Influence of reed (*Phragmites australis*) belts in the Baltic Sea archipelago on pike (*Esox lucius*)

– and other coastal fish species

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Abstract

Eutrophication, near shore building and human disturbances by dredging and shore alteration have led to increased expansion of the common reed *(Phragmites australis)* in the archipelago of the Baltic Sea. Reed has an important ecological function such as nursery habitat for many fish species. Pike *(Esox lucius)* is a predatory fish whose larvae and young-of-the year fish find both food and shelter in coastal reed beds. But due to the increased amount of reed, more homogenous reed belts are formed, the overall biodiversity is reduced, and dense reed belts can reduce pike foraging. During the last decades, pike populations in the Baltic Sea have declined and are now mainly found in the inner bays of the archipelago but seem to have declined also in these core areas. No study has yet studied how pike abundance in inner archipelagos is related to reed characteristics like reed area, perimeter and heterogeneity. Here I study the impact of reed on abundance primarily of pike, but also of other coastal fish species: perch *(Perca fluviatilis)*, roach *(Rutilus rutilus)* and three-spine stickleback *(Gasterosteus aculeatus)*. More specifically I tested if more extensive and heterogeneous reed belts have more pike than homogenous reed belts. I conducted a spatial analysis for pike catch per unit effort (CPUE) from angling in relation to reed perimeter and area among 24 bays in the Stockholm archipelago. Pike CPUE was positively associated with both reed area and perimeter. The data showed that below 0.5 ha reed or a reed perimeter of 2500 m pike populations started to decline drastically, and there was no indication of lowered pike density in bays with the highest amounts of reed. Of the other coastal species, roach also showed a positive correlation with reed cover while perch abundance showed a positive correlation with pike abundance. Wave exposure was negatively correlated with pike and positively correlated with three-spined stickleback, indicating a transition zone between pike and sticklebacks along an exposure gradient.

To study if reed management by cutting reed impacts pike populations, I did a angling survey in two coastal bays to test if pike utilized the more heterogeneous reed cut areas over homogenous reed belts. Unfortunately, too few pike were caught to allow statistical analysis, longer time series of pike abundance data are necessary.

This study concluded that there is a positive association between pike abundance and reed, and there is a lower reed limit threshold for stable occurrence of pike. I could not find that very extensive reed belts would be negative for pike, nor that reed management by cutting reed would be beneficial but more data is required for a more certain conclusion.

Keywords: Reed, pike, Baltic Sea, spatial distribution, habitat utilization, angling investigation

Preface

To Daniel, who brought back my childhood passion for fishing by bringing me down to the river to fish one spring day. That day set my passion for aquatic wildlife and was the keystone for entering my studies.

Table of contents

List of tables

List of figures

1. Introduction

The Baltic Sea has during the last decades been negatively impacted by allochthonous nutrient inputs resulting in eutrophication and increased hypoxia that is now also present in the coastal zone around the entire Baltic Sea (Conley *et al.* 2011). Increased eutrophication along with decreased grazing pressure from cattle on coastal perennial species such as (common) reed (*Phragmites australis*) has also led to increased expansion of reed over soft sediments in sheltered areas (Pitkänen *et al.* 2013). Reed belts have become both denser and wider (Pitkänen *et al.* 2013) and have expanded into new areas in the archipelago (Von Numers 2011). This reed expansion may also have a negative impact for coastal ecosystems (Pitkänen *et al.* 2013) as reed is a strong competitor for area, that outcompetes other species and cause a decrease in local plant biodiversity (Munsterhjelm 1997, Altartouri *et al.* 2014). Reed benefits from moderate increased nutrient input (Pitkänen *et al.* 2013) but a main reason for the spread in the Baltic Sea is also human disturbances (Burdick and Konisky 2003, Silliman and Bertness 2004, Bart *et al.* 2006, King *et al.* 2007, Chambers *et al.* 2008). Reed is a pioneer species that settles on virgin soil and shoreline sediments and can therefore spread after human induced alterations, mainly by dredging and near-shore building (Pitkänen *et al.* 2013) and changes in human activities in coastal areas (Ojala and Louekari 2002). Removal of bordering habitats of woody vegetation for coastal development, also leads to increased nutrient release and expansion of reed in coastal habitats (Silliman and Bertness 2004).

On the other hand, reed has an important role for ecosystem dynamics in the Baltic Sea shallow habitats (Altartouri *et al.* 2014). Reed protects the shorelines from wave erosion, buffers internal nutrient loading and absorbs external loading (Kaitaranta *et al.* 2013). Reed has an ecological function as nesting area for birds and spawning area for fish (Altartouri *et al.* 2014). Both old and new vegetative parts of reed have positive functions for fish reproduction by providing spawning substrate and shelter for juvenile (Kallasvuo *et al.* 2011, Snickars *et al.* 2010).

The northern pike (*Esox lucius*) is a piscivorous fish associated with reed beds in the Baltic Sea that has shown a decline in abundance during the last decades (Olsson 2019), although data are limited due to non-standardized and non-representative catching methods along with fragmented time series (Olsson 2019). Recruitment failure, habitat exploitation, fishing and changes in the offshore ecosystem are some of the possible causes for the decline pike in the Baltic Sea (Ljunggren *et al.* 2010, Olsson 2019). Also, fish species like perch (*Perca fluviatilis*) and roach (*Rutilus rutilus*) have shown to be negatively impacted from boating and shoreline construction due to loss of reproduction habitats and changes in vegetation cover (Sundblad and Bergström 2014). Shoreline construction affects 0.5% of available recruitment habitat per year, and in 2005 around 40% of the available recruitment habitats in Stockholm archipelago since the 1960-ies had been degraded (Sundblad and Bergström 2014). Predation on eggs and larvae from three-spined stickleback (*Gasterosteus aculeatus*), a species that has increased in abundance in the Baltic Sea, can also have negative impact on pike and coastal fish recruitment (Bergström *et al.* 2015, Nilsson 2006). Another mortality factor on pike is predation from cormorants and seals that can have a negative impact on pike and perch on a local level (Östman *et al.* 2013). Hence, there are likely multiple causes to the decline of pike that may differ between areas.

Fish species such as pike, pikeperch (*Sander lucioperca*), burbot (*Lota lota*) and perch are top predators and important for ecosystems since they can regulate mesopredator abundance and through trophic cascades top predators can reduce eutrophication symptoms and conserve essential habitats (Östman *et al.* 2016). This is called a top down effect and can be equally beneficial as nutrient reductions for limiting ephemeral algae growth (Östman *et al.* 2016, Lynam *et al.* 2017). Without any top-down regulation by piscivore fish on mesopredators, this can result in increased abundance of ephemeral algae over perennial macroalgae and seagrasses due to the mesopredator's predation on invertebrates that otherwise would graze on ephemeral algae (Östman *et al.* 2016). It is therefore important to achieve a high abundance of fish predators to mitigate eutrophication syndromes in the coastal zone.

How reed density, complexity and reed beds spread affect fish populations is poorly studied. Pike spawns in sheltered and shallow areas that contains macrophyte substrate (Bry 1996, Lappalainen *et al.* 2008). Early spawning species like pike and burbot, spawn among old submerged reed stems (thatch) and hatched pike larvae later feed on the later hatching species, e.g. roach, bream (*Abramis brama*) that spawn later among the fresh reed shoots (Kallasvuo *et al.* 2011). This difference in hatching timing between species reduces inter-specific competition as resources are partitioned over time also in homogenous reed beds (Kallasvuo *et al.* 2011).

The recruitment failure of pike and perch is suggested to at least partly be due to limited food availability of zooplankton abundance in coastal areas (Ljunggren *et al.* 2010). Zooplanktons like cyclopoid copepods and cladocerans are important prey for pike larvae and has been shown to be 10-100 times more abundant in reed belts compared to other habitats (Kallasvuo *et al.* 2009). Young-of-the-year (YOY) pike selects reed beds in early life stages (Hawkins *et al.* 2003) and most pike larvae are found on flattened reed from previous year in around 20-80 cm water depth (Lappalainen *et al.* 2008). A study from the western Gulf of Finland suggested that pike cannot completely utilize the slowly increasing reed belts in the middle to outer archipelago (Lappalainen *et al.* 2008). Pike larvae abundance varies from inner- to outer archipelago (Lappalainen *et al.* 2008) with a gradient in larvae abundance from 0% in the outer- to 86% middle- and a 100% of the reed sites in the inner archipelago (Kallasvuo *et al.* 2009). Pike larvae in the outer archipelago have a higher risk of mortality compared to inner archipelago larvae when they shift from the yolk sac to start predating (Lehtonen *et al.* 2000). Another cause for recruitment failure may be predation from three-spined stickleback on pike eggs and larvae (Eklöf *et al.* 2020, Nilsson *et al.* 2019). Stickleback appears in higher abundance that predate on pike larvae in outer and middle archipelago resulting in high mortality of pike recruits (Eklöf *et al.* 2020, Nilsson *et al.* 2019).

Inner bays generally have higher turbidity than outer archipelago bays and higher turbidity also affects pike larvae behaviour by higher prey attack rates and spending less time swimming due to reduced ability to catch zooplankton prey (Engström-Öst and Mattila 2008). Zooplankton community composition is also affected from turbidity by less content of fatty acids and lower density of copepods in the inner more turbid areas of the archipelago (Salonen *et al.* 2013, Engström-Öst and Mattila 2008). Foraging gets negatively impacted and pike larvae gain less weight then pike larvae in less turbid water (Salonen *et al.* 2013, Engström-Öst and Mattila 2008). Engström-Öst and Mattila (2008) suggested that the higher attack rates in high turbidity is due to energy cost when searching for food, however they also suggested that prey density was an effect on attack rate. In turbid water, pike larvae spend less time in vegetation and show less habitat choice, since predation risks are reduced in high turbidity but also increase foraging efforts (Engström-Öst and Mattila 2008). The Kallasvuo *et al.* (2009) study suggested that the higher temperature in the inner areas affects productivity but also the spawning for roach, which small pike could feed on (Kallasvuo *et al.* 2009). Thus, even though inner bays have higher turbidity, pike larvae foraging in the reed belts face a very high abundance of zooplankton that are important for pike populations that can compensate the behaviour and loss of higher quality food.

Results from stocking of pike suggest that a minimum 30% of an area should be covered by vegetation for pike to establish (Vuorinen *et al.* 1998, Grimm 1983, Grimm and Backx 1990). Eklöv (1997) showed that body size of northern pike was inversely related to vegetation density of loosely structured submerged reed and *Typha* (cattail) habitats. Several studies have shown positive correlation between depth of habitat and YOY pike body size until they reach 15 cm in length

(Casselman and Lewis 1996, Vuorinen *et al.* 1998). However, studies from Skov and Berg (1999) have shown that water depth does not influence habitat choice for YOY pike. In August YOY pike start to use less dense reed, *Typha ssp*, and vegetated habitats (Skov and Berg 1999, Hansen *et al.* 2018). Over summer pike smaller than 16 cm use more dense and complex structured habitats than larger pike (Eklöv 1997). In early winter there is a shift from reed habitats to congregation in more open pool habitats for YOY pike (Hawkins *et al.* 2003). For pike recruitment it is therefore important that vegetation of different complexity and structure is available (Hawkins *et al.* 2003, Skov and Berg 1999, Eklöv 1997).

Although reed belts provide sheltered habitats with ample prey abundance for pike larvae and YOY, in lakes dominated by reed, predation on zooplanktivorous fish was lower compared to lakes dominated by a habitat with more complex habitat structure (Skov and Berg 1999). Pike YOY occurrence in dense vegetation leads to a decrease in foraging ability but increased predation refuge. A negative correlation between pike abundance and density of YOY roach prey supports this habitat selection effect (Skov and Berg 1999). In summer YOY pike avoided simpler *Typha* and *Phragmites* habitat and instead utilized more complex and dense habitats (Eklöf 1997) but with increasing size in late summer, and less predation risk, the less complex reed is used more (Skov and Berg 1999). In contrast, perch shows decreased predation rate with increasing reed density (Nelson and Bonsdorff 1990). No YOY pike were caught in areas absent of vegetation (Skov and Berg 1999). Young pike, thus, needs vegetation and cover, and reed provides a substrate for early life stages but with bigger size, less complex and larger water depth is needed.

Instead of adding structure, reed cutting can change the structure of reed beds and stems become shorter and denser (Valkama *et al.* 2008). In freshwaters, plant biodiversity increases by 90% when reed is managed with harvesting, however in saltwater marshes there are no such effects (Valkama *et al.* 2008). Reed management had a negative impact on abundance of invertebrate communities after 1-2 years, but before 1-2 years reed cutting had no effect on invertebrate communities (Valkama *et al.* 2008). Burning and harvesting of reed reduce passerine birds' abundance by about 60%, mainly due to food limitation of insects and seeds (Valkama *et al.* 2008). Therefore Valkama *et al.* (2008) suggested that management should be set into intervals to decrease impact on birds and invertebrates. However, Valkama *et al.* (2008) did not test for heterogenic effects from leaving patches of reed, therefore the effects could even be positive, since reed is still important.

In a North American lake 20% of macrophytes in the littoral zone were removed by cutting spaced lanes (Olson *et al.* 1998) resulting in more heterogeneous habitats which showed positive effects on body growth of piscivore fish. The year after the cutting age classes 3 and 4 of two piscivore fish species, bluegill (*Lepomis macrochirus)* and largemouth bass (*Micropterus salmoides*) increased in body size compared to a control lake (Olson *et al.* 1998). Other year-classes showed less response but overall body growth of piscivore fish increased from the management (Olson *et al.* 1998).

1.1. Aim of thesis

Reed belts are spreading and is the dominant macrophyte in the coastal system of the Baltic Sea, resulting in more homogenous shoreline habitats. Reed is important for spring spawning fish, but close after spawning submerged macrophytes and more complex environments are important as well for pike. Both artificial habitats and biomanipulation show more heterogeneous habitats can have positive effects on specific fish species and ecosystems.

I therefore hypothesize that increased heterogeneity in reed belts will have a positive effect on pike. Reed with high perimeter in relation to area in bays represents a more heterogenous habitat compared to bays with low perimeter to area (homogenous habitat). To further test this hypothesis, I studied effects of reed biomanipulation as a potential restoration to create more heterogenous habitats by cutting tunnel passages in homogenous reed belts. If pike populations can be restored and a top down effect on the ecosystem strengthened, this could both reduce eutrophication symptoms as well as facilitate recreational boating in inner archipelagos of the Baltic Sea.

This study is based on data from two different projects along the western Baltic Sea coastline. The first is a spatial comparison of 24 coastal bays located along the Sweden Stockholm archipelago, where pike abundance have been estimated through angling in 2017-2019 within the Refisk project, coordinated by the County Administrative Board of Stockholm and financed by the Swedish Agency for Marine and Water Management. In the same bays fish communities have been surveyed with standardized gillnets in 2017. Second, I have used angling to survey pike distribution and abundance in a reed management area on Gräsö, north of Stockholm archipelago, where reed has been cut to increase the heterogeneity of the reed belt.

1.1.1. Pike distribution and biology

The northern pike is a coastal fish species in the Baltic Sea that utilizes the warmer water above the thermocline during growth periods (Hanson *et al.* 2017). It is an ambush predator that waits for prey to pass (Diana, 1996, Skov and Berg 1999) and often attacks prey from submerged vegetation into open water (Holland & Huston

1984, Skov and Berg 1999). Pike spawns in sheltered, shallow areas that contains macrophyte substrate (Bry 1996, Lappalainen *et al.* 2008). Bays are mainly structured into less isolated bays that are dominated by vascular plants and algae from inner and outer archipelago, and isolated bays that are dominated by high vegetation cover (Rosqvist *et al.* 2010). Within shallow areas pike eggs are scattered on emerged- and submerged plants and in filamentous algae (Nilsson 2006). Adult pike does not show territorial defense, but social grouping and individual spacing (Hawkins *et al.* 2003). Pike selects high productive areas and they follow individual spacing distribution in an ideal free manner (Haugen *et al.* 2006). However, during spawning pike shows aggregation in spawning areas and can form temporary territories for a couple of days (Grabowski and Isley 2008) and after spawning they start to disperse widely (Rosell and MacOscar 2002).

Pike is versatile in habitat utilization (Chapman and Mackay 1984) but the selection is not random event though there is high individual variability (Kobler *et al.* 2008). Submerged macrophytes has a positively relation with pike abundance both in winter and summer (Kobler *et al.* 2008). In summer pike utilizes submerged vegetation more than in winter in both clear and turbid freshwater but in winter pike selects summer covered submerged macrophyte habitats equally to other habitats (Jepsen *et al.* 2001, Kobler *et al.* 2008). The littoral zone is mainly utilized (Vøllestad *et al.* 1986), and the pelagic zone is less utilized in summer than during winter, but higher turbidity does increase the utilization of the pelagic zone (Kobler *et al.* 2008, Vøllestad *et al.* 1986).

1.1.2. The common reed

The Baltic Sea´s common reed is a native helophyte that is wildly distributed along the Baltic Sea coast (Meriste *et al.* 2012). Reed disperses mainly through rhizome shoots and distribution (Haslam 1972). Reed grows best in nutrient-rich habitats but can grow from fens to open aquatic communities (Ikonen and Hagelberg 2007). They frequently grow along shores adjacent to agricultural-, urban- and vegetated areas along the shores (Altartouri *et al.* 2014). Inner coastal bays have on average a 11% higher reed coverage in each reed belt site compared to outer archipelago, with wider and denser reed belts and a lower part of reed being flattened after each winter (Kallasvuo *et al.* 2011). Reed are dominant in sheltered shorelines and bays where it grows into shallow waters down to one meter but can extend deeper over time but are unlikely to progress below two meters (Altartouri *et al.* 2014). Waters in reed belts differs between inner and outer archipelago (Kallasvuo *et al.* 2011). In inner reed belts water is less saline, has higher temperature and lower secchi-depth compared to outer reed belts (Kallasvuo *et al.* 2011, Kallasvuo *et al.* 2009). These changes occur along a gradient also in surroundings areas without reed (Kallasvuo *et al.* 2011).

Reed is a strong competitor and stress tolerant species (Ikonen and Hagelberg 2007). Rhizomes can form lateral and vertical buds that are sturdy and prevent root competition (Ikonen and Hagelberg 2007). It grows so dense that it inhibits light to reach down to surface or sediments which prevents competitional growth of other vegetations (Ikonen and Hagelberg 2007). Old reed can form litter mat covers that prevent germinating and growth on the ground and in the water (Ikonen and Hagelberg 2007). Expansion of reed has led to problems with conservation of valuable habitats since it out-competes other species (Ikonen and Hagelberg 2007). However, reed becomes less competitive if it becomes shaded by other plants, severe winter frost, extensive drought during the vegetative period, strong waves, ice movement, grazing, mowing and burning (Ikonen and Hagelberg 2007).

Cutting of reed results in the new shoots that are denser and shorter (Valkama *et al.* 2008), which may have a positive effect on pike abundance in habitats where few other macrophytes are present. However, reed beds are often cut and removed completely in areas and therefore do not have a positive effect as a heterogenous cut would.

2. Methods and Materials

2.1. Spatial comparison

In a projected called “Refisk” coordinated by the County board of Stockholm the effects of fishing closure during spawning on fish communities has been studied in 24 bays along the western Baltic Sea coastline in Swedish archipelago from Västervik to Östhammar. Half of the bays were protected from recreational fishing (spawning closure) during spring from 1 April–15 June and the others had no fishing restrictions.

In this project, pike data was gathered using angling. Two anglers per boat fished for four hours in a protected bay with no restrictions on fishing equipment. After four hours they switched to the reference bay and fished for four hours in the afternoon. Next day they switch order of bays and fished for four hours in each bay. After a minimum of seven days these bays where fished again with the same method. Data on pike catches from April-June in 2017-2019 are used in this study which contain pike catch per fisherman per hour (CPUE) data, catch positions and pike lengths. Wave exposure and distance to open sea (Swedish inner waters) from these 24 bays had already been calculated using GIS and were available.

Sampling of other fish species in these bays were done in May 2017 using standardized Nordic lake monitoring gillnets. Number of gillnets (effort) differed between bays but varied from 3-8 gillnet per bay. Pike caught in this gillnet survey were too few (29 in total), due to gillnets being a poor method for pike sampling and not used.

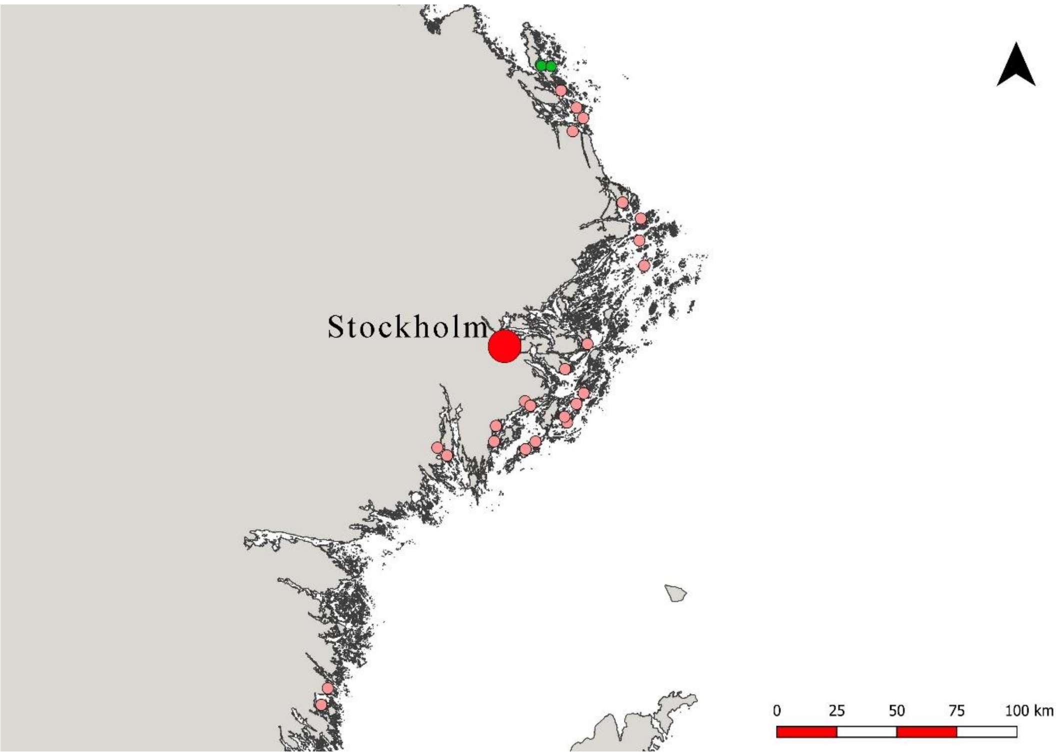

Figure 1. Map of study sites along the western Baltic Sea coastline. Refisk bays positions (pink dots), Gräsö reed management locations (green dots). Coastline: National shoreline (NSL), © Swedish maritime administration (2018), © Läntmäteriet (2018). Capital city of Sweden Stockholm (Big red dot).

2.1.1. Reed distribution

To study if there was a connection between the spatial extent of the common reed in coastal bays and fish abundances, I measured spatial extent (area) and perimeter of the reed belts in the 24 bays used in the Refisk project (Figure 1). SWEREF99TM geographically referenced RGB aerial photos with a precision of 0.5 meters were placed as template to digitally mark reed belts. Since reed belts degrade or expand depending on time of year, photos from Google maps and Eniro.se/kartor with aerial photos from other seasons where used to complement the aerial photos. If a satellite image had more reed in them than aerial photos the reed from satellite data was added to map. Satellite images were added as an overlay image on the aerial photo by georeferencing photos in Qis (Figure 2). Polygons were drawn by tracing reed from the photo layers.

Using Qgis by digitizing polygons around reed belts, identified visually from aerial and satellite photos I created vector graphic of reed belts shape in each of these 24 bays I extracted data on reed area and perimeter for each bay using Qgis version 3.4.15 (Qgis.org 2020).

2.1.2. Bay area/study zone

The area of a bay was defined by visually locating the mouth of the bay, i.e. the transition zone from a closed bay towards open water where greater mixing and habitat shifts occur with other water masses. GPS positions of pike catches were mapped to make sure pike catches were all within the bay boundaries. If pikes where caught close to study border or outside, then study border was extended to overlap the reported catch location within the bay. The extension was moved to the next natural narrow passage in the bay before the transition zone to open water. If a pike was caught close to open water or direct next to a sharp transition zone, then the extension only expanded enough to just cover the point.

2.1.3. Coastline

Reed naturally grows past the waterline on to land and therefore crosses the shoreline border. Since I was only interested in reed growing in the water, I used a shapefile of the Swedish shoreline from a collaboration project between two Swedish authorities, SWEDISH MARITIME ADMINISTRATION and Lantmäteriet, called “National shoreline” (NSL) to define the coastline and the inner boundary of the reed belts in bays. This way an objective definition of the shoreline and inner boundary of reed belts was used. To create graphical vectors for reed, polygons were drawn following the perimeter of reed belts and patches in the aerial photos from each bay (Figure 2).

2.1.4. Calculations of reed area and heterogeneity

Before calculating area and perimeter, vectors where checked for errors, using Qgis “Check for validity” function (Qgis 2020). This function controlled that there was no crossings of polygon lines or other malfunctions with polygons. Once reed belt was judged as valid, reed area and perimeter were calculated. Length of the coastline within a bay was calculated by cutting out coastline from within a bays study area border and then all line vectors were summed up to give a total length of bay coastline (Figure 2). Bay area was estimated as the area of a polygon covering a whole bay and cutting it with the coastline, removing all land vectors, and calculate area of polygons inside a bay (Figure 2).

The cutting process for polygon vectors in Qgis could create lines with perimeters but no area inside the bay area. These perimeter values were removed since they only represented lines created by the program and not polygons of reed. This artifact was due to mismatch with points in polygons that crossed borderlines and got cut of and resulting in only two points inside the bay trying to create a polygon but resulted in a line.

In addition to total reed area (*RA*) and perimeter (*RP*) I used three measures of reed characteristics in each bay:

$$Reed\ ratio\ (RR, unitless) = \frac{Reed\ perimeter\ (m) - Coastline\ (m)}{Coastline\ (m)}$$

$$Reed\ coverage\ \%\ of\ bay\ (RC) = \frac{Reed\ area\ (m^2)}{Bay\ area\ (m^2)}\ x\ 100$$

$$Reed\ depth\ (RD, m) = \frac{Reed\ area\ (m^2)}{Bay\ coastline\ (m)}$$

2.1.5. Jetties and wave exposure

In addition to reed characteristics I obtained measures of jetties and wave exposure in the bays. For jetties I used a shapefile of Sweden's jetties mapped by Törnqvist *et al.* (2018). The layer showed length of each jetty but not width. Since jetties cross the coastline and sometimes reach far up upon land, they were also cut at the coastline so that only the length of jetty on water was used (Figure 2). The sum of jetty-meters per bay was transformed as an index of jetty density as jetties-meter per hectare.

Wave exposure data (m^2/s) was obtained from modelled data for the complete Swedish coast (Isæus 2004). The wave exposure model accounts for fetch, wind speed and direction.

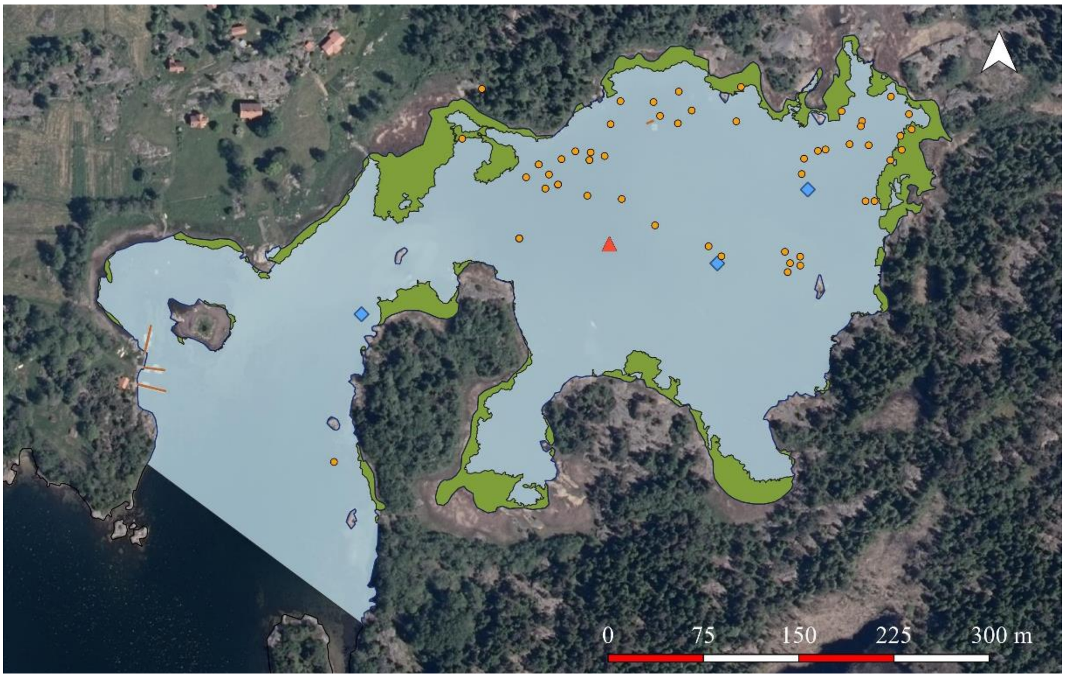

Figure 2. Aerial photo of one bay (Gisslingöfladen SWEREF99^{TM}: 6633610, 733784) with created vectors. Coastline (black line), bay area (light blue), reed beds (green). GPS positions of pike (yellow dots), net (blue rectangle), angling boat (red triangle), Jetties (Brown lines). Background image: GSD-Ortofoto, 0.5m RGB ©Lantmäteriet (2019).

2.2. Reed management

At the island of Gräsö, two connected inner bays were used in a pilot project for reed management, Västerbyfjärden and Österbyfjärden. I used a reference bay approximately 4 km away, Måssten (Figure 3).

Figure 3. Map showing reed management area on the island of Gräsö in Roslagen archipelago. with the two managed bays and the reference area. Västerbyfjärden (SWEREF99^{TM} 6697813, 692031), Österbyfjärden (SWEREF99^{TM} 6697371, 692358) and reference bay Måssten (SWEREF99^{TM} 6697085, 696481). Background image: GSD-Ortofoto, 0.5m RGB ©Lantmäteriet (2019).

In total 40 000 m^2 common reed was cut at the bottom in August 2019 in the two bays, Västerbyfjärden and Österbyfjärden (Figure 3,4). However, not all reed was cut but in some parts the reed belt was left untreated, whereas in other areas reed was cut to open up channels in the reed belt, thereby, creating a more heterogenous reed habitat.

2.2.1. Angling investigation.

To study if the reed management had any effect on pike distribution, angling investigations were conducted before reed treatment in spring 2019 (by staff at SLU) and in 2020 (by me). All fishing was conducted by two fishermen at all time. In 2019 angling fishing was conducted 30 May – 31 May 2019. I conducted my fishing monitoring during 1 June - 3 June 2020 and 8 June – 11 June 2020. At the first occasion the two reed managed bays were fished for two days and the reference bay on 3 June for 2 hours. The second tour I fished for two days, one day in Måssten and the second in the managed bays.

In 2019 the bays were fished without any restriction of equipment (rods, lures and hooks) and where in the bays, gathering data of number of pike caught, hours fished and in which bay similar to the ReFisk project method. However, for 2020 I first tried a more standardized method to differ catches between different types of reed belts. Reed in the managed bays where grouped into cut, homogenous- and (“natural”) heterogenous reed belts. 8-10 positions of each type of reed habitat were selected for fishing. In addition, five pelagic (still not deeper than 6 m) sites were

Figure 4. A cut lane into a homogeneous reed belt at Österbyfjärden, Gräsö Island. Photo by Örjan Östman.

chosen. Each site was fished for ten minutes of efficient fishing time, during catches and data collection from which, time was paused. To fish the entire water mass within the fishing sites a throwing pattern was conducted with a clockwise throwing pattern to cover the entire site in a 180° pattern. Each fisherman fished 90° each of the total 180° area. However, as there were very few fish caught with fishing positions, fishing method had to change to the same as in 2019.

I also used a standardized set of fishing equipment. The fishing lures had no barbs on the hooks (maximum hook size width 2.5 cm) and the lures were less than 25 cm long to avoid causing severe injuries or bleeding (Figure 5). Only one pike showed severe bleeding from hooking injury.

Figure 5. Photo of barbless hooks on lures used (right) and original hooks (left) on the same type of lure. Barbs where squeezed with a plier resulting in barbless lure. Photo by Niklas Niemi.

When a fish was hooked it was captured in a large meshed net without knots and hooks were removed from the fish in the net with the fish still in the water. Then the fish were placed directly in a trough that was large enough for the fish to have a neutral spine position and coverage from sun to reduce stress. There was sufficient water in the trough to cover the fish's body. Water in the trough was replaced after each fish, to maintain well oxygenated high quality water.

When handling a fish, a damp cloth was used to cover the eyes, and reduce stress and soothe the fish. When fishing in strong sunlight or wind, caught fish were kept in shade/shelter when handled, by blocking sun or wind with the researcher’s back. The fish was placed on a measuring board where it was measured and labeled with one trimming in the abdominal fin. The fish was released by being lowered into the water with nets and allowed to recover for a few minutes before being released. If a pike showed low signs of life prerelease, fish were placed in a second trough, to recover for up to one hour. If all vital signs of recovery were detected and stable pre one hour, the fish was released. This happened for one pike and it recovered after 20 minutes. The samplings and treatments of fish was approved by Uppsala Animal Welfare Committee, No: 03233/2020.

2.3. Statistical method

All statistical analyses were done in R version 3.3.2 (R Core Team 2016). First a correlation matrix was produced to give an overview of strengths of single correlations between logarithmic pike CPUE and predictor variables to study intercorrelation between different predictor variables (reed characteristics, jetties, wave exposure, spawning closure (closure/open). Predictor variables were log-transformed or square-root transformed to better fit normal distributions. I also did a correlation matrix for CPUE of pike and other fish species with log-transformed parameter values.

To account for variation explained by other factors than reed, jetties and other fish species, I for each fish species used ANCOVA to study the variation explained by the fixed predictors: wave exposure and spawning closure treatment. For all species but pike, temperature at fishing was also used as a fixed predictor, whereas for pike I instead used year as a fixed predictor as the study was repeated over several years. I calculated adjusted R-square-values to study how much variation these fixed factors explained. This way I got an estimate of how much variation the fixed factors not related to reed, jetties or other fish species explained. This way I could estimate the additional unique variation explained by reed, jetties and other fish species.

After this initial analysis, abundance of fish species was tested against reed variables, jetties or other fish species using ANCOVAs including these fixed variables.

All models were tested for significance using type 2 models in the 'car'-function for R (Fox and Weisberg 2019). Estimates of total variation explained, and adjusted R^2 were calculated with the 'summary'-function in R.

GGplot package in R studio (Wickham 2016) was used to plot the most significant results from the statistical models.

3. Results

3.1. Spatial comparison

Of the habitat variables, logarithmic pike abundance (CPUE) showed strongest positive correlations to reed area (r = 0.44) and perimeter (r = 0.60), while negatively correlated with wave exposure (r = -0.44) and jetties/ha (r= -0.37) (Figure 6).

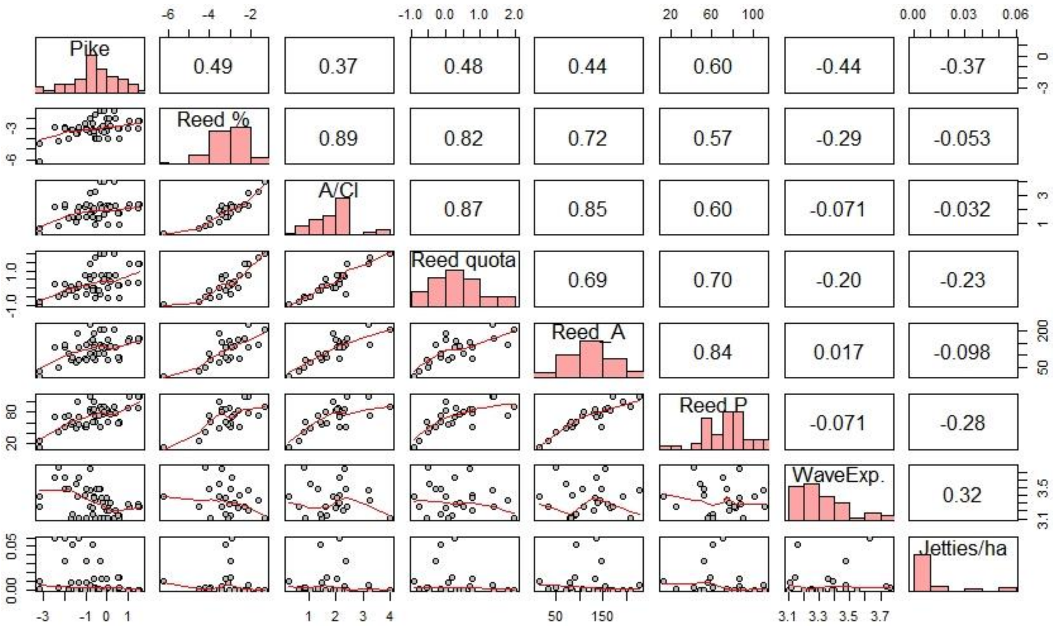

Figure 6. Correlation panel between logarithmic transformed pike abundance CPUE and reed variables and abiotic factors. Histogram of variables are placed diagonal. Upper right section shows correlation values between variables and lower left plots of values. A= reed area, P = reed perimeter, % = Reed coverage, Reed depth = A/Cl and Wave exposure = Waveexp. Numbers are Pearson´s correlation coefficent.

In relation to abundance of other fish species, pike CPUE showed positive (r = 0.49) correlation to perch and an even weaker but negative correlation (r= -0.11) to three-spined stickleback abundance (Figure 7). Roach (> 20 cm), roach and stickleback showed a small negative correlation (Figure 7).

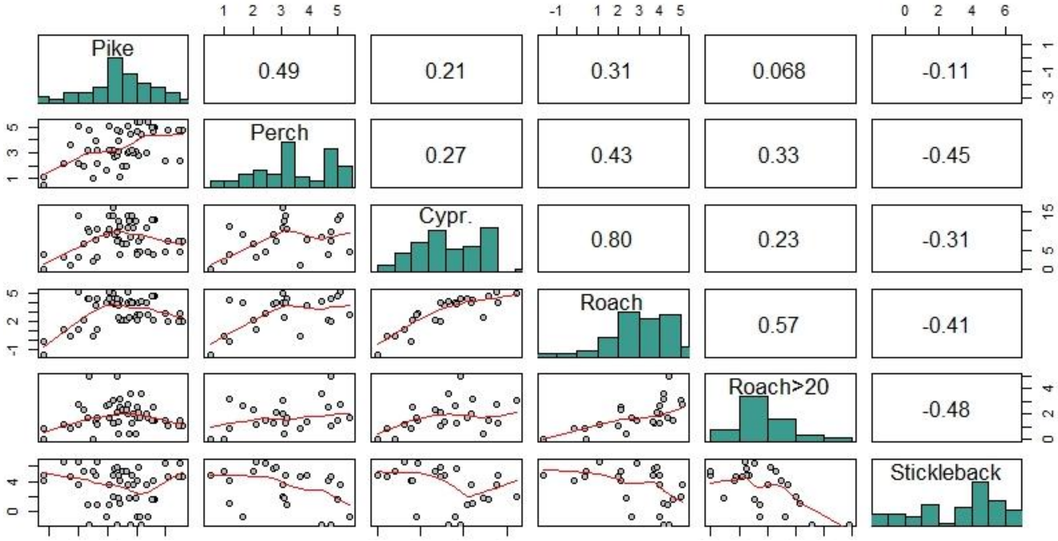

Figure 7. Correlation panel of logarithmic transformed pike CPUE and CPUE of other fish species from the gillnet monitoring in the 24 bays. Cypr. = cyprinid species. Histogram of variables are diagonally. Upper right section shows correlation values between variables and lower left plots of values. Numbers are Pearson´s correlation coefficent.

3.1.1. Pike

Of the fixed factors spawning closure treatment, wave exposure and year, shortened as *TWY*, wave exposure and spawning closure best explained variation in pike CPUE (adjusted r^2= 0.41, Table 1). Wave exposure showed a negative correlation with pike abundance and abundance was higher in protected bays (Figure 8). While controlling for TWY, there was no significant relationship between pike CPUE and Jetties/ha (ANCOVA: df = 1, f = 0.3, p = 0.58, adjusted r^2 = 0.42).

Table 1. Summary of regression analyses with log transformed (pike CPUE) as response against the fixed variables treatment, wave exposure (WaveExp) and year (Yr). TWY is the model including all three variables. Total sample size is 72.

Factor	Model df	F-value (model)	P-value (model)	Adjusted r^2 (model)
Pike~ TWY	4	10.7	<0.001	0.43
Pike~ WaveExp+Treatment	2	18.9	<0.001	0.41
Pike~ Treatment+Yr	3	6.7	0.002	0.25
Pike~ Treatment	1	14.2	<0.001	0.21
Pike~ WaveExp+Yr	3	5	0.004	0.19
Pike~ WaveExp	1	12.1	0.001	0.18
Pike~ Yr	2	2	0.15	0.04

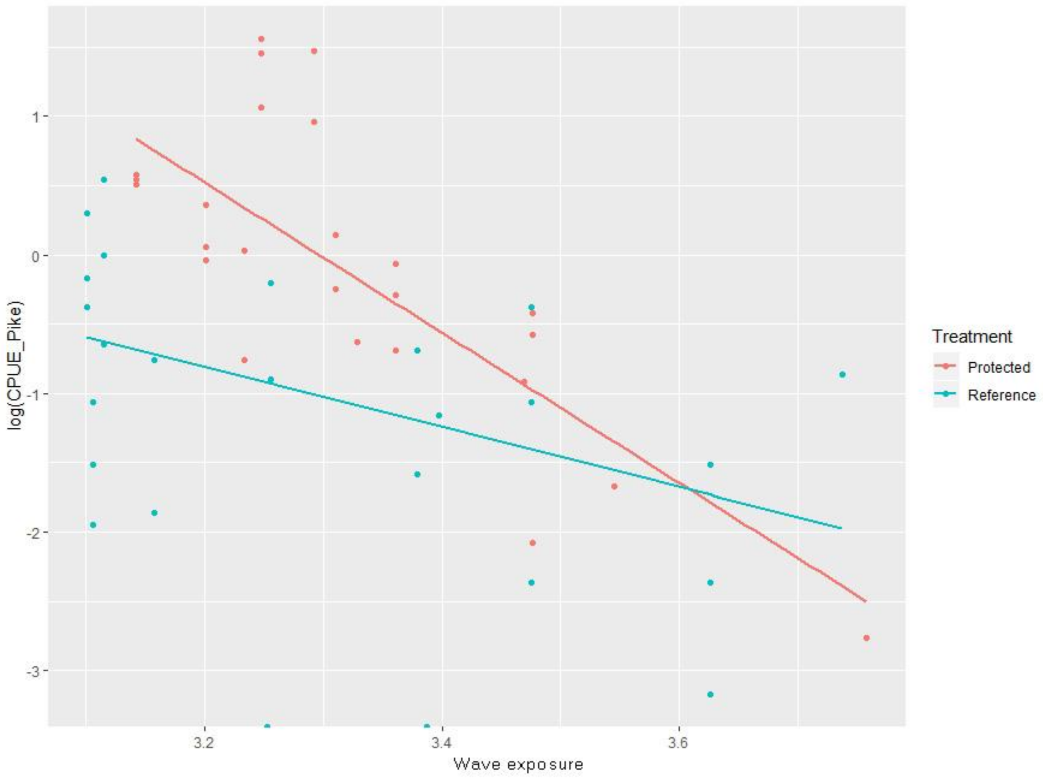

Figure 8. Plot of pike abundance CPUE (Y-axis) against Wave exposure (X-axis) showed a negative relation and was higher in protected bays (red) than in reference bays (blue). Model adjusted r^2 = *0.41, p= <0.001.*

All three reed perimeter variables were significantly correlated with pike CPUE (Table 2). Of these, total reed perimeter (*m*) explained most additional variation to the fixed variables, 18% (Table 2; Figure 9), whereas the other two (Reed Ratio, Reed Perimeter/Coastline) were significant and explained around 10% additionally to the TWY model. Also, all reed area predictors showed positive correlations to pike CPUE (Table 2). Absolute reed area also explained 18% additional variation to TWY (Figure 10), whereas the Reed Depth (p = 0.004) and Reed Coverage (p = 0.007) could explain around 8-10% additional variation each.

Table 2. Results from regression analyses with log (pike) as response against transformed perimeter and area related predictors. ReedP/CL = Reed perimeter / coastline. All tests were conducted with wave exposure, treatment and year.

Factor	Model df	F-value (model)	P-value (model)	Adjusted r^2 (model)
Pike ~ log10(RA)	1	22.7	<0.01	0.61
Pike~ √(RP)	1	22.4	<0.01	0.61
Pike~ RR	1	9.7	<0.01	0.52
Pike~ ReedP/CL	1	9.7	<0.01	0.52
Pike ~ √(RD)	1	9.1	<0.01	0.52
Pike ~ RC	1	8.1	0.01	0.51

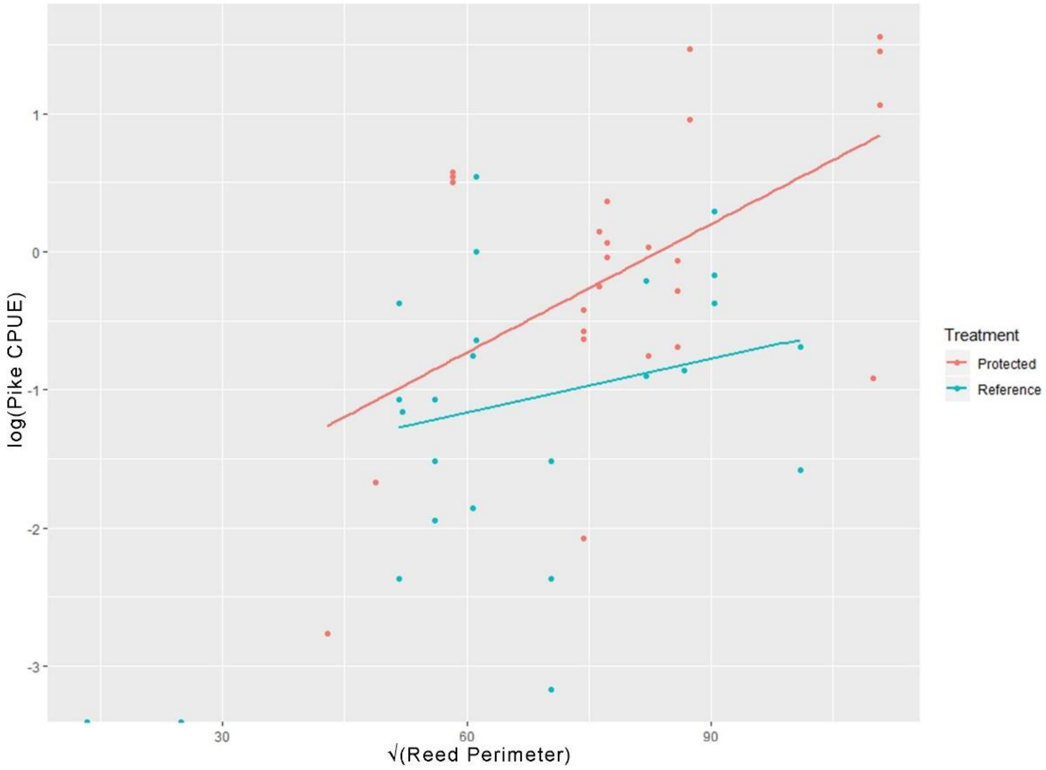

Figure 9. Plot of logarithmic transformed pike abundance CPUE (Y-axis) against reed perimeter (X-axis) with different treatments, protected (red) and reference (blue). Plot shows a positive correlation between pike and reed perimeter with higher correlation among protected bays. Model adjusted r^2 = 0.61, p = < 0.01.

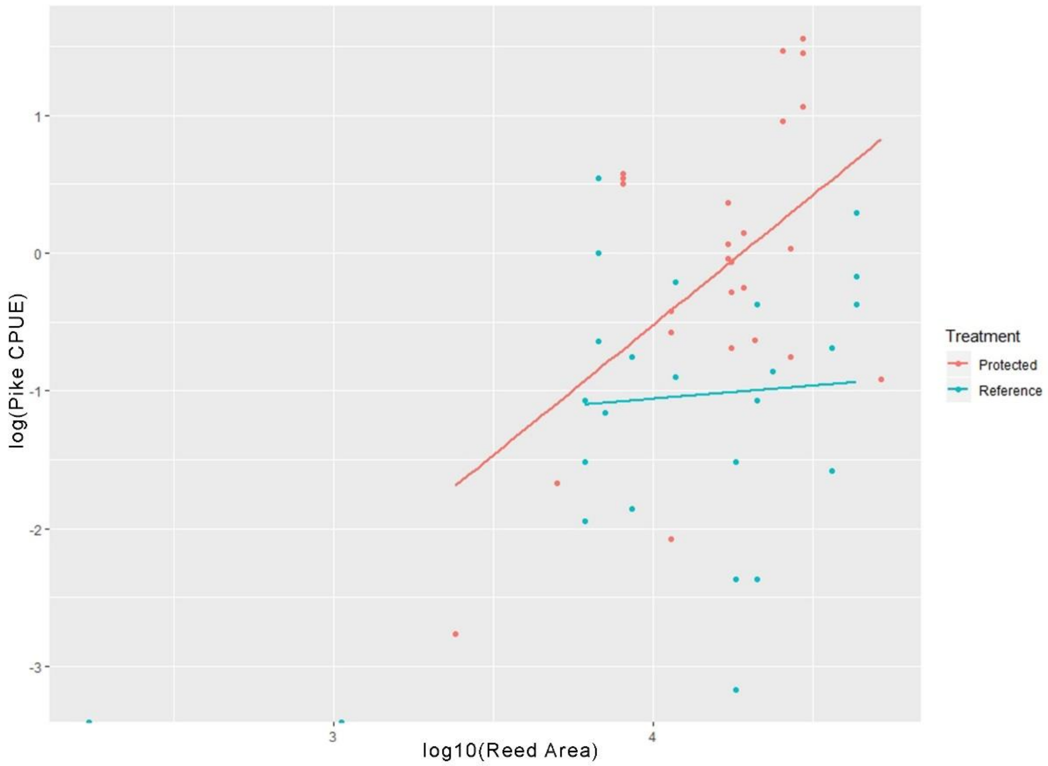

Figure 10. Plot of logarithmic transformed pike abundance CPUE (Y-axis) against 10 logarithmic reed area (m) (x-axis) with different treatments, protected (red) and reference (blue). Among protected bays there is a high correlation. Model adjusted $r^2 = 0.61$, $p = < 0.01$.

In relation to other fish species, pike CPUE showed a significant positive relationship with perch CPUE also when controlling for the fixed predictors but not with any other species (Table 3; Figure 11).

Table 3. Results from regression analyses of variance table. ANCOVA test for pike CPUE against other fish species, with fixed predictors (Protection treatment, wave exposure and water temperature at fishing) in models.

Factor	Factor df	F-value (factor)	P-value (factor)	Adjusted r^2 (model)
Pike~ √Perch	1	8.4	0.01	0.51
Pike~ log(Stickleback)	1	1.1	0.29	0.43
Pike~ Cypr.	1	0.8	0.38	0.43
Pike~ √Roach	1	0.7	0.41	0.43

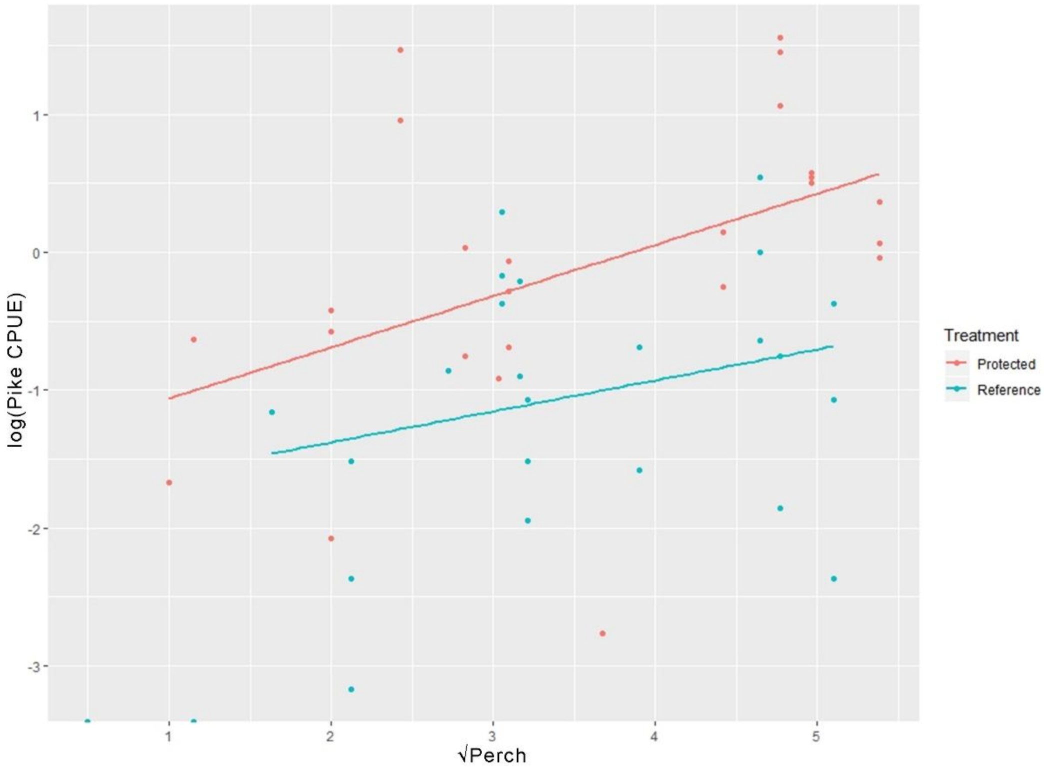

Figure 11. Plot of logarithmic transformed pike abundance CPUE (Y-axis) against square root perch (X-axis) with different treatments, protected (red) and reference (blue). Pike shows a positive correlation with perch. Model adjusted r^2 = 0.51, p = 0.01.

3.1.2. Other fish species

Of the fixed predictors, spawning treatment, wave exposure and temperature (*TWT*), roach showed a significant positive relation with temperature (Table 4). Most cyprinids caught were roach, therefore the cyprinid group mainly represent roach data. The Cyprinid regression against TWT was also significant (Cyprinid's ~(TWT): df = 3, f = 3.154, p = 0.05, adjusted r^2 = 0.22).

Table 4. Results from regression analyses. Values from summary models. Total sample size is 24.

Factor	df	F-value	P-value	Adjusted r^2
Roach ~ WaveExp,Temp	2	2.9	0.08	0.14
Roach ~ Temp	1	4.5	0.05	0.13
Roach ~ Treatment,Temp	2	2.4	0.11	0.11
Roach ~ TWT	3	2	0.15	0.11
Roach ~ WaveExp	1	1.3	0.27	0.01
Roach ~ Treatment,WaveExp	2	0.7	0.53	-0.03
Roach ~ Treatment	1	0.2	0.71	-0.04

Roach abundance in addition showed significant relationship for all reed area predictors with Reed area/ perimeter explaining most variation (Table 5; p = 0.001). The results indicate roach has a lower limit approximately around 3% of reed coverage (RC = log(-3.5)) where abundance rapidly became lower (Figure 12).

Table 5. Results from regression analyses with √roach against predictors. All tests were conducted with wave exposure, treatment and Temperature. Total sample size is 24.

Factor	df	F-value	P-value	Adjusted r^2
√Roach ~ log(Reed A/P)	1	15.1	<0.01	0.38
√Roach ~ RC	1	10	<0.01	0.28
√Roach ~ √(RD)	1	9.8	0.01	0.27
√Roach ~ √(RA)	1	7.4	<0.01	0.21

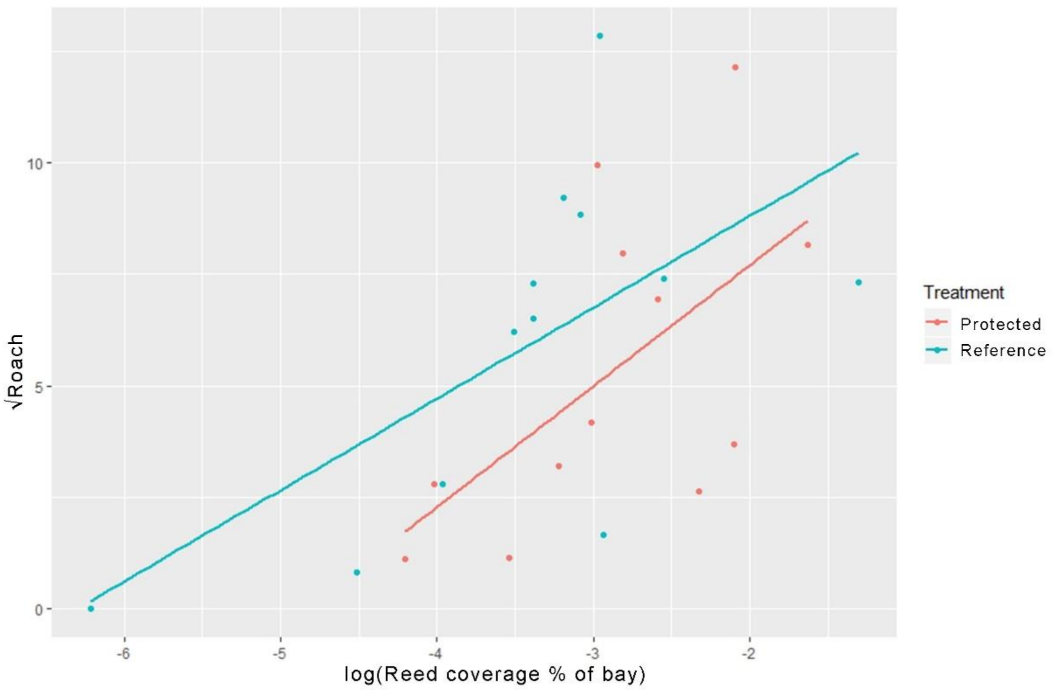

Figure 12. Plot of roach abundance (y-axis) against reed coverage % of bay (x-axis) with treatments, protected (red) and reference (blue). Reed coverage shows a positive correlation with roach and reference shows the highest effect. Roach~reed coverage: r^2 = 0.28, p = <0.01.

Reed predictors showed no significant relation with perch abundance in the regression analyses when controlling for the fixed predictors. However, perch abundance was significantly positively related with temperature, which explained low degree of variation (Table 6).

Table 6. Results from regression analyses. Perch against predictors. All tests were conducted with wave exposure, treatment and year. Total sample size is 24.

Factor	df	F-value	P-value	Adjusted r^2
Perch ~ WaveExp, Temp	2	4.9	0.02	0.25
Perch ~ Temp	1	6.7	0.02	0.20
Perch ~ Treatment, Temp	2	3.2	0.06	0.16
Perch ~ WaveExp	1	2.6	0.12	0.06
Perch ~ TWT	2	1.4	0.27	0.03
Perch ~ Treatment, WaveExp	2	1.4	0.27	0.03
Perch ~ Treatment	1	0.2	0.70	-0.04

Reed predictors showed no significant relation with three-spined stickleback abundance in the regression analyses after accounting for the fixed predictors. Abundance of three-spined stickleback was significantly positively related with wave exposure (Table 7), opposite to pike (Table 1). Less wave exposure shows large variation in abundance of sticklebacks, but in more wave exposed bays stickleback is more stable in abundance (Figure 13).

Table 7. Results from regression analyses. Three-spine stickleback (Sb) response tested against fixed variables. Total sample size is 24.

Factor	df	F-value	P-value	Adjusted r^2
Sb ~ WaveExp	1	4.4	0.05	0.13
Sb ~ WaveExp,Temp	2	2.7	0.09	0.13
Sb ~ Treatment,WaveExp	2	2.3	0.13	0.10
Sb ~ TWT	3	1.9	0.16	0.10
Sb ~ Treatment	1	0.10	0.76	-0.04
Sb ~ Temp	1	0.7	0.42	-0.01
Sb ~ Treatment,Temp	2	0.4	0.67	-0.06

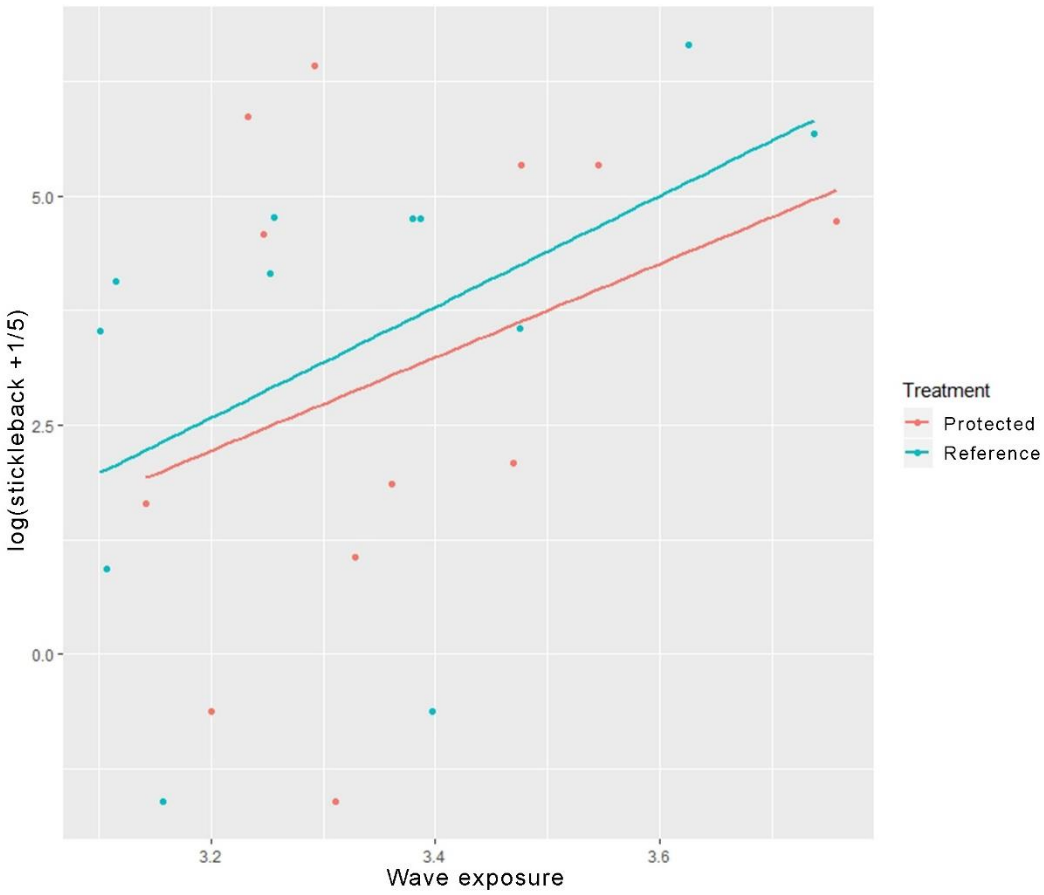

Figure 13. Plot of stickleback abundance (Y-axis) plotted against wave exposure (X-axis) with treatments, protected (red) and reference (blue). Three-spine-stickleback shows a positive correlation for wave exposure with higher in reference, no significance with treatments. Model adjusted $r^2 = 0.10$, $p = 0.13$.

3.2. Reed management

In total 53.5 hours were fished by two anglers in 2020 and a total of 11 pikes where caught (Table 8). That means a catch per fishing effort of 0.21 pike per hour overall in 2020 compared to 0.91 in 2019 (Table 8). Pike CPUE was reduced between 2020 and 2019 in both the reed management area and in the reference area (Måssten).

The number of pike sampled were too few for any formal statistical tests.

Table 8. Number of pike caught from angling investigation on Gräsö during 2019 and 2020. Number of hours fished, number of pike caught and calculated from those variables: pike catches per hour (CPUE).

	Total hours fished		No. of pike caught		Pike CPUE	
	2019	2020	2019	2020	2019	2020
Österbyfjärden	16	29.5	10	5	0.63	0.17
Västerbyfjärden	0	7	0	1	0	0.14
Måssten	17	17	20	5	1.18	0.29
Overall:	**33**	**53.5**	**30**	**11**	**0.91**	**0.21**

The angling investigation shows a decrease in number of caught pike in Österbyfjärden and Västerbyfjärden from 2019 to 2020 (Table 8; Figure 14). Size of pike shows a higher mean length in 2020 than 2019 (Table 8; Figure 15).

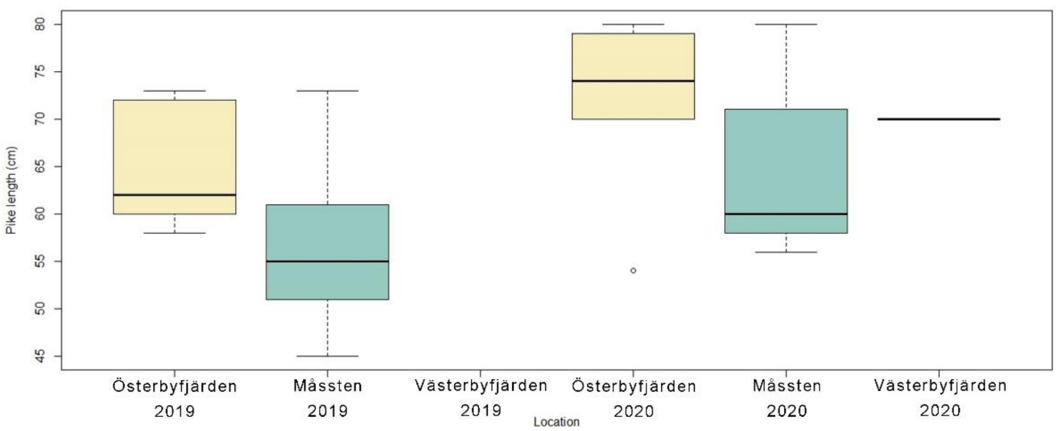

Figure 15. Boxplot of pike length (cm) in the fished bays in 2019 and 2020.

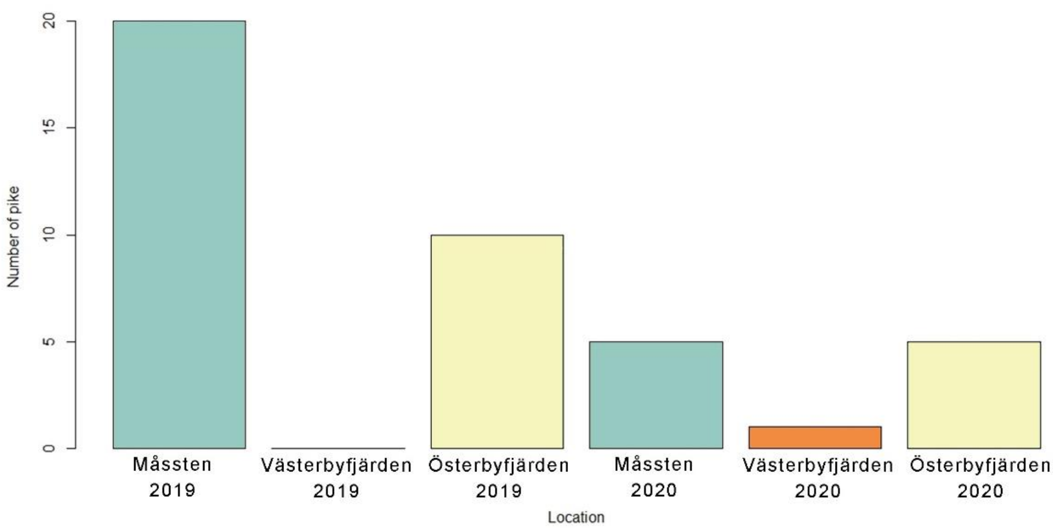

Figure 14. Bar plot of number of caught pike in each bay in 2019 and 2020.

4. Discussion

Reed characteristics explained significant variation in pike and roach abundance among the 24 studied bays, but reed did not explain perch and three-spine stickleback abundance. Perch explained the most additional variation to pike among all other fish species. Reed variables showed high covariance (Fig. 6), both area and perimeter variables are inter-linked, resulting in high covariance. For pike abundance, therefore both reed area and perimeter, separately, explained around 20% unique variation in the statistical models with a positive correlation of pike abundance with increased area or perimeter of reed, but I cannot tell which reed character is most important for pike abundance. Reed variables explained more variation in models of pike abundance than of other fish species, which may suggest pike responds stronger to reed than other fish species considered here.

The angling investigation in the reed managed bay at island of Gräsö could not show if pike utilize heterogenous reed belts more than homogenous due to an overall lack of pikes caught (11 pikes). Why so few pike was caught is difficult to explain. Maybe increased temperature at early June may have gotten pike to migrate out into deeper water and not utilizing the bay more than just during spawning season. However, 30 minutes of fishing was conducted outside Österbyfjärden in the transition zone to more open archipelago to check if pike had migrated outside the bay, but no pike where caught there.

4.1. Pike

Although pike abundance clearly increased with total reed area and perimeter, I could not find any statistical evidence that a too large homogenous reed distribution would be detrimental to pike abundance. The method only target pike that were in areas available for fishing and could not show if pike utilized the inner parts of the reed beds. Pike may face a lower limit of reed coverage in order to have habitat protected from wind and waves to create a habitat that has enough submerged substrate to benefit survival and growth. Inferred from the ReFisk dataset a lower threshold for how much reed there must be in a bay to sustain a pike population is around 5000 square-meters ($10^{3.7}$ m^2 in Fig. 10) in the present state of the Baltic Sea. With more reed, pike abundance varies greatly between bays but have a stable occurrence (Fig. 10). Similar to reed area, reed perimeter also shows a lower limit at around 2500 m, above which a more stable pike occurrence was found (Fig. 9). This result should be considered as a minimum target guideline for reed management in coastal bays.

From this study from coastal bays around Stockholm archipelago, it is difficult to separate the positive effects of reed area and reed perimeter on pike abundance but the result clearly shows a need of reed for pike in these bays. It is interesting that total amount and perimeter of reed explain more variation in abundance of spawning pikes than percentage coverage or perimeter in relation to shore-length. This suggests it is total amount/perimeter of reed that is most important. As habitat selection differs with body size of pike, reed may have a positive influence for larvae and small pike that become recruits into the sampled adult pike populations since reed is important as spawning and nursery habitat for pike. Alternatively, large bays in general can host denser populations of spawning pikes. However, no maximum abundance of reed area or perimeter was found. Once the lower limit is reached, the spawning population may be too small in order to sustain pike, while above this limit abundance may be a matter of spatial and feeding resources needed for pike.

Reed cutting may create more complex structures that should have a positive effect on small pike since they mainly utilize reeds until the pike reach 15 cm in length (Casselman & Lewis 1996, Vuorinen *et al.* 1998), but anglers from the Refisk project have also witnessed pike larger than 15cm in the reeds. If reed density decreases from cutting, then the cut reed habitat may have a positive effect on pike in length sizes above 15 cm. These cut reed habitats may benefit pike populations by creating a more heterogeneous environment. In my study at the reed cutting area I could unfortunately not make any conclusions about reed complexity due to too little data.

If the reed cutting is repeated over many years, reed will be excluded from the cutting area, which has not happened yet in the reed cutting sites I studied as they were cut for the first time in August 2019. In the managed bays around 4 ha of reed will be removed after cutting the management project will be terminated 2021. Based on the spatial comparison of the 24 Refisk bays this reed reduction is predicted to decrease pike abundance. On the other hand, the reed perimeter is predicted to be similar or even increase due to cuts of lanes in homogeneous reed belts in this area (Fig. 4), which could mitigate potential negative effects or even increase the pike abundance. If the pike abundance would continue to be low and the reed abundance in the bay would be below the limit after harvesting in 2021, then the abundance of reed may be more important for pike than the heterogeneity of reed belts. Future studies from this area will provide data on how reed area and perimeter influence pike abundance.

Future studies should also try to separate influence of reed area and perimeter on pike, by onsite do transects sampling with density of reeds along with categorizing reed-beds based on their density-characteristics. This way there will be a higher spatial resolution of characteristics in bays. In this study, density of reed (Stems/m^2) was not available, and therefore not included as a factor, but is something that should be considered. It should be tested if there is a difference between dense and

Figure 16. Photo of reed belts with different density and characteristics due to cutting the previous year. From the Västerbyfjärden bay at Gräsö. Photo by Niklas Niemi.

scattered reed-beds for pike. Reed can have a variety of density and shape of belt growth (Fig. 16). Therefore, categorizing and quantifying different types of reed bays along with pike CPUE may provide additional information on how pike respond to variation in reed density- and reed belt size characteristics. This was not tested in this study as it was not planned before this study and as field time was limited. Furthermore, future studies should study if pike sizes above 15 cm utilize cut reed more or if they used untreated reed equally, and study if cut reed benefits pike with increased growth.

4.2. Other fish species

Apart from pike, roach abundance also showed a significant positive correlation with reed coverage, even though pike and roach abundances were not significantly correlated. These two species seem to have a similar “scenopoetic niche” (Hutchinson 1978) in reed bays where the abiotic factors differ from surrounding archipelago. In the reed bays roach is a main prey of pike (Jacobson *et al.* 2019) and a higher abundance of roach is likely positive for pike. Instead pike abundance showed a positive correlation with perch abundance (Table 3), and increasing temperature seems to be beneficial for both species (Fig. 11, Hanson *et al.* 2017) since they are utilizing the same type habitats. Bays with more reed usually have a lower salinity and higher temperatures (Kallasvuo *et al.* 2011, Kallasvuo *et al.* 2009), but also the reed bays contain high abundance of plankton and sediments for roach to search for food in (Fig. 12). Therefore, both species may have higher recruitment and abundance in these bays.

Roach showed significant associations with all reed perimeters and stable abundance even in as low reed coverage as 3% of a bay (Fig. 12). Roach may need only low abundance of reed in order to have a suitable habitat. The reed is a hydrophyte, so perhaps the sediment substrate is mainly needed, and increased reed abundance then shows more positive effects.

Perch and roach showed weak positive correlation (Fig. 7), and in a study by Persson *et al.* (2007) in lake systems they showed that roach is more likely to coexist with perch when pike are present. In these lakes, both roach and pike had successful recruitment but suppressed each other with competition and predator/prey interactions (Persson *et al.* 2007). Even though the study was from lake ecosystems it still indicates pike also in the archipelago may facilitate roach and perch coexistence, since pike selectively prey on perch (Persson *et al.* 2007). Therefore, perch may explain more variation of pike CPUE than other fish species even though the additional explanation is weak, but the presence of pike may explain the positive correlation of roach and perch.

Both perch and roach abundance showed a significant positive relationship with temperature. As both species are warm water adapted species, the water temperature at fishing affect abundance in catch since their movement into warmer areas increase, which could partly explain higher abundance of these species in warmer bays. Increased abundance of pike does not reveal any top down effect on perch and roach (Fig. 7) but rather positive correlations instead of negative. A negative correlation was found for three-spine stickleback and pike abundance (Fig. 7) that could be due to stickleback predation on pike larvae (Eklöf *et al.* 2020, Nilsson *et al.* 2019) although predation effects are hard to show it still may be a factor. The negative correlation between pike and stickleback abundance may also reflect their different responses to wave exposure (Fig. 8, 13). Larger pike feed on sticklebacks (Jacobson *et al.* 2019) and stickleback feed on pike eggs and larvae (Nilsson 2006), resulting in predator-prey interactions shifts across their life cycles. Nilsson (2006) showed that egg predation from several species resulted in poor pike recruitment. The high abundance of stickleback may have such an effect on pike recruitment; and wave exposure may indicate if a pike spawning area have high egg predation.

4.3. Wave exposure and Jetties

Wave exposure and jetties showed negative correlation with pike abundance, however, this was only statistically significant for wave exposure. Boat traffic can affect habitats and change vegetation composition (Hansen *et al.* 2018), consequently impacting pike abundance. Species that occur in vegetated areas are often negatively impacted by boat traffic and other human activities, while species that are less prominent to vegetation are less influenced (Sandström *et al.* 2005). Sandström *et al.* (2005) concluded that pike YOY is negatively impacted by boat traffic and human activities that change vegetation structure and diversity.

Considering that pike were more abundant in the archipelago two-three decades ago (Olsson 2019), then changes in wave exposure is unlikely to be the main factor for this negative trend, but rather a factor that has changed more over time that affects pike abundance negatively.

In contrast, three-spine stickleback showed a positive response to a wave exposure. Therefore, there is a transition zone from pike abundant water to more stickleback dominated waters. This was also found in several studies for YOY pike and adult pike but in comparison between inner and outer archipelago (Lehtonen *et al.* 2010, Kallasvuo *et al.* 2009). Wave exposure increases towards the outer archipelago and therefore this result strengthens the conclusion by Kallasvuo *et al.* (2009) that there is a pike abundance gradient from outer to inner archipelago related to variation in food abundance, temperature and salinity. This shift between pike and sticklebacks appears to occur at wave exposure around 3.3-3.5 (Fig. 8, 13). Bergström *et al.* (2015) also found a negative correlation between abundance of pike/ perch and abundance of stickleback (cf Fig. 7).

Since pike is an ambush predator the effects of heterogenous reed management may benefit pike with suitable ambush structures in the reeds out into open water. Changes in reed structure may also affect stickleback and therefore, interactions between pike and stickleback. In the reed managed sites, future studies could investigate how the interaction between pike and sticklebacks are influenced by reed structure.

The stickleback population has increased over time and lead to invasions in the coastal zone during summer (Sieben *et al.* 2011). Sticklebacks feed on grazers resulting in lower abundance of grazers that leads indirectly to increased filamentous algae growth in areas with high stickleback abundance (Eriksson *et al.* 2009, Sieben *et al.* 2010, Bergström *et al.* 2015, Donadi *et al.* 2017). This effect of increased filamentous growth from stickleback may occur even without the effect of eutrophication (Sieben *et al.* 2011). Therefore, meso-predator release can lead to trophic cascades and shifts in coastal food web composition (Sieben *et al.* 2011). It is therefore important to restore top predator populations, like pike, to reduce meso-predators release in the Baltic Sea.

4.4. Recreational fishing

Pike abundance was higher in bays with spawning closure than in reference bays open to fishing (Table 1). It was not the aim of my thesis to investigate this, but closure may be a management option to conserve pike populations. However, pike faces other threats and obstacles depending on stage in life cycle. Therefore, the effect of reed, abiotic factors, human impact and other species can impact the success of pike populations. Catch and release fishing by angling has shown stress effects and can lead to mortality from air exposure and bleeding (Gingerich *et al.* 2007, Fränstam 2009), therefore catch and release may have an impact on pike reproduction success. Apart from mortality, pike can also have a short-term shift in behavior after catch and release (Klefoth *et al.* 2008, Stålhammar *et al.* 2012). Pike under high fishing pressure selected the pelagic zone more than low fishing pressure pike that selected the reed more (Klefoth *et al.* 2008). Some lures have higher mortality from hook placement (Fränstam 2009), management could prohibit some lure types. Fishing closure does have a positive effect on pike with a significant difference between treatments (Table 1) but have not been implemented on large scale and is currently not significant enough to induce positive difference for the pike populations as whole in the Baltic Sea. Hence there are other mortality factors that suppress the pike populations. However, during spring pike aggregates in shallow bays (Haugen *et al.* 2006) where they become more accessible for fisherman and therefore it would explain the pike abundance difference between treatment bays. However, the increase in pike abundance in bays with more reed may also be because it creates a barrier and shelter that makes the bays less accessible for fishermen or creates a refuge from apex predators like seals and cormorants and therefore reed reduces mortality, indicated by the significance in bay reed coverage (Table 1). Therefore, reeds may be important for reducing pressure on pike.

4.5. Reed management

The angling- based study on the effects of reed management did not produce enough data to evaluate if adult pike utilize heterogenous over homogenous reed belts and therefore the hypothesis can neither be rejected nor confirmed. As there were so few pikes caught in both the reed management area and in the reference area, it may suggest a decline in pike abundance related to other factors. In addition, the reed management is so new that it is not likely to affect total pike abundances yet.

From 2019 to 2020 pike mean length increased in all bays with fewer pike, particularly in the reed management area (Fig. 14, 15). This may indicate that in general recruitment of juvenile pike to adult pike is failing and mainly adult pike survive. A study in Nothamn in the Western part of Gulf of Finland showed that large pike could handle the decrease of natural vegetation and bladder wrack in the archipelago and grew larger at the same time as the amount of small pike decreased in the outer archipelago (Lehtonen *et al.* 2010). Therefore, it indicates that small pike need suitable vegetation to reach adult age.

Since the management project is only one years old, long-term effects that may have benefitted smaller individuals are not yet available in the angling investigation data. Therefore, studies over several years should be done in order to see the direct effects of reed management. Additionally, a juvenile investigation to see if there is a response in early year classes would also be beneficial.

There might be other macrophytes that can play a crucial role for pike. Bladder wrack (*Fucus vesiculosus*) is mainly found in wave exposed rocky littoral areas where reed does not grow and could perhaps provide shelter (Lehtonen *et al.* 2009) and increase the connectivity between habitats for pike (Englund *et al.* 2020). Bladder wrack does not support spawning, but it provides shelter for young and adult pike in outer archipelago (Lappalainen *et al.* 2008) creating suitable areas outside their core areas in the sheltered bays.

Kautsky *et al.* (1986) show a strong decline in bladder wrack from the 1970 and around 10% of bladder wrack remaining compared to previous states (Lehtonen *et al.* 2010). Since the decline in bladder wrack and pike have happened during the same time period it has been suggested to be interconnected (Lehtonen *et al.* 2010). Pike has declined in the outer areas where there used to be bladder wrack but has maintained more stable trends in inner archipelago where other macrophytes are dominant (Lehtonen *et al.* 2010).

Within a bay there are usually several types of macrophytes growing. Other vegetation types may contribute to a more complex habitat and pike utilize other areas in water depths where reed does not grow, therefore creating more habitat diversity that benefits pike, and hence overall heterogeneity in bays.

4.6. Management applications

Reed management may have potential positive and negative affects pike populations, but also for biodiversity in general. If management removes reed below the threshold, there may be negative effects, but management above that creates heterogeneity may have positive effects on pike abundance. local management actions such as restoration of wetlands, can have a large impact on pike larvae abundance. Larsson *et al.* (2015) suggest that about 50% of pike in the Baltic Sea are born in fresh-water but as a management action it is limited geographically to some suitable location (Larsson *et al.* 2015) and only provides a spawning habitat but no suitable habitat for growth and survival as a habitat restoration would. Reed management, in contrast, can be implemented in many areas along the Baltic Sea coast, but also in other aquatic environments where reed is dominant.

Still reed management needs to be studied more to understand its effects before large-scale application. Management of reed still can have positive effects on biodiversity and decreasing the spread of reed at a rate that pike cannot utilize. Yet this study concluded that a minimum of 0.5 hectare and a minimum reed perimeter of 2500 m of are needed in bays for more stable occurrence of pike. Below these limits pike abundances are unstable.

Vegetation complexity utilization for pike decreases with size and pike larger than 15 cm requires increased water depth and substrates on other water depths than what reed grows on. Substrates other than reeds should be considered for a suitable habitat. Still, reed plays a crucial role for adult pike during spawning and perhaps even over other parts of their life cycle since data is limited on pike interaction with reed. Reed should be maintained as important spawning and nursery habitats but also above the reed limit for population stability.

Since the abundance of pike is declining in the Baltic Sea, studies should also find which stages in the pike life cycle that has the highest mortality that effects population growth and where efforts should be directed in order to get population growth for reestablishing historic normal levels. Reed management shows positive effects for biodiversity, but the effects of reed management on fish in general and pike in particular are still unclear, and at which life stages it may have an effect.

As pike populations are declining in the Baltic, these inner bays with reeds belts are needed for maintaining the species. By improving habitats and finding management actions such as reed cutting, the pike conservation may even be improved.

5. References

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