The Effects of Creek Morphology on Saltmarsh Fish Communities in the Dutch Wadden Sea

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Msc project 1

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6-2-2022

Abstract

Saltmarshes are important intertidal ecosystems, serving as nursery habitats and shelter/feeding grounds for many fish species. After a historic decline due to overexploitation and land reclamation, the Dutch saltmarshes are now slowly being restored through intense management. However, it is not clear how the restoration management of the marches affect the fish community. In this master thesis, I modelled the effect of salt march properties on fish biodiversity. Previous research has shown that the morphological characteristics of saltmarsh creeks affect the abundance and diversity of fish communities within them. I therefore studied the relationship between the fish community and creek characteristics such as length, slope and depth. I did this on a naturally developing march on the island of Schiermonnikoog and a restored and modified march along the coast of Groningen. To accomplish this, fishing assays were done using fyke nets, starting in March 2021 and ending in June 2021. A clear effect of creek morphology on fish communities was demonstrated. Among other findings low bank steepness had a positive effect on fish abundance and diversity. The findings of this research are valuable for the management of the Dutch saltmarshes, as maintaining the right morphological characteristics can lead to a higher abundance and diversity of fish species in the intertidal creeks.

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Introduction

Background on saltmarshes

Salt marshes are an important intertidal environment, known to serve as nursery habitat for fish and other nekton (Friese, Temming & Dänhardt, 2021). They also provide a nesting and foraging habitat for many birds which use the area for breeding or passage (Dierschke & Bairlein, 2004). As water flows into the saltmarshes, the shallower waters and vegetation help break wave action, making saltmarshes effective barriers against storms and tides (Baaij et al., 2021). Fish benefit from saltmarshes in a variety of ways. First of all, salt-march creeks, tributaries, and vegetation provide shelter for fish. For small fish the plants surrounding the saltmarsh creeks and gullies provide shelter from predators. Larger predators are also unable to enter the saltmarsh environment due to its often shallow and temporary creeks (Friese, Temming & Dänhardt, 2018). Saltmarshes also provide fish with a variety of food sources, as invertebrates and other sources of nutrients end up in the creeks. During high tide, where the water level often rises into the actual marsh, fish may also use the area as foraging grounds (Minello, Rozas & Baker, 2011). Saltmarshes can be found all along the coast and barrier islands of the Netherlands, Germany and Denmark, as part of the UNESCO world heritage site of the Wadden Sea (Elschot et al., 2020). The Dutch saltmarshes and the Wadden sea area as a whole have experienced a long history of decline due to human activities. Starting in the 1600s, land reclamation, dredging and eutrophication have all contributed to a harsh decline in the quality and quantity of Dutch saltmarshes, with a minimum areal distribution somewhere in the middle of the twentieth century (de Jonge, Essink, Bondinke, 1993). Before the twentieth century the exploitation of plants and animals in the Wadden Sea was entirely unregulated, and as a result several bird, fish, mammal, and invertebrate species have gone extinct (Wolff, 2005; Lotze, 2005). In recent years, as part of the Natura 2000 initiative, the European Water Framework Directive and the Trilateral Wadden Sea Plan, the Dutch salt marshes have begun to regrow. Through erosion and height monitoring, active management of grazing, and the creation and upkeep of small wooden dams (rijzendammen) the current size of the Dutch saltmarshes is back up to 9000 hectares (Elschot et al., 2020).

Swimway project and analysis of Wadden Sea communities

Despite the efforts to protect and restore the saltmarshes and Wadden Sea area as a whole, the area is in need of additional management and research regarding the future function of the marches for fish. There are indications that the quality of salt-march habitat is threatened. Sea level rise is one obvious factor that threatens the function of saltmarshes. Under purely natural circumstances, the rising water level would lead to the marshes moving further inland, but the presence of human-built structures like dikes and roads often makes this impossible, causing the saltmarshes to shrink as the sea level rises(Baaij et al. 2021). Another clear indicator for the diminishing health of the Wadden Sea is the large decline in fish stocks in the area. Initiatives like the Wadden Tools Swimway project, attempt to address the issues affecting the Wadden Sea through research and evaluation of management strategies ("SWIMWAY- NIOZ", 2020).

Management and creek morphology

Like most ecosystems in the Netherlands, the saltmarshes are heavily managed for a multitude of purposes and in a multitude of ways. Management is necessary to allow the marshes to flourish and regrow according to the guidelines set by the Trilateral Wadden Sea Plan. Grazing regimes allow succession to stagnate, maintaining the saltmarsh environment. While sand and clay replenishment and construction of dams, allow the saltmarsh to resist the forces of erosion and sea level rise (Elschot et al., 2020; de Groot, van Wesenbeeck & van Loon-Steensma, 2013). The creeks and channels that run through the saltmarshes also undergo monitoring and management and are often dredged or filled to maintain their depth. This is done to ensure that succession does not proceed too fast, and that appropriate drainage can take place to allow vegetation to take hold in the soil (de Groot, van Wesenbeeck & van Loon-Steensma, 2013). Although such interventions are necessary to maintain the marsh, they do alter the morphology of the creeks, and thereby are likely to affect the organisms within them.

The effects of morphology

Previous research on intertidal habitats has shown that width and depth of creeks are great predictors of nekton communities within. Christian and Allen for instance, demonstrated this through a comparison of biomass between several creeks, where shallower broader creeks contained more biomass than narrower deeper creeks (Christian & Allen, 2013). This was in line with earlier research by Allen et al., as well as research by Jinn et al., which also showed shallower creeks to contain a greater abundance of fish (Allen et al., 2007; Jin et al., 2014). The proposed mechanism for fish preferring shallower creeks lies with the availability of food as well as shelter. Shallower waters are less accessible for larger predators and may also have lower competition (Kneib, 1997). The slope of the creekbank is also believed to be an important geomorphological characteristic, as it is through the banks that fish are able to enter the marsh during high tide. McIvor and Odum established in 1988 that fish seem to prefer gentler sloping depositional banks over steeper erosional banks as a means to access the marsh surface (McIvor & Odum, 1988). Findings from both Jin et al. as well as Williams and Zedler indicate that the abundance of fish in different creek morphologies may vary on a species-to-species basis. Bottom-dwelling fish like gobies for instance are shown to be more abundant in creeks with gentler slopes (Jin et al., 2014; Williams & Zedler, 1999). As the length of creeks corresponds directly to the amount of available marsh edge, length is also believed to be an important variable for fish abundance, where creeks with greater lengths provide a larger marsh edge for fish to exploit (Minello & Rozas, 2002). If dredging management could have an impact on the fish species within saltmarsh creeks, evaluating what morphological variables are most accommodating to the fish, could help ensure that the saltmarshes remain an area where fish can shelter and feed. Management should seek to mimic the natural characteristics that support the highest diversity and biomass of nekton in order to maximize the ecosystem services that the saltmarsh creeks can provide.

Research question/purpose

Past research has illustrated a link between certain morphological variables and measures of fish diversity in a variety of salt marshes around the world. In this report, the goal was to find out the link between creek morphology and abundance/diversity of fish communities in the saltmarshes of the Dutch Wadden Sea.

Hypothesis

We hypothesize that shallower creeks that exhibit gentler slopes, wider widths, and greater lengths, will show a greater abundance and diversity of fish.

Materials and Methods

Sampling sites

The field sites for this study were a number of spots in the north of the Netherlands in an area known as Groninger wad (Gwad) as well as on the island of Schiermonnikoog (Schier) (fig. 1, 2).

Figure 1. Our sampling sites along the coast of Groningen (Gwad)(Google Earth, 2018a).

Figure 2. Our sampling sites on Schiermonnikoog (Schier)(Google Earth, 2018b).

We investigated seven creeks on Schiermonnikoog in the saltmarshes of the southern coast. In Groninger wad, we investigated nine different creeks. We fished these creeks over a period of four months, from March 2021 until June 2021. At the start of this study, we had two fishing sites at each of our creeks (with exception of creeks 5-7 on Schiermonnikoog), one near the mouth of the creek in low marsh condition, and one further inland, in high marsh conditions. For creeks 1 to 4 on Schiermonnikoog we kept the two sites per creek all throughout the study. In Groninger wad, we decided to switch to one net per creek, as fishing both upstream and downstream in the same creeks lead to problems estimating our catches. For instance, if we had caught and counted fish upstream, a number of those might get caught in our downstream net once we released them, potentially causing us to count the same fish multiple times. This was not a problem on Schiermonnikoog, as there we did not fish the two sites at the same time.

Fishing protocol

The sites were marked using GPS and the majority on Gwad had permanent poles placed to attach the nets to. The nets we used were fyke nets with a mesh size of 6mm. We placed these nets in either the morning or afternoon low tide, returning roughly twelve hours later (in the next morning or afternoon low tide) to unset the net and count our catches. The unsetting was done by opening the cod end of the nets, allowing us to maintain the positions of our nets. After counting and releasing our catches, we reset our nets, and returned twelve hours later for the final counting and unsetting. The total fishing period was thus approximately 24 hours. We counted and measured all fish in the field, and then released them back in the water alive. We measured and identified all fish as well as counting all the non-fish species (such as shrimp and other invertebrates).

Creek morphology

The variables used to describe the morphology of our creeks are as follows; creek width, mean steepness, max depth, total creek length, main creek length, combined tributary length and tributary dominance. These morphological variables have been shown in literature to influence total fish abundance, as well as diversity and abundance of individual species. (Jin et al., 2014; Williams & Zedler, 1999). The on-site creek morphological variables were measured after our fishing assays, in June of 2021. Creek width was measured in the field using the Leica Disto X3 laser on the smart horizontal distance function at the sites where the fykes were set. Where creek width was not possible to determine using the laser, we analyzed google earth images for the width instead. The laser was also used to create a profile of the creek at our fishing sites. Where the laser had trouble penetrating the water, we took a laser measurement on a board at the water surface and then measured the actual depth of the water by hand (See figure 3). The profiles we created were then used to calculate mean steepness. Steepness was calculated from the horizontal distance between the lowest vegetation point (here our first measuring point) to the deepest point of the creek, divided by the elevation change. Mean steepness is then the mean of both creek sides for each measuring point, where a greater value means gentler slopes as outlined in Williams & Zedler, 1999. The deepest point found in the steepness measurement was also what we used as our measure for maximum depth. The various creek lengths were estimated using Google earth, where the main creek length was the distance from the end of the marsh to the end of the longest tributary. Combined tributary length is the sum of the length of all other tributaries of the creek. Tributary dominance was calculated by dividing the combined tributary length by the main creek length (Jin et al, 2014).

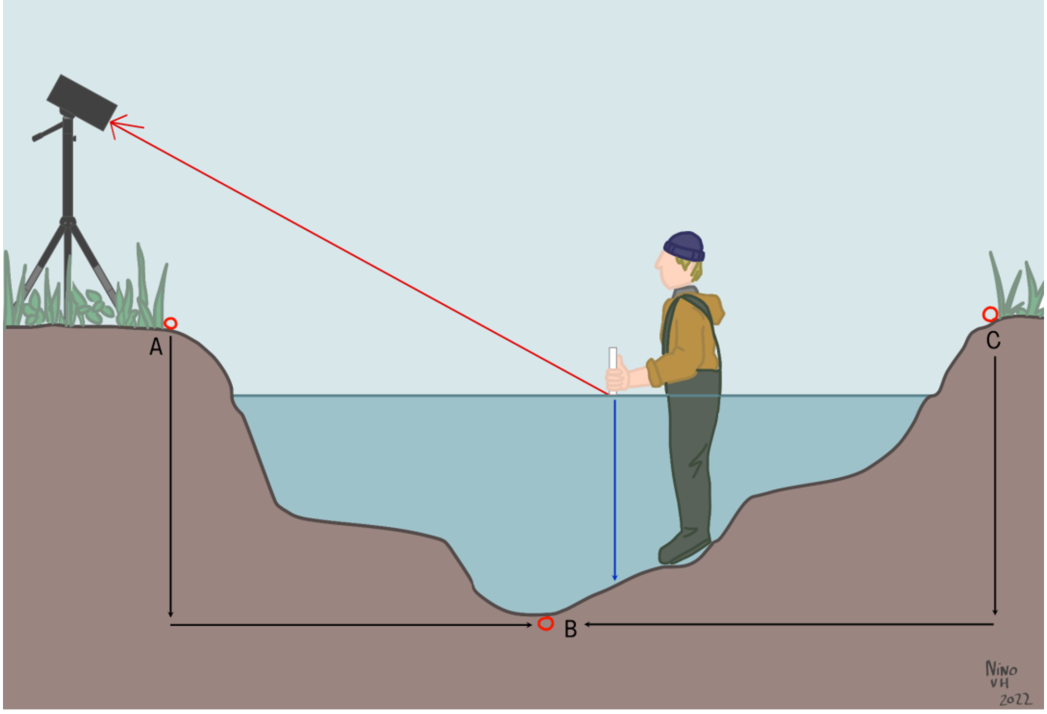

Figure 3. An illustration of how the creek morphology measurements were taken. The laser shines down onto the creek bed, taking measurements if possible. Shown in the figure is how we would measure the depth where the water was too deep for the laser to take an accurate measurement. The blue arrow indicates the distance measured by hand which is then added to the laser measurement. Point A and C indicate our first and last measuring point at the edge of the vegetation. Point C is the deepest point measured. By dividing the horizontal distance between A and B by the vertical distance between these points we get the bank steepness variable. After doing the same for point B and C we can average these values for the mean steepness of the cross section.

Data analysis

Data analysis was done in R version 4.1.1, with use of the 'Vegan', 'BiodiversityR', 'dplyr', 'ggpubr', 'devtools', 'MuMIn', 'lme4', 'PerformanceAnalytics', 'car', 'ggplot2' and 'ggbiplot' packages (Barton, 2020; Bates et al., 2015; Fox & Weisberg, 2019; Kassambra, 2020; Kindt & Coe, 2005; Oksanen et al., 2020; Peterson & Carl, 2020; R core team, 2021; Vu, 2011; Wickham, 2016; Wickham et al., 2021a, 2021b). Following the study by Jin and colleagues, the creek-morphological variables were analyzed for correlation both using spearman correlation (fig. 4) and a principal component analysis (PCA) (fig. 5) (Jin, 2014). The PCA revealed that the length measurements were significantly positively correlated. As such, total creek length was not included in the final models as it was most correlated with the other variables. All creek morphology variables were tested for normality through histograms in the correlation matrix (fig. 6) and using the Shapiro Wilk test. As none of the variables were normally distributed (they did not meet the requirement of $p > 0.05$), a number of transformations were applied. Although many transformations were attempted (sqrt, x^2, 1/x, log10, log1p, sqrt +0.5) the only variable that ever returned as normal was the mean steepness variable, which showed a significant P-value on the Shapiro Wilk test after a log1p transformation ($p = 0.096976$) as well as after a log transformation ($p= 0.061087$). Visual inspection showed that a log transformation created the nearest to normal distribution for all variables with exception of the mean steepness variable (fig 7). Homogeneity of variance of the creek morphological variables was assessed with a visual inspection and appeared to be relatively homogenous (see fig. 7). As a measure of the fish communities, the abundance, species richness, Shannon-Weaver diversity index, and inverse Simpson index were calculated. Preliminary models showed a higher significance when month was accounted for and was therefore included as a potential interaction variable in the final models. Using Cook's distance, outliers were removed for the data of each specific model. Using the dredge function form the MuMIn package, the best additive linear model was selected from all creek morphological variables for each of the diversity measures (abundance, richness, Shannon-Weaver index, inverse Simpson), as well as for each of the abundances of our four most common fish species (herring, common goby, flatfish, smelt). As the dredge function merely ranks models on the basis of their AICc score, the top five models for each response variable were run to see if any additional significant predictor variables appeared. If month appeared to be a significant variable in a model with at least one other significant variable, the model was run again, but with month as an interaction variable. The significant predictor variables for each response variable were plotted, as well as any significant interactions with month.

Correlation coefficient, rho P-value	Creek width		Total creek length		Main creek length		Combined tributary length		Tributary dominance		Mean steepness		Max depth	
Creek width	-	-	0.58	1.074e-07	0.60	3.197e-08	0.51	6.673e-06	0.20	9.586e-02	0.46	5.018e-05	0.47	3.691e-05
Total creek length	0.58	1.074e-07	-	-	0.93	2.200e-16	0.95	2.200e-16	0.63	5.119e-09	0.24	0.047	0.48	1.894e-05
Main creek length	0.60	3.197e-08	0.93	2.200e-16	-	-	0.81	2.200e-16	0.39	8.243e-04	-8.92e-04	0.994	0.67	1.98e-10
Combined tributary length	0.51	6.673e-06	0.95	2.200e-16	0.81	2.200e-16	-	-	0.81	2.2e-16	0.36	2.146e-03	0.32	7.059e-03
Tributary dominance	0.20	0.096	0.63	5.119e-09	0.39	8.243e-04	0.81	2.200e-16	-	-	0.48	2.448e-05	-0.03	0.804
Mean steepness	0.46	5.018e-05	0.24	0.047	-8.92e-04	0.994	0.36	2.146e-03	0.48	2.448e-05	-	-	-0.48	2.165e-05
Max depth	0.47	3.691e-05	0.48	1.894e-05	0.67	1.980e-10	0.32	7.059e-03	-0.03	0.804	-0.48	2.165e-05	-	-

Figure 4. Spearman’s ranked correlation between each creek morphology variable.

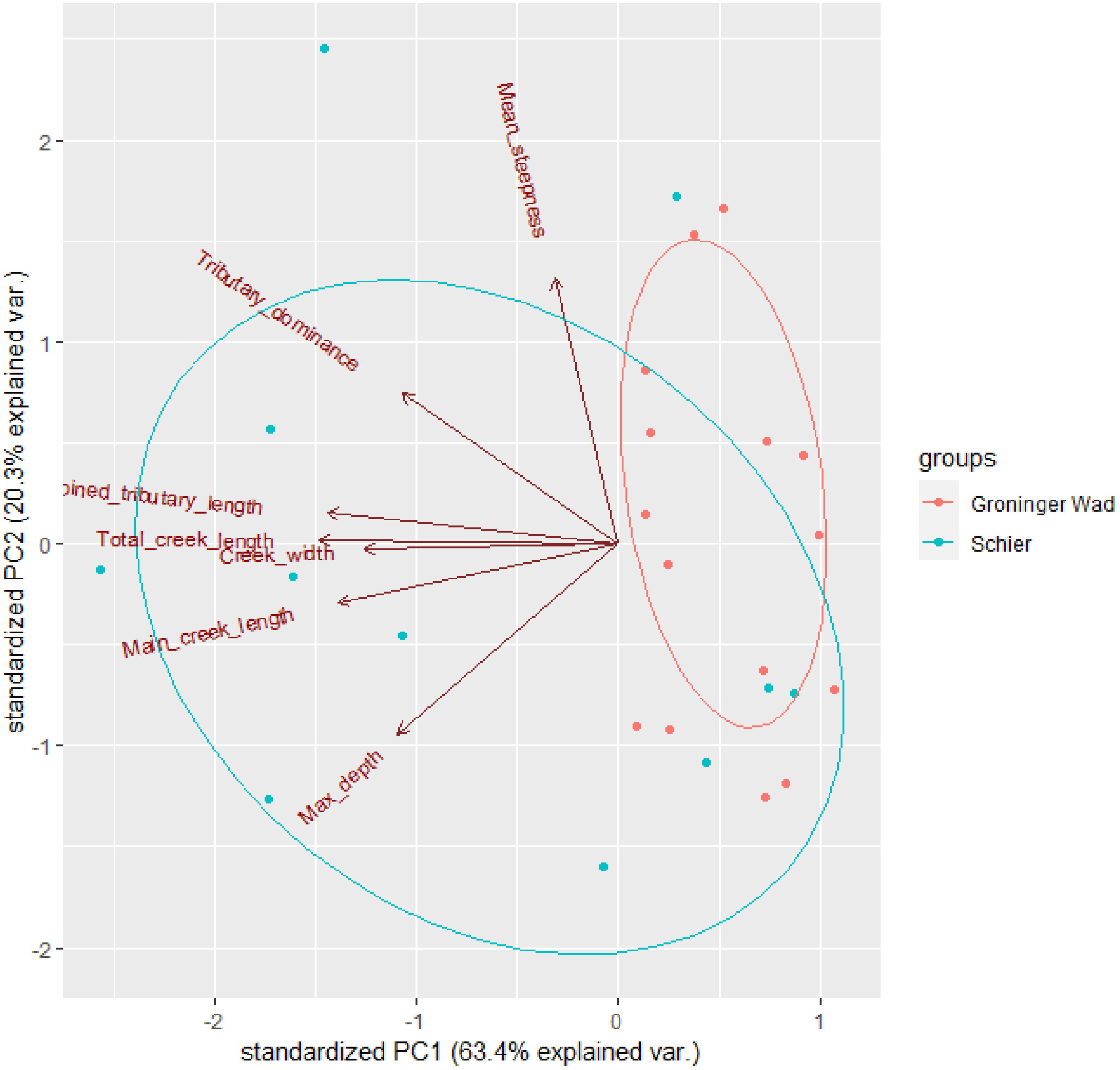

Figure 5. A PCA of the creek morphological variables, with the colored ellipses indicating the effect of the different sites. Here a smaller angle between two variables indicates a greater correlation.

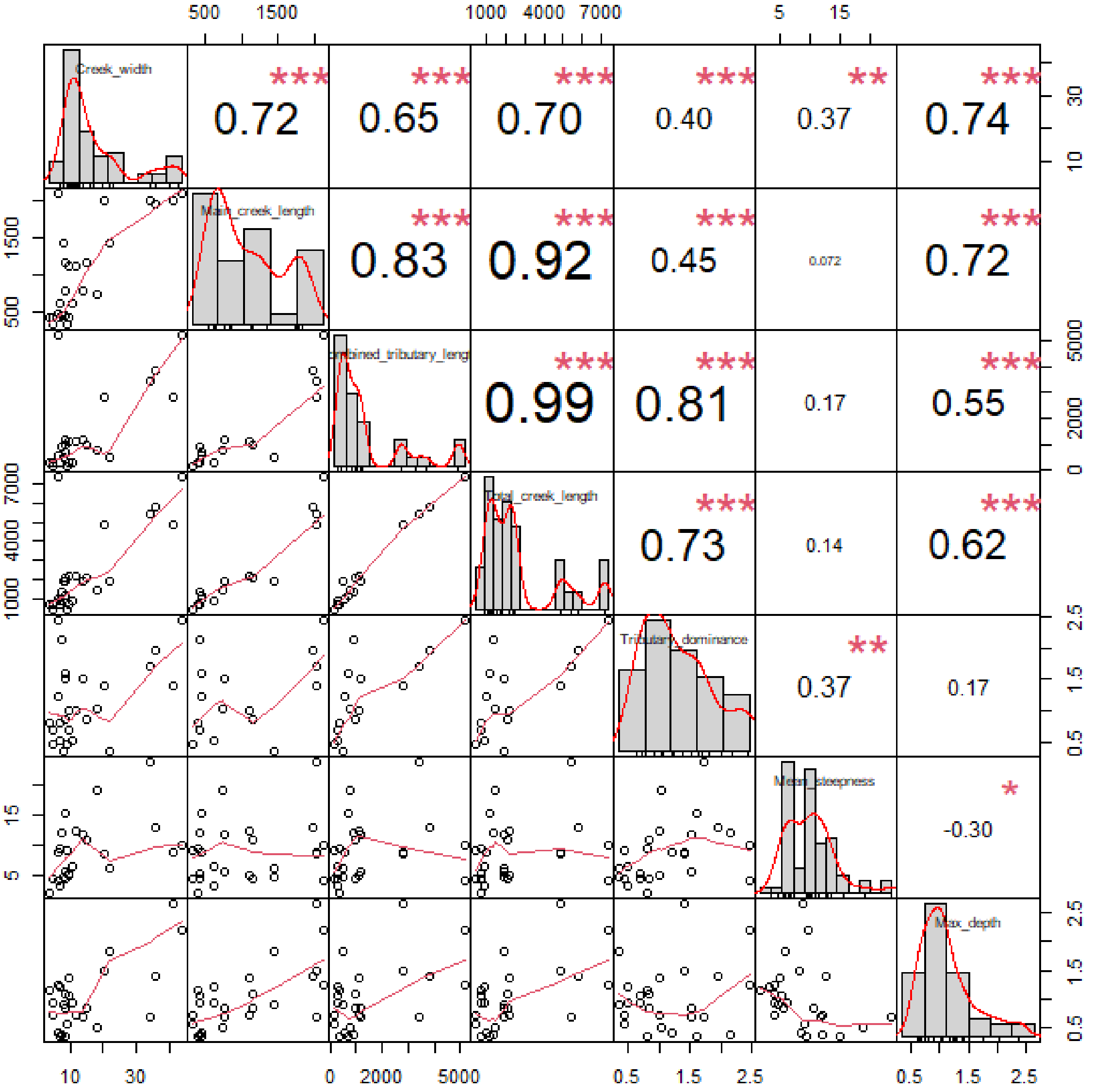

Figure 6. The correlation matrix of the creek morphological values with histograms for normality.

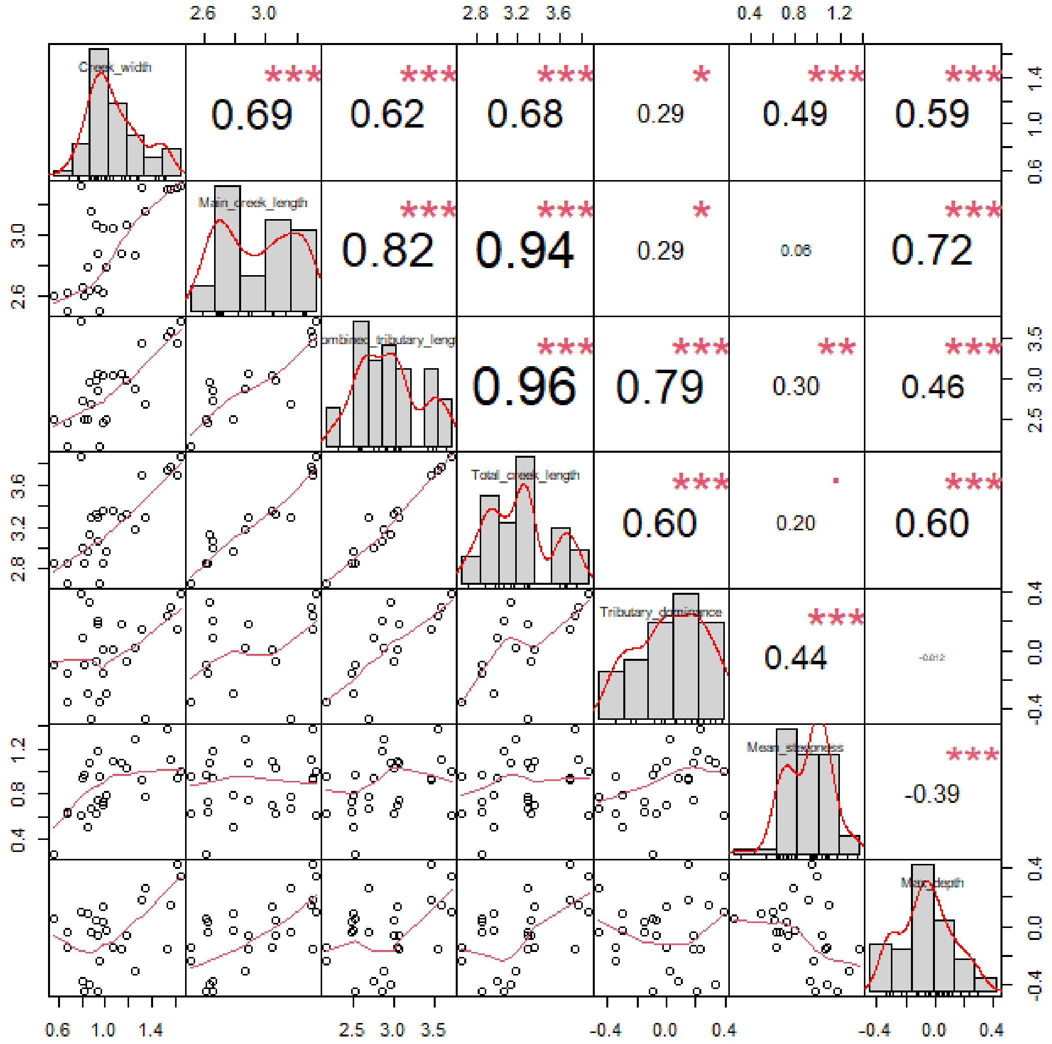

Figure 7. The correlation matrix of the log transformed creek morphology variables with histograms for normality (which also display the homogeneity of the data below them).

Results

The most common species of fish encountered in our fishing assays were the common goby (*Pomatoschistus microps*) and herring juveniles and larvae (Clupea)(Fig. 8). Other frequent species were European smelt (*Osmerus eperlanus*), three-spined stickleback (*Gasterosteus aculeatus*) and various juvenile flatfish. Only part way through the project were we able to identify the different species of flatfish as either European flounder (*Platichthys flesus*), European plaice (*Pleuronectes platessa*), common sole (*Solea solea*) or turbot (*Scophthalmus maximus*). As such, the designation ‘flatfish’ or ‘juvenile flatfish’ is used. For the regression analysis, all flatfish were analyzed together as a single group.

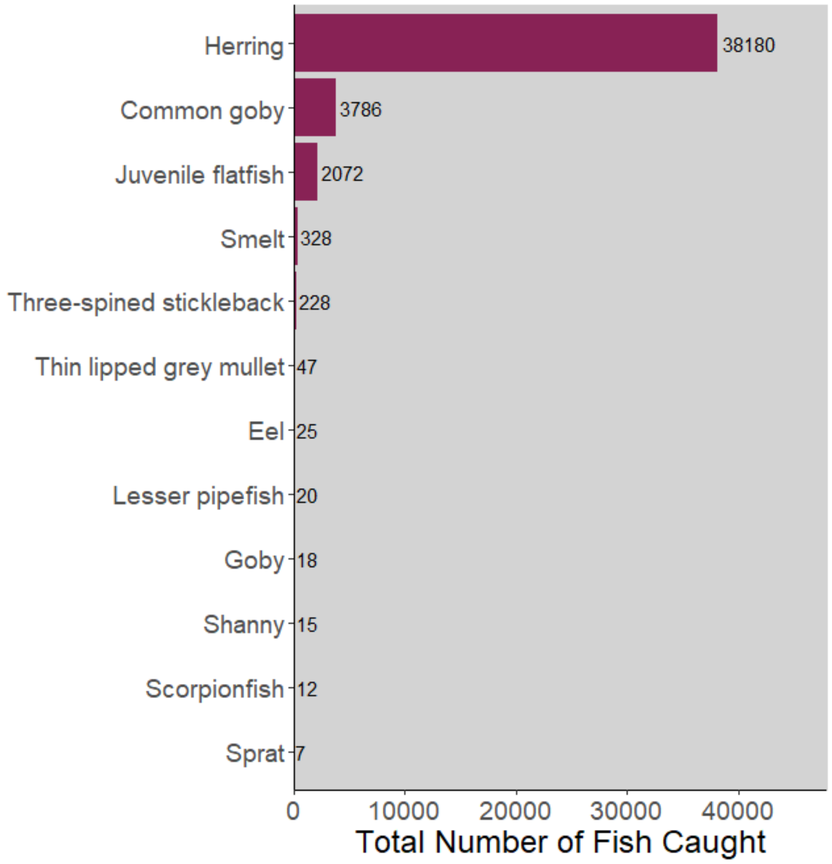

Figure 8. A bar graph displaying our total number of catches, with the species sorted by order of greatest to lowest abundance.

Abundance

The total abundance of fish was best explained by the length and steepness of the creeks bank (Fig. 9). The selected model included the two variables combined tributary length and mean steepness (lowest AICc: abundance ~ Combined_tributary_length + Mean_steepness; $F_{2,66}$ = 7.1, p=.005, $R^2_{adj.}$ = 0.15). Observing the top 5 models suggested that main creek length was an important factor for total abundance of fish (abundance ~ Main_creek_length + Mean_steepness; $F_{2,66}$ = 7.1, p =0.005, $R^2_{adj.}$ =0.15). Abundance decreased with both combined tributary length and main creek length. A larger positive relationship was found with mean steepness, where gentler slopes exhibit greater abundance (Fig. 9).

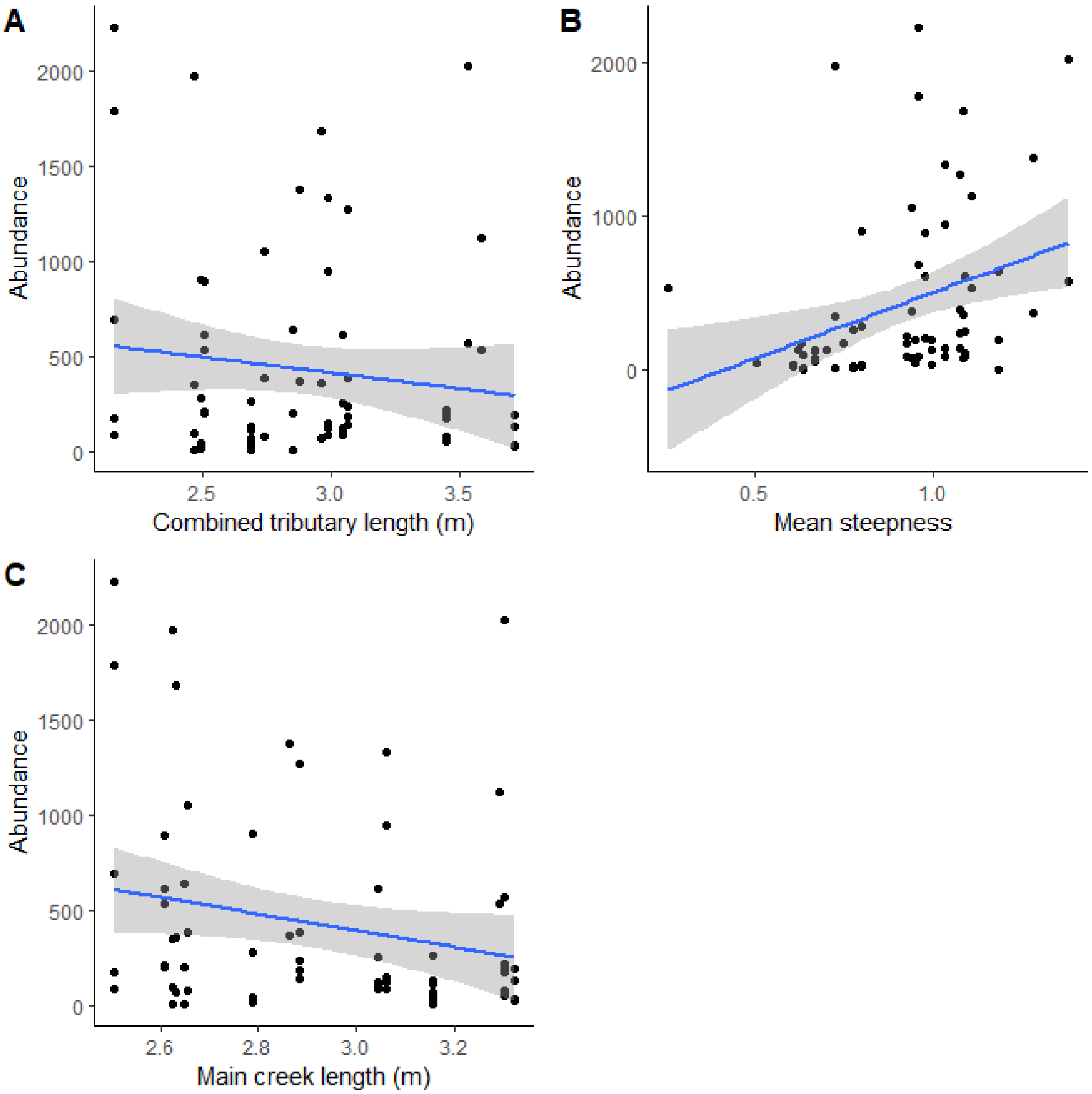

Figure 9. Total abundance of fish, depending on the combined tributary length (A), steepness of the creek bank (B) and main creek length (C).

Richness.

The number of species was best explained by the steepness of the creek bank and month (best model according to AICc: richness ~ Mean_steepness + Month $F_{4,59} = 7.6$, $p < 0.001$, $R^2_{adj.} = 0.29$). Richness increased moderately with gentler creek banks (Fig. 10a), and appeared to be greatest in March, lowest in April and May, before rising again in June (Fig. 10b). No additional significant predictor variables were found in the top 5 models. However, there was a significant interaction between month and mean steepness (richness ~ Mean_steepness * Month, $F_{7,56} = 5.5$, $p < 0.001$, $R^2_{adj.} = 0.33$). In the month of April, the effect of mean steepness on richness was the largest, followed by June, whereas in March and May the effect was less pronounced (Fig. 10c).

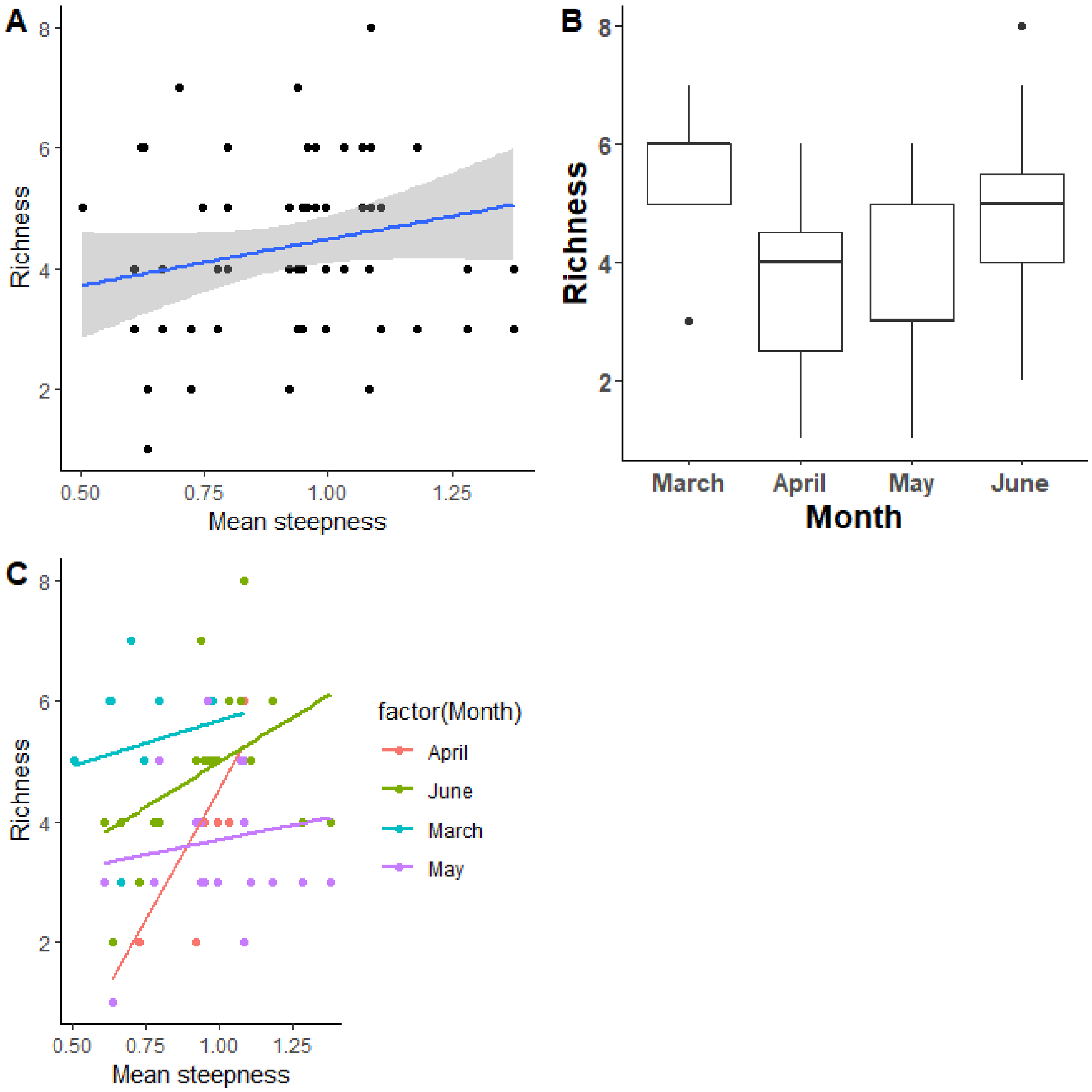

Figure 10. Species richness of fish depending on the steepness of the creek bank and month. (A) scatterplot of richness plotted against mean steepness, (B) boxplot showing median richness over the months, and (C) scatterplot of richness plotted against mean steepness for each individual month.

Shannon-Weaver index.

The Shannon-Weaver index was best explained by the length of the main creek (lowest AICc model: Shannon ~ Main_creek_length $F_{1,64}$= 9.6204, p< .005, $R^2_{adj.}$ = 0.11709). The Shannon-Weaver index increased moderately with longer main creeks (fig. 11A). Analyzing the rest of the top five revealed Maximum depth, combined tributary length and tributary dominance as additional significant variables (Shannon ~ Main_creek_length + Max_depth $F_{2,63}$= 4.8781, p< .05, $R^2_{adj.}$ = 0.1066) (Shannon ~ Combined_tributary_length + Tributary_dominance $F_{2,63}$= 4.7431, p< .05, $R^2_{adj.}$ = 0.10328). Combined tributary length (fig. 11B), and maximum depth (fig. 11D) both caused a similar moderate increase in the Shannon-Weaver index, where longer tributaries and deeper creeks both cause a higher index. The Shannon-Weaver index also increased slightly with creeks with a greater proportional length of tributaries (fig. 11C)

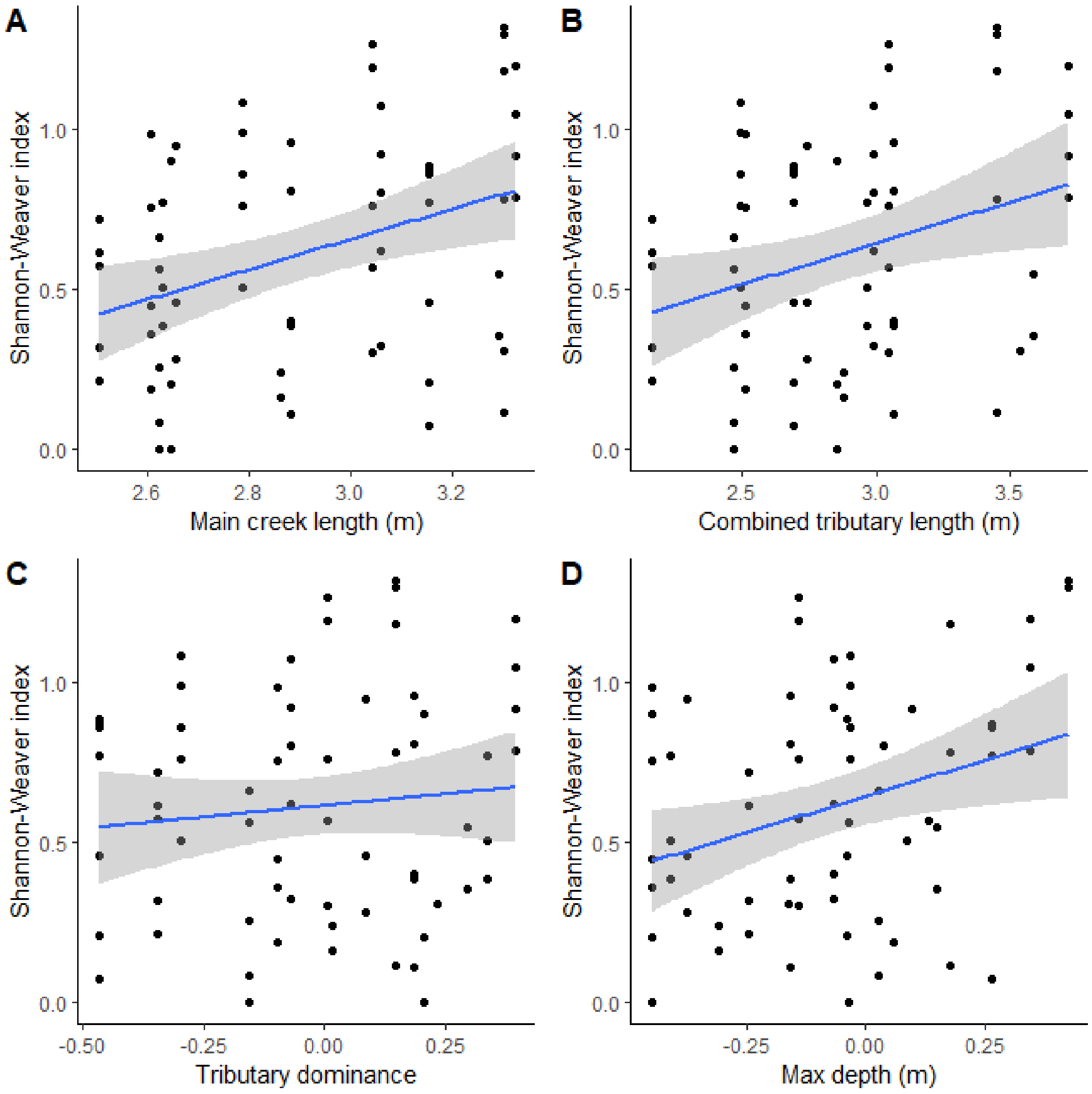

Figure 11. Shannon-Weaver index, depending on (A) main creek length, (B) combined tributary length, (C) tributary dominance, and (D) maximum depth.

Inverse Simpson

The inverse Simpson index was best explained by the length of the main creek (model with the lowest AICc value: inverseSimpson ~ Main_creek_length + 1 $F_{1,63}$= 6.1363, p< .05, $R^2_{adj.}$ = 0.074292). The inverse Simpson index increased moderately with long main creeks (fig. 12B). Analysis of the top five models also revealed maximum depth to be a significant variable (inverseSimpson ~ Max_depth $F_{1,63}$= 5.9083, p< .05, $R^2_{adj.}$ = 0.071229). Here, the index increased moderately with deeper creeks (fig. 12A).

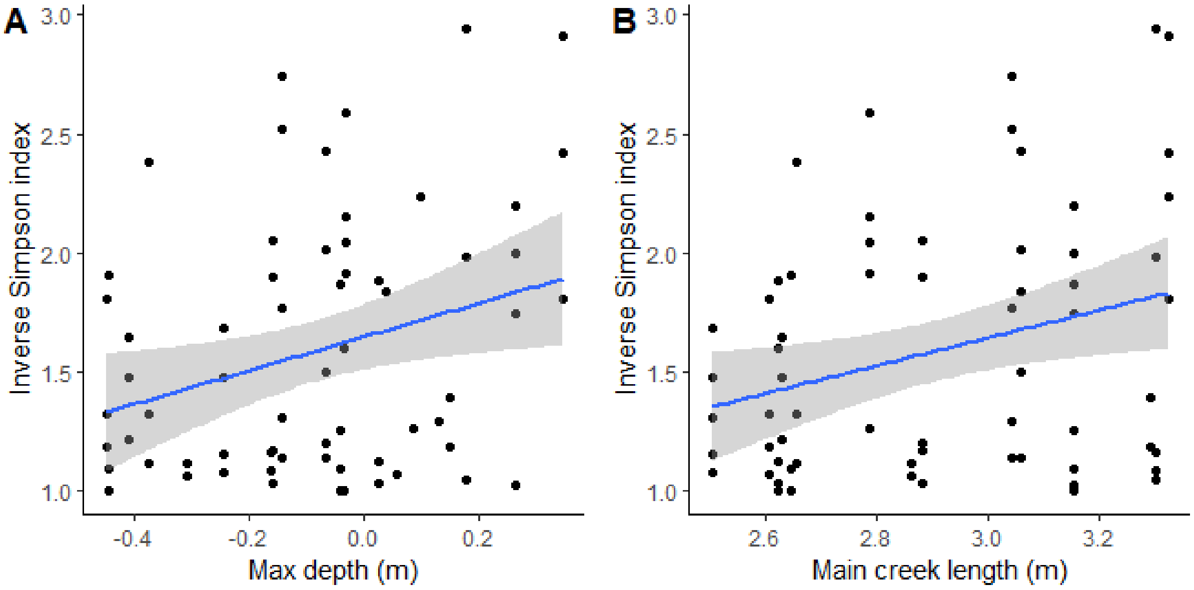

Figure 12. Inverse Simpson index, depending on (A) maximum depth, and (B) main creek length.

Herring

Herring abundance was best explained by combined tributary length and mean steepness of the creek bank (best model according to AICc: Herring ~ Combined_tributary_length + Mean_steepness $F_{2,66}$= 8.985, p< .000, $R^2_{adj.}$ = 0.19019). Herring abundance decreased slightly in creeks with greater combined tributary length (fig. 13C), but increased moderately in creeks with gentler sloping banks (fig. 13A). Analysis of the top five models also identified main creek length as a significant variable (Herring ~Main_creek_length + Mean_steepness $F_{2,66}$= 8.9777, p< .000, $R^2_{adj.}$ = 0.19005). Herring abundance decreased slightly in longer main creeks (fig. 13B).

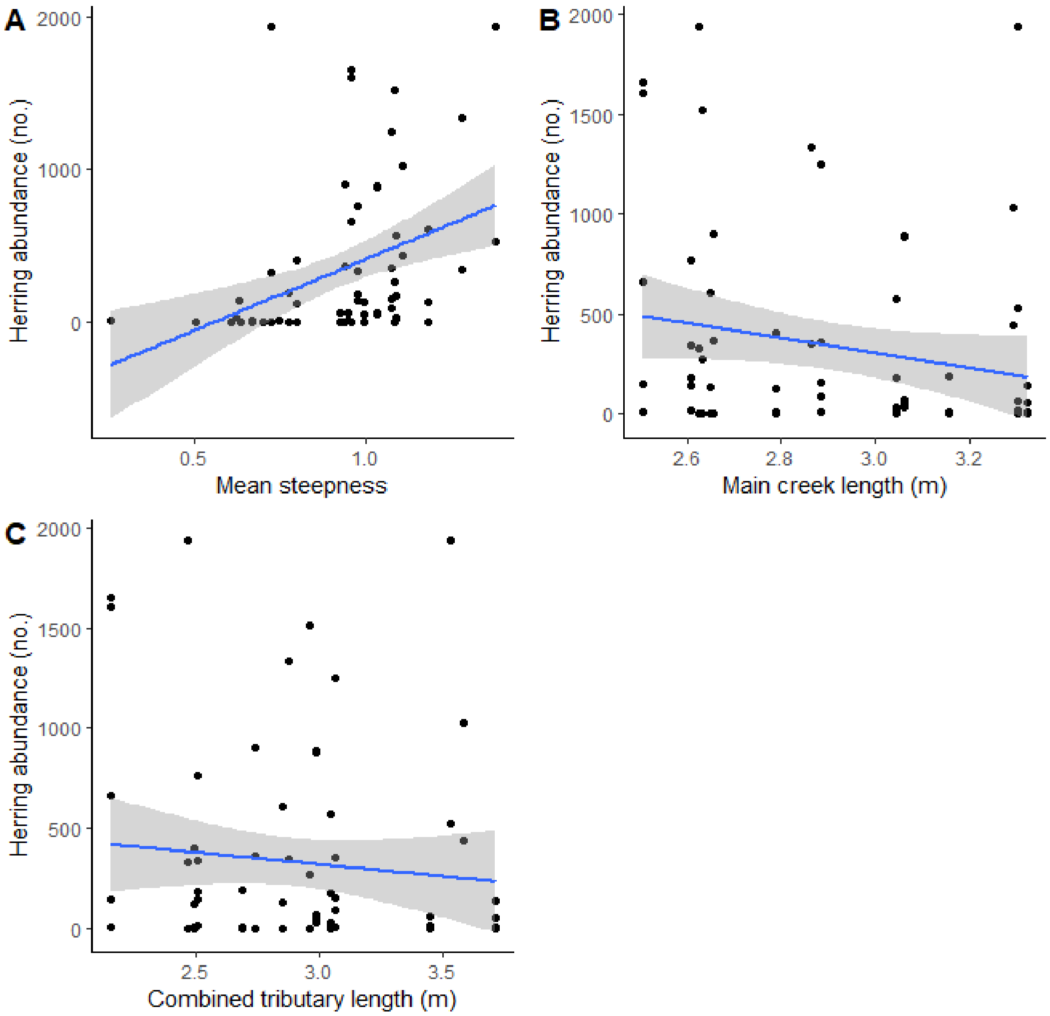

Figure 13. Total abundance of herring, depending on (A) steepness of the creek bank, (B) main creek length, and (C) combined tributary length.

Common goby

Common goby abundance was best explained by both the length of the main creek and month (model with the lowest AICc value: Common.goby ~ Main_creek_length + Month $F_{4,64}$= 4.9462, p< .005, $R^2_{adj.}$ = 0.1884). Common goby abundance appears to show a downward trend as the months progress, its lowest median value being in June (fig. 14A). Goby abundance decreased minimally as a result of longer main creeks (fig. 14B). Further analysis of the top five models revealed no additional significant variables. An interaction effect between main creek length and month was observed (Common.goby ~ Main_creek_length * Month $F_{7,61}$= 3.4587, p< .005, $R^2_{adj.}$ = 0.20198). There is a positive effect of main creek length on common goby abundance in March, May, and June, (with the effect being strongest in June) but the overall negative trend seems to originate from the negative effect of main creek length on goby abundance observed in April (fig. 14C).

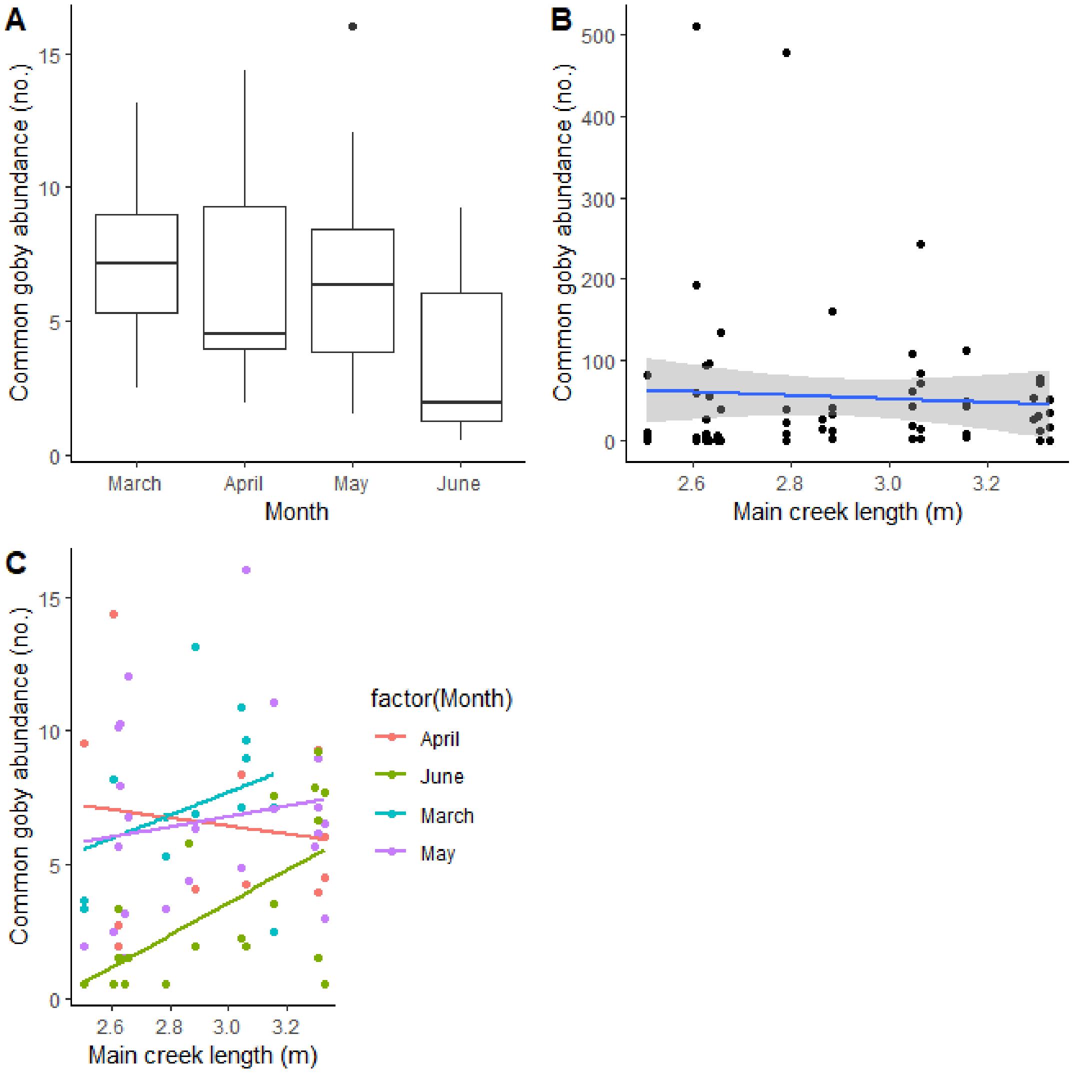

Figure 14. Total abundance of common gobies depending on month and main creek length. (A) boxplot of common goby abundance over the months, (B) scatterplot of common goby abundance over main creek length and (C) scatterplot of common goby abundance plotted against main creek length for each individual month.

Flatfish

Flatfish abundance was best explained by month (model with the lowest AICc value: all_flatfish ~ Month, $F_{3,66}$= 3.7844, p< .05 $R^2_{adj.}$ = 0.10799). Flatfish abundance appears to climb from the lowest values in March to a peak in May before starting to decrease again in June (fig.15). Analysis of the top 5 models revealed no additional significant variables for flatfish abundance.

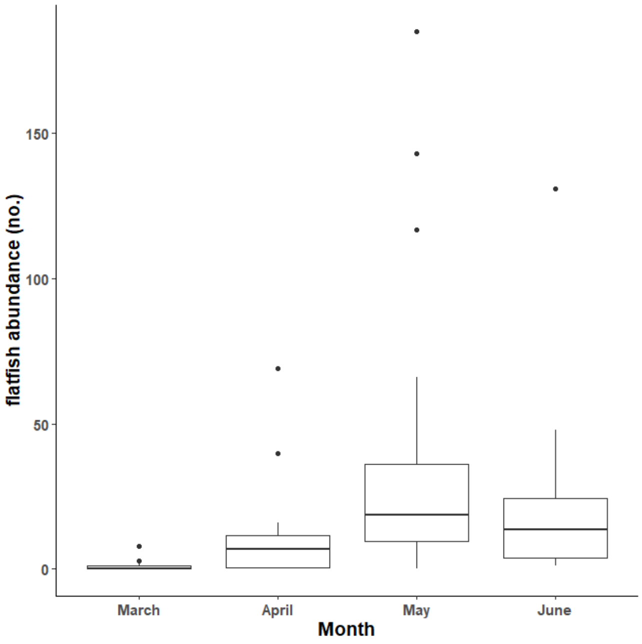

Figure 15. Total flatfish abundance over the months.

Smelt

Smelt abundance was best explained by month and maximum depth (model with the lowest AICc value: Smelt ~ Max_depth + Month + 1, $F_{4,63}$= 5.3052, p< .000 $R^2_{adj.}$ = 0.20447). There appears to be a slight amount of monthly variance in smelt abundance, as the median number of smelt decreases between March and April. While the median value does not increase after this point, the upper quartile of smelt abundance does increase greatly between May and June (fig. 16A). Smelt abundance decreased slightly with greater maximum depth (fig. 16B). Further analysis of the top five models revealed no additional significant variables. An interaction effect between maximum depth and month was observed (Smelt ~ Max_depth * Month, $F_{7,60}$= 6.3925, p< .000 $R^2_{adj.}$ = 0.36036). The negative effect of maximum depth on smelt abundance is greatest in the month of June and much less pronounced in the other months, the months of April and May even seeing a slight positive effect (fig. 16C).

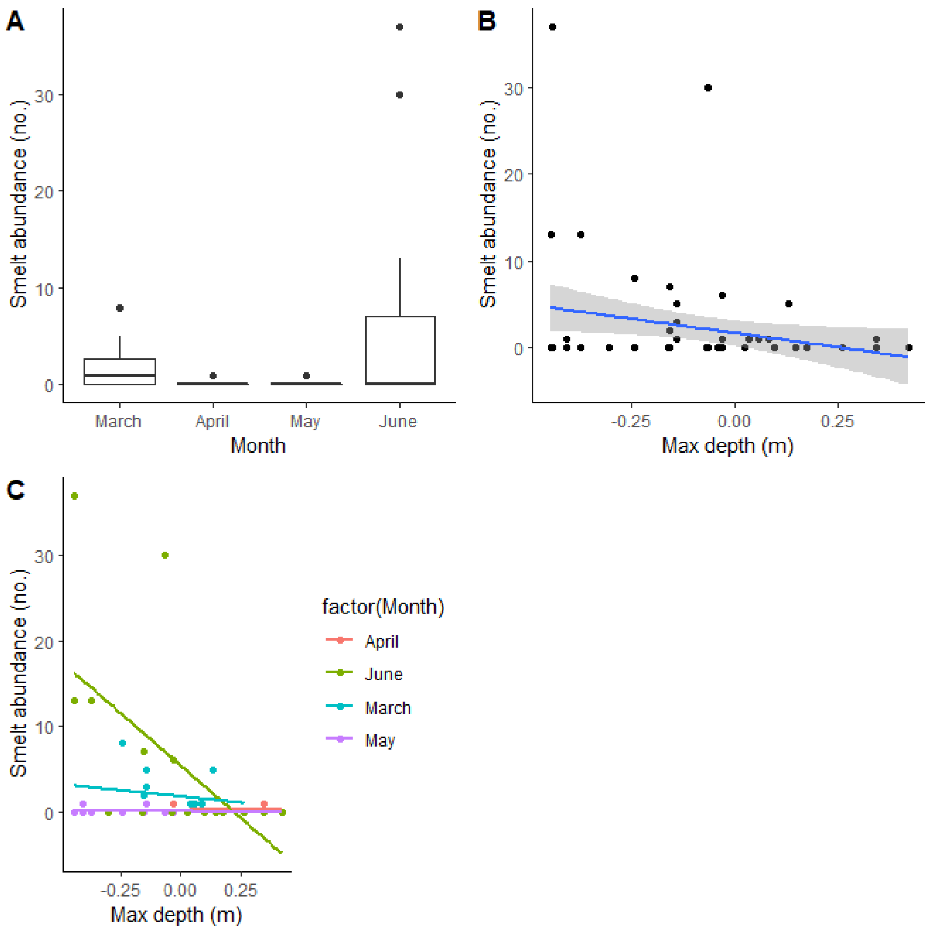

Figure 16. Total smelt abundance depending on moth and maximum depth. (A) boxplot of smelt abundance over the months, (B) scatterplot of smelt abundance over maximum depth and (C) scatterplot of smelt abundance plotted against maximum depth for each individual month.

Discussion

My results support that a gentler slope of the creek bank is a very important morphological characteristic for fish that sustains greater abundances and diversity of fish. This effect was the strongest in overall fish abundance and herring abundance but could also be observed in richness, which is in line with theory that shallower slopes allow for easy passage into the marsh surface during high tide (McIvor& Odum, 1988; Rozas, 1992).

The positive relationship between the diversity indices and the depth of the creek mouth is interesting. Although we expected to find a greater diversity and abundance of fish in shallow creeks, these results seem to indicate the opposite. However, it has been observed in literature that different hydrogeomorphological characteristics may impact different groups of species differently (Jin et al., 2014; Williams & Zedler, 1999). For example, in California marches resident species preferred lower order, shallower creeks, while there was a greater diversity of species and a greater abundance of marine transients in deeper higher order creeks (Visintainer, Bollens & Simenstad, 2006), which may be the case for our creeks as well. What is especially interesting is that the only fish that did seem to occur more frequently in shallow creeks is the European smelt which is a marine transient species (de Groot, 2002). The overwhelming majority of smelt we caught were far below their adult size (4-5cm as opposed to close to 30cm) lending credence to the mechanism of shallow creeks providing shelter to juvenile species and serving as a nursery habitat (de Groot, 2002; Talley, 2000).

Main creek length as well as combined tributary length appear to have a negative relation with abundance. We expected to find that longer creeks, and thereby longer marsh edges would result in a greater abundance of fish, but that appears to not be the case. This is not entirely unexpected, as several other similar studies also failed to find such a relationship (Jin et al., 2014). Our results instead appear to be more in line with studies of different order creeks, where the shorter creeks with lower flow had higher levels of abundance of certain fish species (Visintainer, Bollens & Simenstad, 2006 ;Gewant, Bollens, 2012). This specifically seemed to be the case for both the common goby and the herring, as these species also had a significant negative correlation with main creek length. Given that the length of a creek (as well as many other morphological characteristics) is often related to the flow of that creek, and flow has on occasion been found to be a very important factor in predicting fish biomass and abundance, it would be interesting to incorporate flow in future studies of the Dutch saltmarshes to determine whether length or flow is accountable for the observed abundance values (Allen et al., 2007). It is also possible that the total abundance value was skewed by the herring, which seem to show a preference for shorter creeks and make up the largest part of our total fish abundance. There was a positive correlation observed between main creek length and inverse Simpson index as well as between both main creek and combined tributary length, and Shannon-Weaver index. This correlation could perhaps be an indication that while there is no evidence that a longer marsh edge benefits total fish abundance, it does support a greater diversity of fish. Tributary dominance also has a slight positive effect on the Shannon-Weaver index. A greater tributary dominance means a larger marsh edge, as more of the creek's length is made up out of individual tributaries, which is then well in line with our findings about creek length and the Shannon-Weaver index and supports the idea that the longer marsh edge allows for a greater diversity of species to flourish.

Month itself seems to also have had a significant effect on our different parameters. For the abundance of the individual fish, this pattern is to be expected, as the migration and breeding patterns of different fish affects which species are present in the saltmarshes at different times in the year. Such seasonal patterns can be observed in the abundance of common gobies, smelt and flatfish, and consequently also in the overall observed richness. This seasonal variability of different species may also explain why there is a different effect of mean steepness on richness over the months. As has been demonstrated elsewhere, different species of fish do prefer different kinds of slopes (Williams & Zedler, 1999; Visintainer, Bollens & Simenstad, 2006), species which will likely not show uniform seasonal variability. We also observed seasonal variation in how creek morphological characteristics (max depth, main creek length) affect the abundance of specific species (smelt and common goby), which could be an indication of how different fish in different life stages prefer different kinds of creeks.

There are of course additional variables that may affect the abundance and diversity of fish in saltmarshes. Presence of vegetation, invertebrates, vegetation type and grazing regimes may for instance impact abundance (Stolen et al., 2009; Rozas, 1992). Rate of flow is also stated to be an important variable in fish abundance but was not feasible to determine during this study (Jin et al. 2014). Our creek morphological variables are also restricted by the fact that we were only able to take point measurements for most of them. Whereas a more extensive study would look at values like mean depth and mean width, we were restricted to the depth, width, and steepness of the cross sections at our fishing locations. These measurements may not be reflective of the larger profile of the creeks as a whole, and other variables that depend on the entirety of the creek, such as flow, could also not be ascertained. The steepness variable we used in this study also has an interesting downside. As McIvor and Odum discuss in their 1988 paper, creeks often have a depositional side with a gentle sloping bank as well as an erosional bank with a high steepness (McIvor& Odum, 1988). The way our steepness measure is calculated does not account for situations where there is one steep and one gentle bank. Future research at these sites, or research building off of these findings, may benefit greatly from expanding the morphology measurements to the entire creek, allowing other variables of note such as elevation or drainage area to also be considered. A final methodological concern of this study is the fact that tributary dominance appeared to correlate with a number of our other morphological variables. In the end I chose to still include it in our analysis, as without total creek length, tributary dominance was the only variable that described the entire marsh edge, and not just either the tributaries or the main creek.

Setting aside some of the methodological considerations, we can observe clear effects of creek morphology on the saltmarsh fish communities. The effect of steepness on both diversity and abundance being especially notable. Although we did not find every relationship we expected to find given the literature, it is important to note that most of the studies cited in this report are from North America or Asia, and that these studies generally only make claims about their specific saltmarsh ecosystems (Christian & Allen, 2013). Further research might help clarify or solidify some of the relationships we have found, but the most important takeaway from this study is that creek morphology is an important parameter to consider in saltmarsh management, as it is shown to both affect the abundance of fish as well as the diversity of fish found within the marshes. Given this conclusion, establishing the exact morphological characteristics associated with the current saltmarsh management would be a logical next step. Although a comparison between managed and unmanaged marsh falls outside of the scope of this research, our analysis of the creek morphology in the managed marshes of Groninger wad and the much less managed marshes of Schiermonnikoog appears to suggest that both systems have a distinct geomorphological character (fig. 5). Finding out to what degree this distinction in morphology is a direct result of management may help future studies hoping to assess the effects of management on the creek morphology in this area. On the basis of our results, we cannot outline a clear piece of advice about the exact considerations managers of marsh creeks should take, but research building off of these findings might well arrive at such an advice.

Acknowledgements

This research was done as part of the Swimway Project, under the supervision and guidance of H.C. Charan-Dixon and B.D.H.K. Eriksson. The fieldwork component of this project would not have been possible without the great help and collaboration of Hannah Charan-Dixon, Anni Ziebel, Casey Yanos, Klemens Eriksson and Lucia Irazabal Gonzalez. Special thanks go out to my incredibly supportive field work partner Anni, whose great care and drive made the work both fun and easy.

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