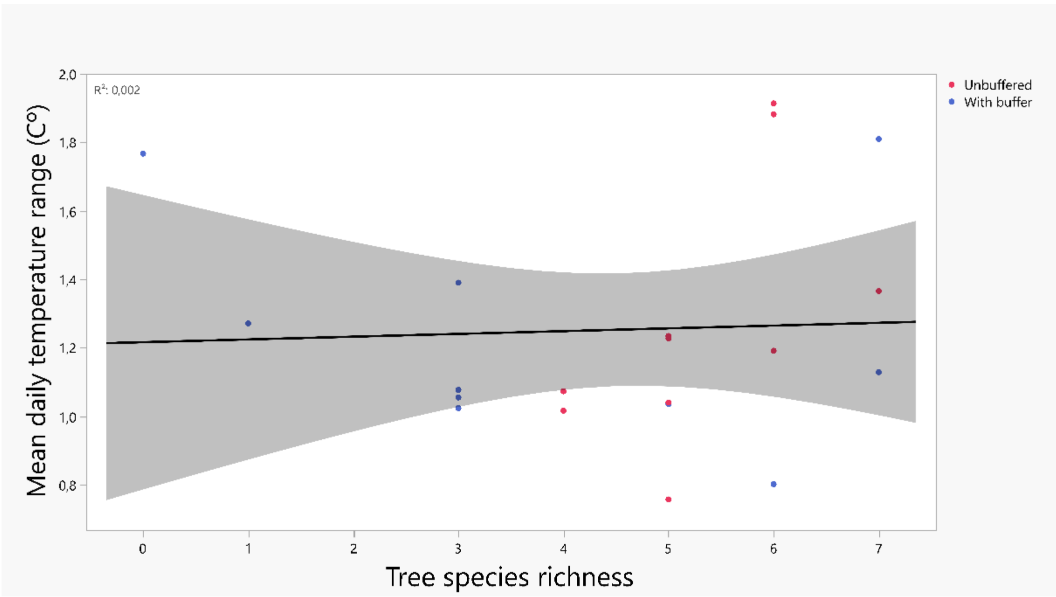

Figure 13. Linear regression modelling the relationship between tree species richness and mean daily temperature range. R^2 value 0,002. Grey area indicates 95% confidence interval around the regression line.

3.2 Biodiversity

Macroinvertebrate species richness was affected by buffer presence, buffer length, and buffer tree cover density (Table 4). The buffer presence increased macroinvertebrate species richness. A longer buffer length as well as a higher tree cover density were associated with increased macroinvertebrate species richness (Figure 14-16). Macroinvertebrate Shannon diversity was positively affected by a higher riparian condition index and tree species richness (Table 4, Figure 18-19). There was also a tendency for higher Shannon diversity in buffered stream sections, but this was not significant at the 5% level (Table 4). Diatom species richness showed no significant relationship with any of the response variables. Diatom Shannon diversity also did not show any significant relationship with any of the response variables.

Table 4. Final linear models for biodiversity variables variables: significance levels (p-values) for buffer properties retained in the models following model reduction. ns = not significant, Red = significant (p<0.05).

Biodiversity variables				
	Response variables			
	Macroinvertebrate		Diatoms	
Buffer property	Species richness	Shannon diversity	Species richness	Shannon diversity
	p-value	p-value	p-value	p-value
Buffer presence	0.0231	0.0643	ns	
Buffer length	0.0219		ns	
Buffer width				ns
Buffer tree cover density	0.0457		ns	
Tree species richness	0.1071	0.0420	ns	
Riparian condition index	0.1645	0.0292	ns	

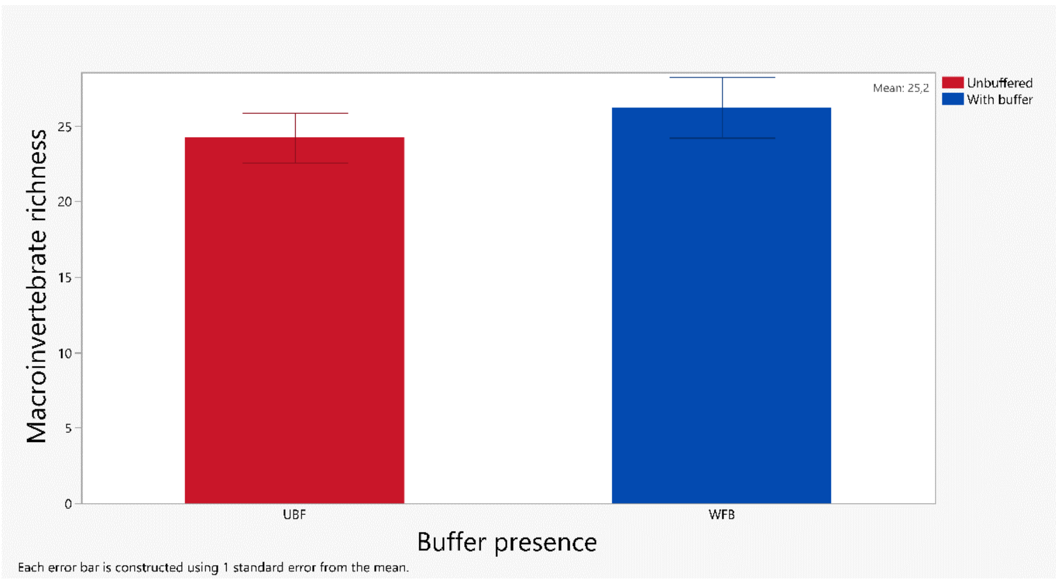

Figure 14. Relationship between buffer presence and mean (±1 SE) macroinvertebrate species richness.

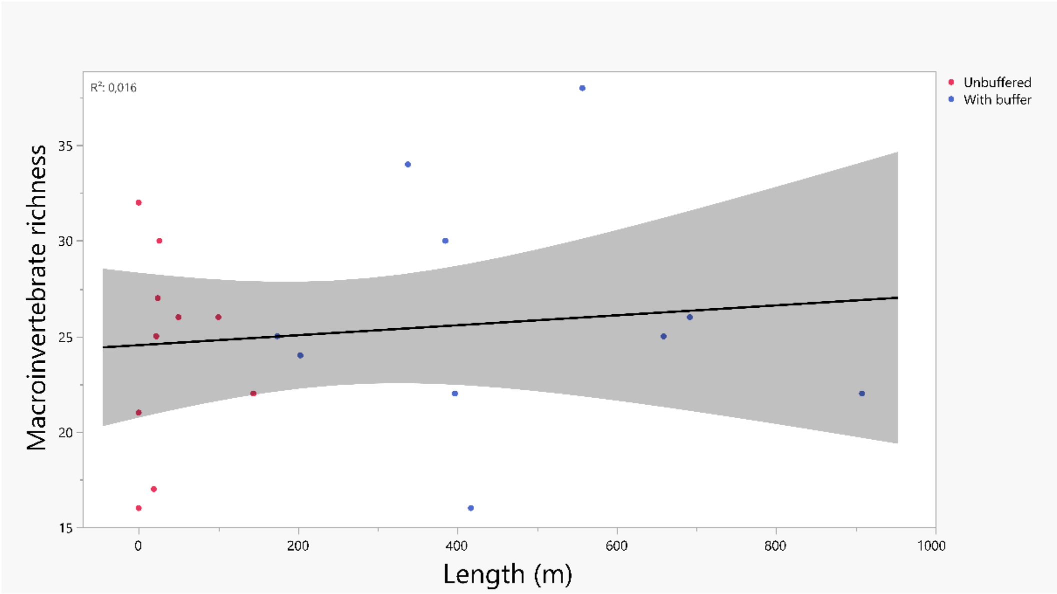

Figure 15. Linear regression modelling the relationship between buffer length and macroinvertebrate richness. R^2 value 0,016. Grey area indicates 95% confidence interval around the regression line.

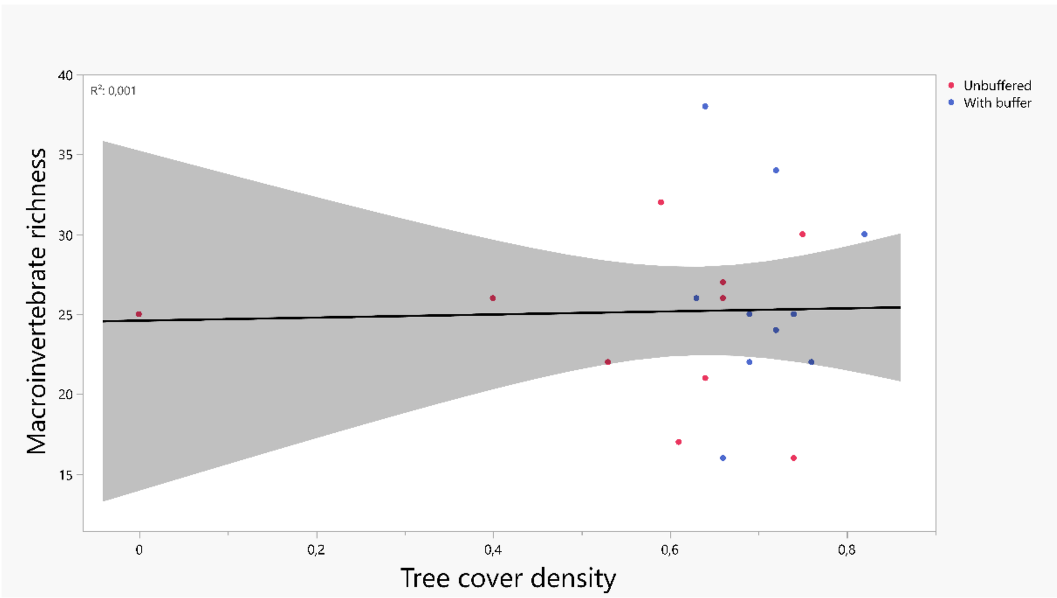

Figure 16. Linear regression modelling the relationship between tree cover density and macroinvertebrate richness. R^2 value 0,001. Grey area indicates 95% confidence interval around the regression line.

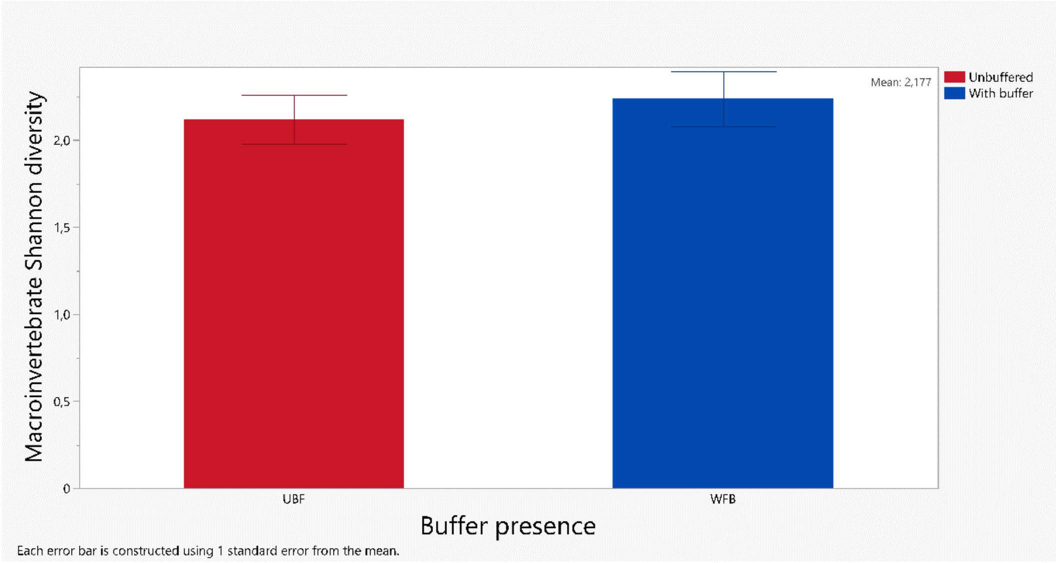

Figure 17. Relationship between buffer presence and mean (±1 SE) macroinvertebrate Shannon diversity.

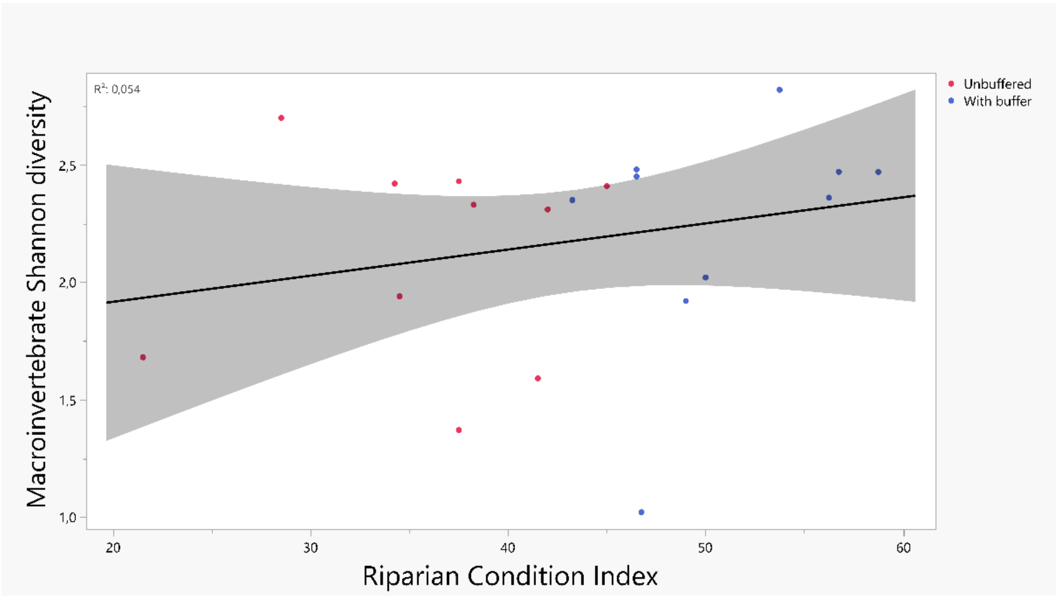

Figure 18. Linear regression modelling the relationship between the riparian condition index and macroinvertebrate Shannon diversity. R^2 value 0,054. Grey area indicates 95% confidence interval around the regression line.

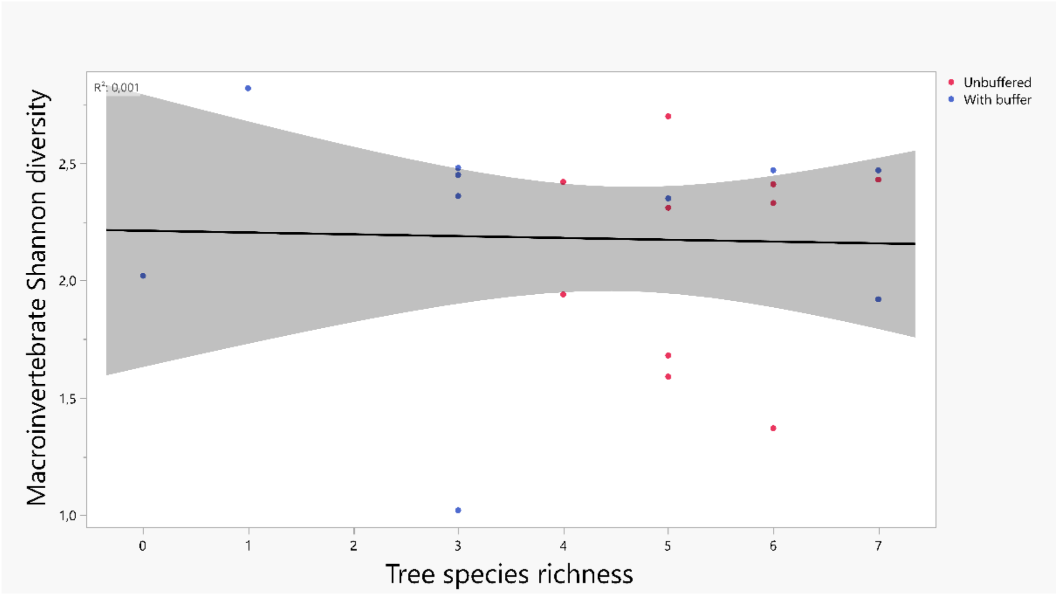

Figure 19. Linear regression modelling the relationship between tree species richness and macroinvertebrate Shannon diversity. R^2 value 0,001. Grey area indicates 95% confidence interval around the regression line.

3.3 Biomonitoring indices

Macroinvertebrate ASPT (Average Score Per Taxon) showed an increasing trend with increasing riparian condition index, although not significant at the 5% level (Table 5). Macroinvertebrate EPT-richness increased with increasing riparian condition index, and buffer width, and slightly with tree cover density, but decreased slightly with tree species richness (Table 5, Figures 21-24). The EPT-richness also showed a positive relationship with buffer presence that was almost, but not fully at the 5% level, with a tendency for higher richness in buffered sections (Table 5 Figure 25).
Diatom IPS was significantly postively correlated with buffer length and buffer presence (Table 5, Figure 26-27). There was also a relationship between diatom IPS and tree species richness but not significant at the 5% level (Table 5, Figure 28).

Table 5. Final linear models for biodiversity variables variables: significance levels (p-values) for buffer properties retained in the models following model reduction. Red and yellow numbers indicating significance. ns = not significant.

Biomonitoring indices			
	Response variable		
Buffer property	Macroinvertebrate ASPT	Macroinvertebrate EPT-richness	Diatom IPS
	p-value	p-value	p-value
Buffer presence		0.0546	0,0463
Buffer length			0,0188
Buffer width		0,0039	
Buffer tree cover density		0,0059	ns
Tree species richness		0.0420	0,0650
Riparian condition index	0,0667	0.0292	ns

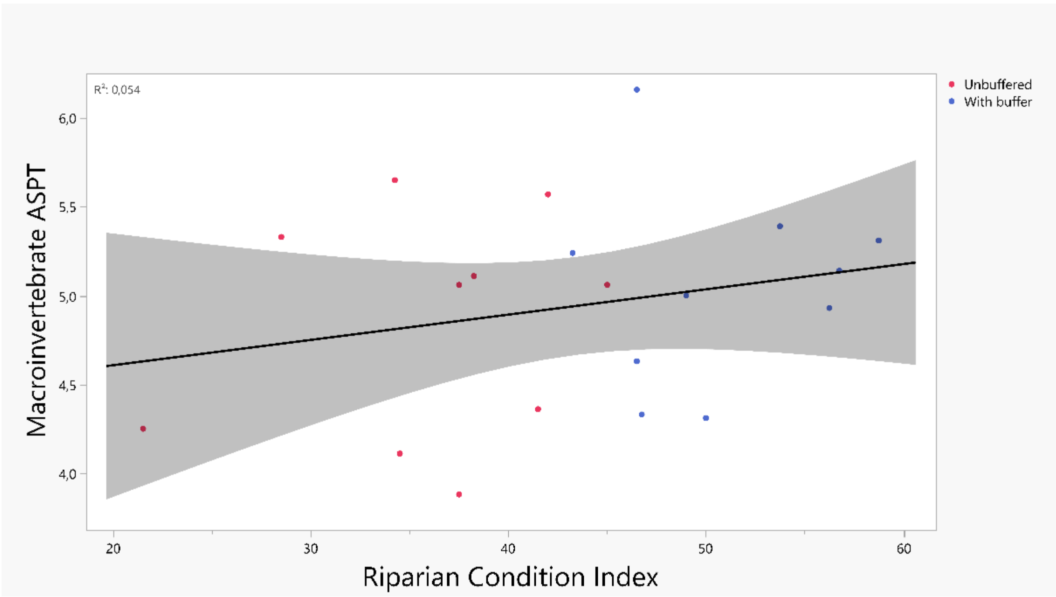

Figure 20. Linear regression modelling the relationship between riparian condition index and diatom IPS. R^2 value 0,054. Grey area indicates 95% confidence interval around the regression line.

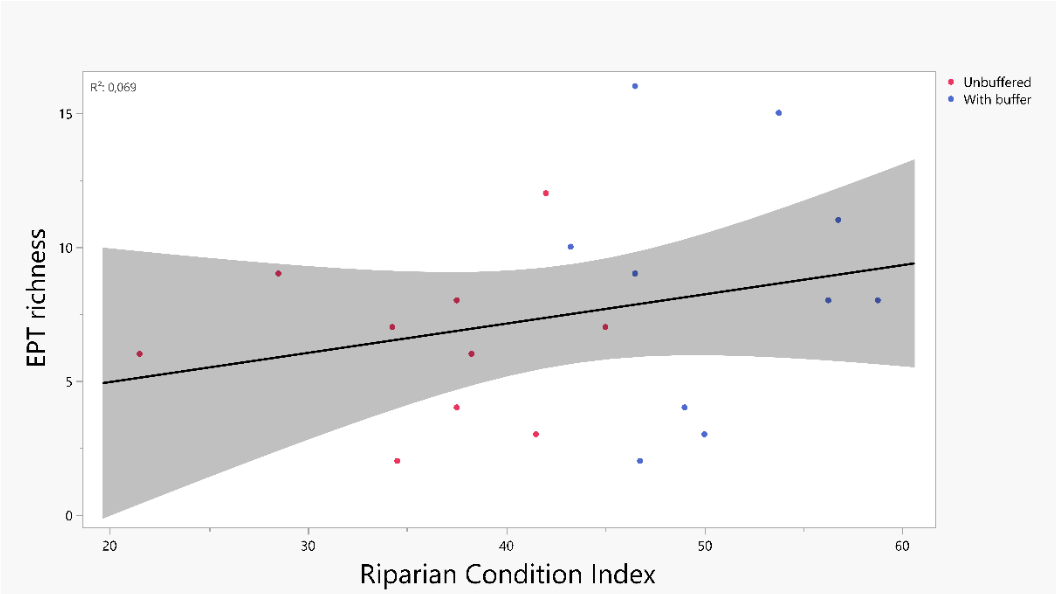

Figure 21. Linear regression modelling the relationship between riparian condition index and EPT-richness. R^2 value 0,069. Grey area indicates 95% confidence interval around the regression line.

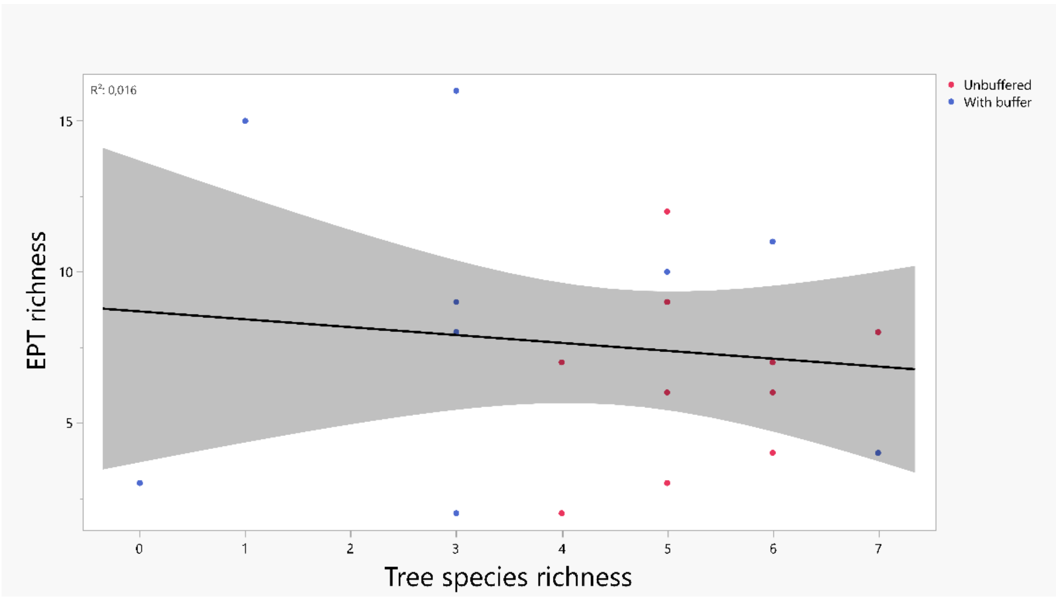

Figure 22. Linear regression modelling the relationship tree species richness and EPT-richness. R^2 value 0,016. Grey area indicates 95% confidence interval around the regression line.

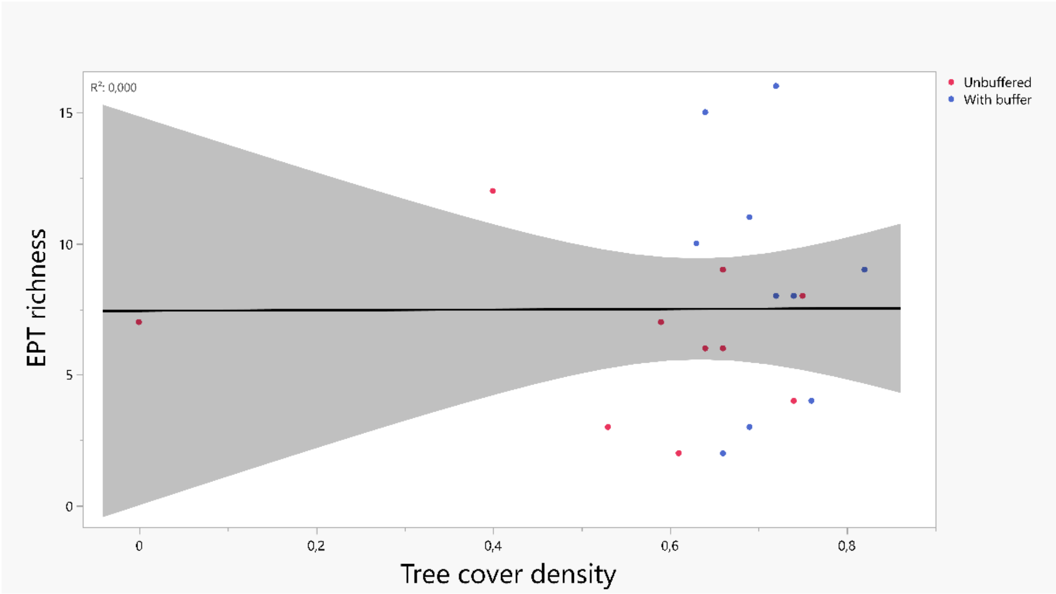

Figure 23. Linear regression modelling the relationship between tree cover density and EPT-richness. R^2 value 0,000. Grey area indicates 95% confidence interval around the regression line.

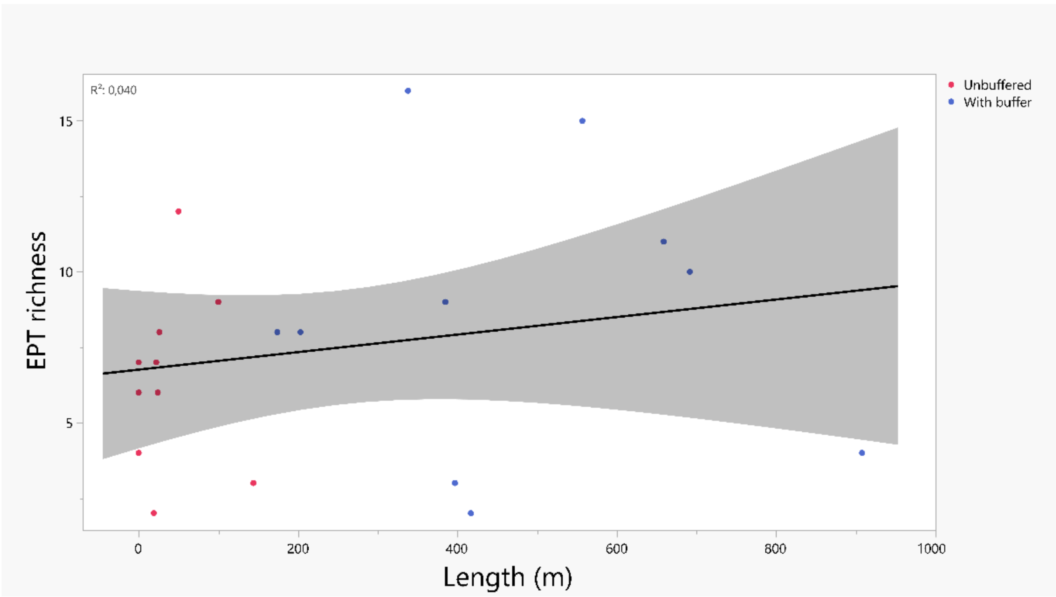

Figure 24. Linear regression modelling the relationship between buffer length and EPT-richness. R^2 value 0,040. Grey area indicates 95% confidence interval around the regression line.

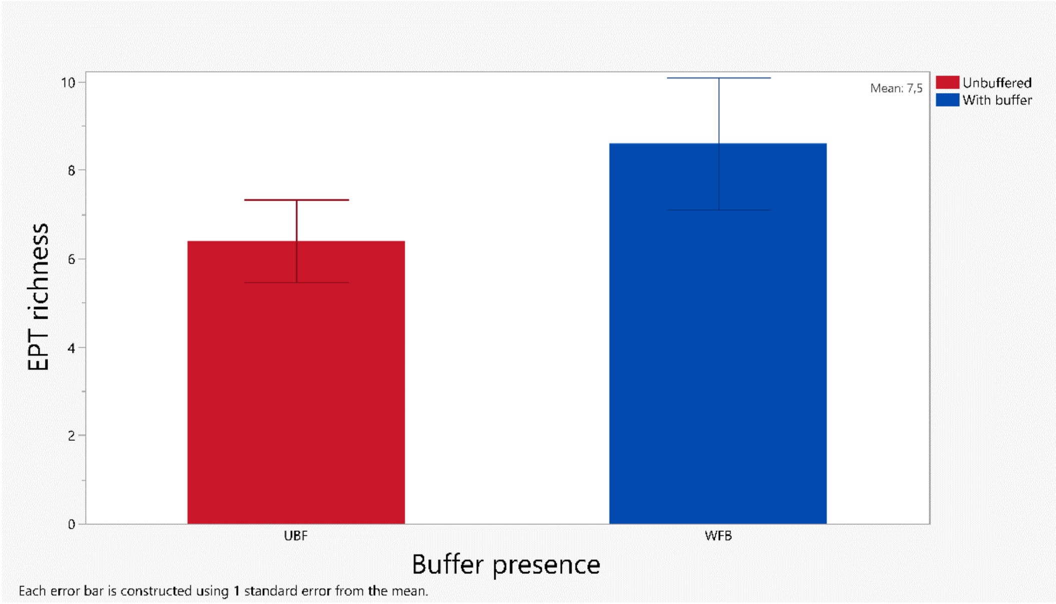

Figure 25. Relationship between buffer presence and mean (±1 SE) EPT-richness.

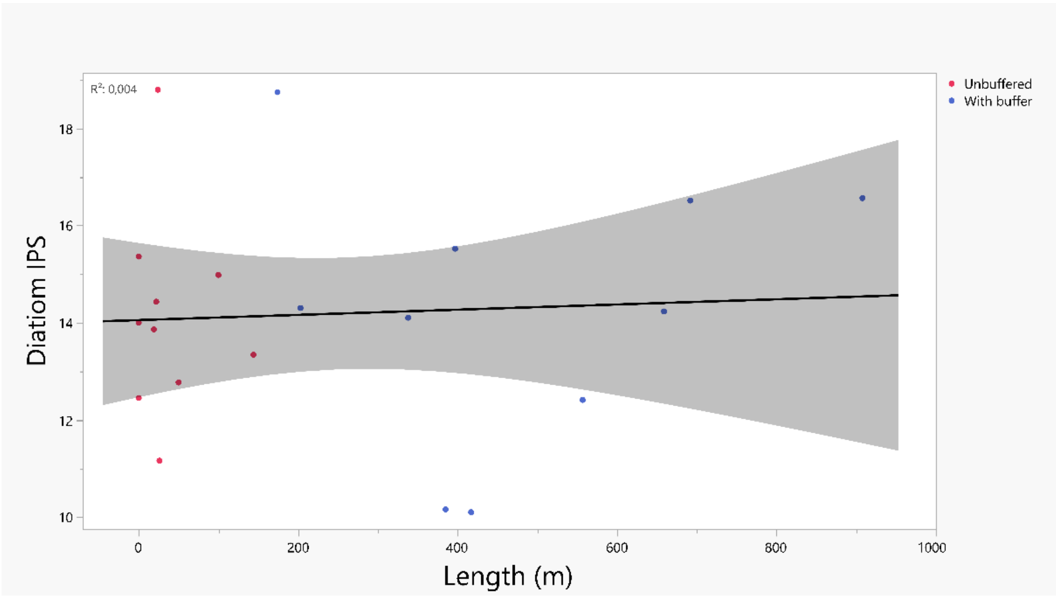

Figure 26. Linear regression modelling the relationship between buffer length and Diatom IPS. R^2 value = 0,004. Grey area indicates 95% confidence interval around the regression line.

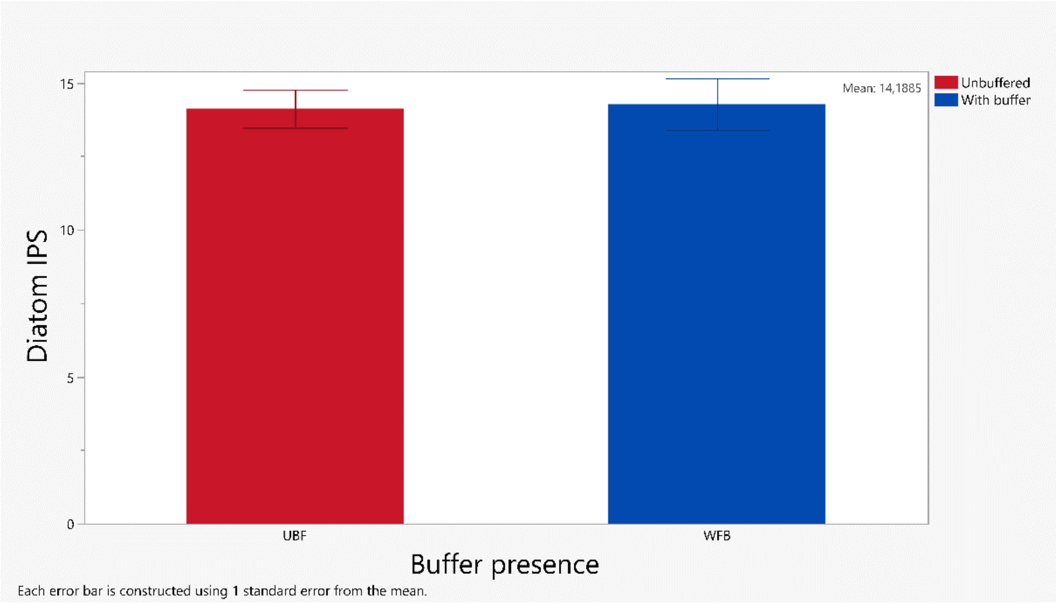

Figure 27. Relationship between buffer presence and mean (±1 SE) diatom IPS.

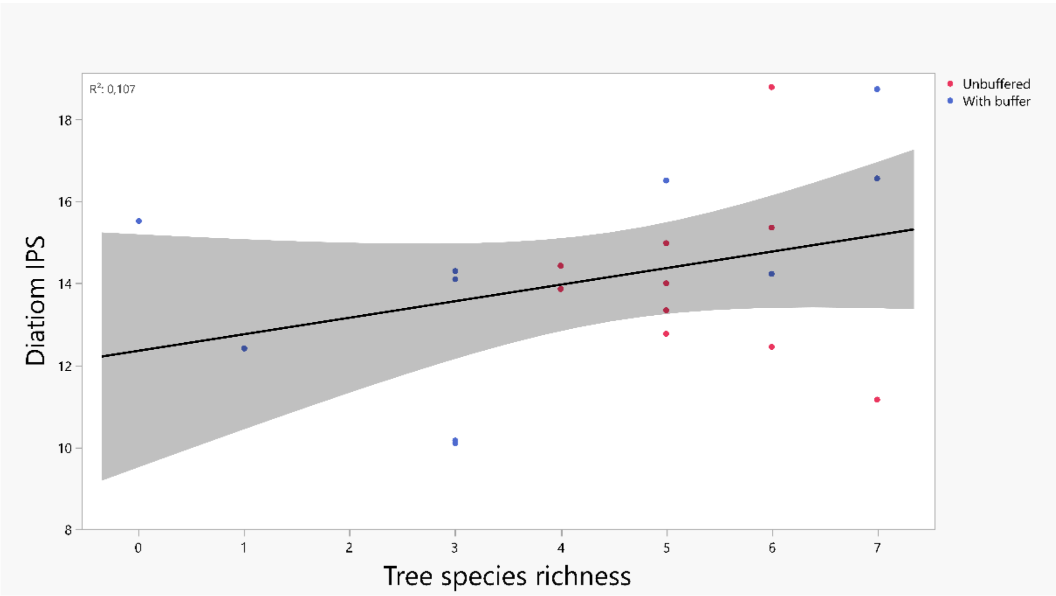

Figure 28. Linear regression modelling the relationship between tree species richness and diatom IPS. R^2 value 0,107. Grey area indicates 95% confidence interval around the regression line.

4. Discussion

My analyses reveal that the simple presence of a forest buffer, regardless of any particular property, reduces sediment and is associated with increased biodiversity of macroinvertebrates, and increased scores for the macroinvertebrate monitoring index EPT and diatom index IPS. Higher scores for these indices imply better conditions for sensitive taxa. However, the answer to this study's main question about which attributes of a riparian buffer contribute most to stream ecosystem health is not necessarily straight-forward.

All of the predictor variables were associated with a significant relationship with at least two ~~(2)~~ response variables (Table 6). Nevertheless, some properties were more likely to be associated with stream ecosystem improvements both in terms of number of responses detected and the strength of the relationships (based on R^2).

Buffer length was significantly correlated with six of the response variables and had a very high effect size on dead wood counts (Table 6). However, buffer width had the highest average R^2 value at 0,227 (Table 6) but only three significant relationships with the response variables. Of the remaining variables, tree species richness was correlated with five of the response variables, and had the strongest correlations with diatom IPS, but a low average R^2 value of 0,027 (Table 6). Riparian condition index correlated with four of the response variables and had the third highest average R^2 value of 0,109, as it had relatively high positive effects on macroinvertebrate Shannon diversity, ASPT and EPT richness, as well as a negative effect on sediment (Table 6).

Tree cover density had only two relationships, which both had weak R^2 values so that the average R^2 value for tree cover density was 0,0005 (Table 6).

Overall, these results indicate that focusing on aspects of buffer size (length and width) when designing forest buffers is most important for maximizing benefits for stream ecosystems.

Table 6. Table breakdown of predictor and response variable 's significant correlations. Positive correlaitons marked with "+", negative marked with "-". Colours indicating effect size = grey <0.01, purple 0.01-0.049, blue 0.05-0.19, orange 0.2-0.349, red >0.35

Predictor variable \ **Response variables**	Soluble Reactive phosphorus (µ/L)	Total inorganic nitrogen (µ/L)	Sediment	Dead wood	Shade	Annual Maximum Temperature (Cº)	Mean daily maximum temperature (Cº)	Mean daily temperature range (Cº)	Macroinvertebrate species richness	Macroinvertebrate Shannon diversity	Diatom species richness	Diatom Shannon diversity	Macroinvertebrate ASPT	Macroinvertebrate EPT richness	Diatom IPS	*Sum of significant correlations*	*Average R^2 value*
Buffer presence			−						+	+				+	+	5	
Buffer length	−			+				+	+					+	+	6	0.12
Buffer width				+	+			−								3	0.227
Tree cover density									+					+		2	0.0005
Tree species richness						−		+		+				−	+	5	0.027
Riparian Conditon Index			−							+			+	+		4	0.109

4.1 Environmental variables

My first hypothesis that buffered stream reaches will generally show lower levels of nutrients, sediment, and temperatre was supported for the most part, except that this study could not show an effect on total inorganic nitrogen (Table 6). My second hypothesis was that buffers that are wider, longer and with higher RCI, tree species richness and tree cover density would lead to greater improvements in the response variables. This hypothesis was only partly supported, as different attributes resulted in different responses. Buffer length was associated with reducing soluble reactive phosphorus, whereas buffer width was associated with greater reductions in sediment and lower mean daily temperature. Effects of tree cover density and RCI on the environmental variables were fewer and generally weak. This indicates that reductions in nutrients can be achieved by the accumulating action of trees along the channel, whereas reductions in erosion of sediment and temperature are more dependent on the width of the forest locally.

Soluble reactive phosphorus decreased with increasing forest buffer length (Table 6, Figure 3), with an effect size of 0,040, indicating that 4% of the variation in soluble reactive concentrations can be attributed to the length of the buffer. Although large fractions of nutrients enter agricultural streams via underground tile drains (Gökkaya et al. 2017), the drains often leak and it is therefore still possible for the root systems to absorb some nutrients. Previously, Lind et al. (2019) and Burdon et al. (2020) have shown that vegetation type and density and a buffer width of at least 11-15 m is important in buffering against nutrients such as soluble reactive phosphorus. Why length but not width was correlated with phosphate concentrations in my analyses might be because it is also important to have a continuous buffer zone bordering the stream. Most of the study's unbuffered and buffered reaches had buffer widths of at least 11 m (mean ± SD 85 ± 42m). Rather my analyses point to the importance of a continuous, elongated buffer throughout the stream, to underpin a cumulative uptake.

None of the predictor variables showed any effect on total inorganic nitrogen. This might be because of underground tile drains that drain water directly to streams (Gökkaya et al. 2017), however, as discussed buffer length was correlated with lower phosphate concentrations, and buffer presence lowered sediment deposition (Table 6). An explanation for why there was no effect on nitrogen could be that the trees are more phosphorus than nitrogen limited (Gonzales et al. 2023). However, my result for nitrogren is also consistent with previous studies where buffered and unbuffered stream sites did not affect total inorganic nitrogen (van Pul 2018; Burdon et al. 2013).

Sediment was lowered by buffer presence and riparian condition index (RCI) (Table 6, Figures 7-8). As previously mentioned, Lind et al. (2019) established that a vegetated buffer of 3-10 m can provide basic filtration of sediments and organic material. In particular, forest buffers can help reduce erosion by binding soils, and thereby reduce sediments. Notably, of the attributes assessed in the RCI, bank stability is a variable that closely affects sediment. Riparian vegetation, in turn, has a strong influence on bank stability, since vegetation and trees make the soil harder and more resilient to erosion and weathering (Harding et al. 2009). Therefore, it is reasonable that both buffer presence and RCI had a decreasing effect on sediment.

The amount of dead wood was positively correlated with both buffer width and length (Table 6, Figures 5-6) and also had the highest effect sizes of 31% for width and 68,8% for length. Length has not previously been this strongly connected to dead wood counts, but a wider buffer has been connected to more instream dead wood (Lind et al. 2019). Riparian vegetation has also been connected to increasing dead wood (Sargac et al. 2021; Bjelke et al. 2016), which makes sense since dead wood is released by old trees and tree parts. It might be somewhat surprising that especially length had such a strong positive effect on dead wood. If dead wood falls and then accumulates downstream by forming debris dams, a longer buffer would increase the amount of dead food falling upstreams to accumulate at the sampling point. I would also argue that it is the amount of old trees that should increase dead wood counts. It would be interesting to examine the age of trees to evaluate if tree age has an effect on dead wood.

Annual maximum temperature was slightly negatively correlated with increasing tree species richness, and the effect size was 0,9% (Table 6, Figure 10), and mean daily temperature range was affected by length, width and tree species richness, where width had the highest effect size of 14% (Table 6, Figures 11-13). A wider buffer decreased the mean daily temperature range reasonably because a wider buffer will give a more solid shade to the stream throughout the day, with fewer gaps for the sun to reach through. This is reflected in the strong effect of increasing width on shade (Table 6) with an effect size of 22,5% (Figure 9), which is likely the main driver of reduced thermal variation. Annual maximum temperature was slightly lower with increasing tree species richness, and the effect size was 0,9% (Table 6, Figure 10). With greater tree richness, there is an increasing likelihood of trees with larger leaves capable of blocking more sunlight. Length and tree species richness had very low effect sizes on mean daily temperature range – 0,1% and 0,2% respectively. Unexpectedly, length was positively correlated mean daily temperature range; this relationship could however be due to one or a few outliers that drove the effect size lower than expected. Mean daily maximum temperature was not shown to be affected by any of the predictor variables (Table 3)

4.2 Biodiversity variables

Effect sizes of the biodiversity and biomonitoring variables were generally lower compared to the environmental variables. These variables are more challenging to explain because organisms are very variable in their ecological requirements and in their mobility. Nevertheless, some effect sizes were larger than 5% which is considered significant for biodiversity data.

As anticipated macroinvertebrate species richness increased with buffer presence, length and tree cover density (Table 6, Figures 14-16). However, the effect sizes were low with length showing an R^2 value of 0,016 and tree cover density showing an R^2 value of 0,001. Previous studies have established that it is the forested aspect of a riparian buffer that increases habitat quality for macroinvertebrates (Sargac et al. 2021; Bjelke et al. 2016), as well as a wider buffer of 25 metres (Lind et al. 2019). Macroinvertebrate Shannon diversity was increased by buffer presence, tree species richness and RCI (Table 6, Figures 17-19). With an R^2 value of 0,054 for RCI, this effect size of 5,4% is more noteworthy. Vegetation composition of buffer is an attribute assessed in the RCI which measures gaps in vegetation in a buffer and/or adjacent land (Burdon et al. 2020). Since the forested aspect of a buffer have previously been linked to increasing the habitat quality for macroinvertebrates, (Sargac et al. 2021; Bjelke et al. 2016), it makes sense that a higher RCI score could be connected to macroinvertebrate Shannon diversity.

Diatom species richness and Shannon diversity was not related significantly to any of the predictor variables (Table 4 and 6).

4.3 Biomonitoring indices

Macroinvertebrate ASPT was positive correlated with RCI (Table 6, Figure 20), but with a moderate effect size of 0,054. Since a higher ASPT score indicates the presence of more sensitive species, this result implies that a higher RCI is desirable for sensitive species. Also, the same explanation could be given to macroinvertebrate ASPT score as for macroinvertebrate Shannon diversity discussed above, namely that the RCI measures vegetation composition, where a higher RCI indicates a higher habitat quality for macroinvertebrates.

EPT richness was affected by five predictor variables: Tree species richness, tree cover density, length and buffer presence (Table 6, Figures 22-25), where tree species richness was the only variable negatively correlated with EPT richness (Figure 22). This unexpected relationship seems to be driven by two outliers where EPT richness was high at low levels of tree species richness, making the relationship is unreliable. However, overall most relationships had low R^2 values with RCI and length having the highest at 0,069 and 0,040, respectively (Figures 21 and 24).

Diatom IPS was positively correlated with buffer presence, as well as with increasing length and tree species richness (Table 6, Figures 26-28). The strongest relationships are between diatom IPS and length and buffer presence (Figure 26 and 27). The effect size of tree species richness on diatom IPS is however relatively high at 10,7% (Figure 28). I will argue that a diversity of trees means a diversity of habitat types, i.e. light habitat variation with some lighter and some darker spots (Mutinova et al 2020). Thus, it is reasonable that the IPS would increase with increased tree species richness.

4.4 Conclusions and future research

Based on my results, buffer restoration should focus on buffer size as the primary variable to manipulate. Not only because width and length were most consistently associated with ecological improvement, but also because it is easier to give landowners and managers concrete guidance on length and width. By contrast, giving advice based on results from the multimetric riparian condition index is more difficult since RCI is based on average scores from 13 different variables. Simply put it can be difficult to decide on which attribute to focus on in an intervention. Accordingly, further study should be on understanding the relationships between macroinvertebrate Shannon diversity, ASPT and EPT richness and RCI scores to pinpoint the important environmental drivers. Likely it is not a single but a combination of variables that explain the relationships between biological responses and high RCI values. A wide and long buffer but with only understory vegetation would not provide much shade, dead wood and uptake of nutrients. In other words, the positive effects are probably cumulated through the addition and emersion of positive elements and also with time.

To further understand the forested aspect's contribution to the positive results that were seen in this study, I suggest incorporating a measure of the tree's age (e.g. based on tree rings) as a predictor variable since the positive effects of a riparian buffer reasonably accumulate over time. There could be a link between the age of trees/forested zone and favourable levels of dead wood counts and various biodiversity variables.

If I were to advise a land owner or an environmental manager on which elements to focus on when designing a riparian buffer zone, it would be buffer width, length and to let the forest age in the riparian buffer zone.

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Thank you!

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