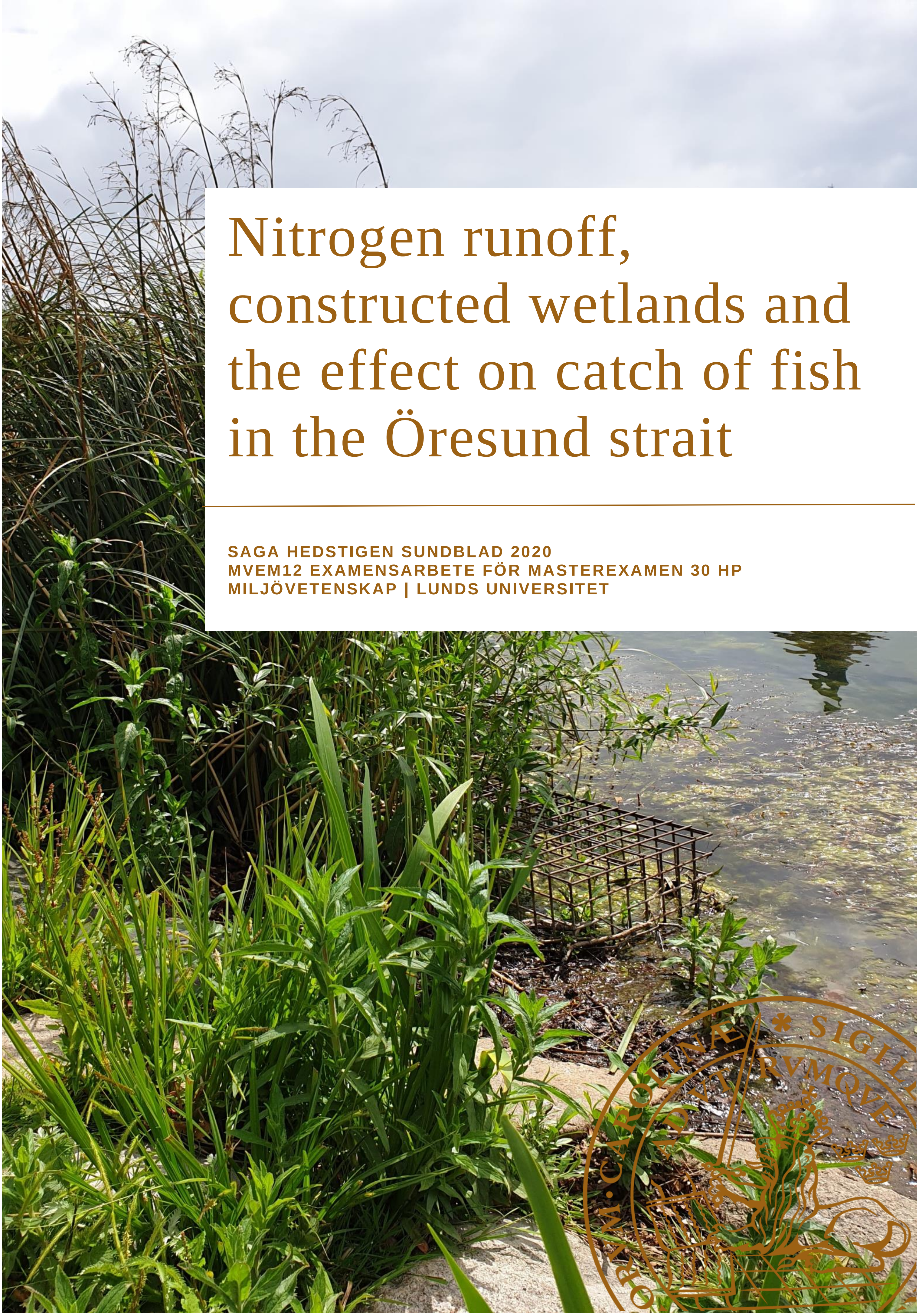

Nitrogen runoff, constructed wetlands and the effect on catch of fish in the Öresund strait

SAGA HEDSTIGEN SUNDBLAD 2020
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Spring wetland in Scania. Own photography.

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MVEM12 Examensarbete för masterexamen 30 hp, Lunds universitet

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Abstract

Eutrophication and low dissolved oxygen levels are spreading all over the world, causing changes in fish distribution and decline in fish abundance and catch of fish. This study assesses the current nitrogen (N) surface runoff to the Öresund strait, the seafloor oxygen demand it cause, the subsequent effect on fish catch, and the constructed wetland area needed to retain current N loads. This is assessed using a nitrogen; phytoplankton; zooplankton; detritus (NPZD) model and historical N load and fish catch data. N loads to the Öresund strait have steadily decreased since 1995 as the total annual fish catch declined with 77% between 1997 and 2017. The results show no negative correlation between annual N load and annual fish catch, instead a positive correlation can be seen for catch of benthopelagic species and total catch. The annual average oxygen demand produced by surface runoff N loading is equivalent to 0.37 $m\ell\ \ell^{-1}$. No conclusion can be drawn that current N loads cause hypoxia or have a negative impact on fish catch in the Öresund strait. The diminishing fish catch can instead be explained by lowered fishing quotas due to environmental status and declining fish populations in adjoining basins.

Keywords: seafloor oxygen demand; fish catch; constructed wetland

Populärvetenskaplig sammanfattning

Fisket i Öresund är en stor ekonomisk källa för både Danmark och Sverige som årligen omsätter runt 570 miljoner SEK. Fiskfångsten i Öresund har kraftigt minskat de senaste decennierna, och mellan 1997 och 2017 gick den totala fångsten ned med 77%. Studiens resultat visar dock att dagens kvävebelastning på Öresund har ett positiv samband med den totala fiskfångsten, vid ökad kvävetillförsel ökade även fångsten. De minskade fiskfångsterna beror till stor del på de reducerade fiskekvoterna för framförallt sill och torsk till följd av de dåliga ekologiska förhållandena i Östersjön. Resultaten visar även att kvävebelastningen genererar en relativt låg syreåtgång och kan därför inte anses ha någon direkt negativ effekt på syrehalterna på havsbotten i Öresund. De åtgärder som tagits för att minska kvävebelastningen genom t.ex. anläggning av våtmarker och kontrollerad gödning inom jordbruket har gett goda resultat.

Tillförsel av näringsämnen som kväve och fosfor ökar tillväxten av alger som till en viss gräns kan medföra en ökad produktivitet med hög tillgång av föda för fisk och andra marina djur. För höga halter orsakar istället övergödning med giftiga algblomningar och döda bottnar som följd. Övergödning i hav och sjöar är ett aktuellt globalt problem och utbredningen av döda bottnar och minskade fångster av fisk och skaldjur ses över hela världen. Östersjön omfattas av the Baltic Sea Action Plan med tydliga mål att minska övergödning och återställa balansen med en god ekologisk status och en hälsosam fiskpopulation i Östersjön samt de danska sunden.

Anläggning av våtmarker är ett funktionellt sätt att fånga upp kväve från t.ex. jordbruk och reningsverk och på så sätt minska den mänskliga påverkan i hav och vattendrag. I våtmarken kan kvävet reduceras genom upptag och skörd av växter eller via frigivning av kvävgas som bildas under denitrifikation i sedimenten. För att genomföra kostsamma anläggningar av våtmarker eller andra gynnande förändringar i landskapet krävs finansiering, ofta från kommuner, landsting eller andra myndigheter. Genom att dra paralleller mellan kvävebelastning och ekonomiskt kvantitativa resurser t.ex. fiske, kan man ta fram ett tydligt och direkt underlag för politiker och andra intressenter. Detta kan ses som ett enkelt sätt att se möjliga vinster eller förluster, inte bara för naturen utan även för människor och myndigheten själv.

I detta arbete har en enkel metod använts för att göra en grov uppskattning av det syre som krävs för nedbrytning av organiskt material på havsbotten genererat av det tillförda kvävet från land. Det beräknade syrebehovet kan sedan användas för att ge en översikt över risken för syrebrist på havsbotten. Studien har även analyserat sambandet mellan landbaserad kvävetillförsel och fiskfångst i Öresund med linjär regression för att utvärdera kvävets påverkan på fisket. En kostnadsberäkning har även gjorts för anläggning av våtmark som krävs för att minska kvävebelastningen från land med ytterligare 30%.

List of Abbreviations

BSAP	The Baltic Sea Action Plan
HELCOM	The Helsinki commission
ICES	The International Council for the Exploration of the Sea
N	Nitrogen
NPZD	Nitrogen, phytoplankton, zooplankton, detritus analysis
SMHI	The Swedish Meteorological and Hydrological Institute
SOD	Seafloor oxygen demand
SSB	Spawning stock biomass

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Introduction

The United Nations Sustainable Development Goal number 14 "*Conserve and sustainably use the oceans, seas and marine resources for sustainable development*" aims to achieve healthy and productive seas and oceans with resilient ecosystems and a significant reduction of marine- and nutrient pollution by 2025 (United Nations, n.d.). As it pertains to the Baltic Sea, the Baltic Sea Action Plan (BSAP) aims for good ecological status by 2021. Through significant reductions in nutrient pollution and fishing regulations, the Baltic Sea should reach natural levels of oxygen and algal blooms and an environment sustaining a diverse and balanced ecosystem (HELCOM, n.d.).

Eutrophication and Hypoxia

Eutrophication of marine and freshwater systems is an important issue globally. Population growth with increasing nutrient inputs from cities, industries and agriculture cause a higher primary production, an influx of organic matter to the sea floor and oxygen depletion (Kalff, 2002; Temino-Boes, et al., 2019; Chu & Tunnicliffe, 2015). Primary production is driven by temperature, light, and nutrient availability often with nitrogen (N) as the limiting factor in marine waters (Wroblewski, 1977; Vahtera, et al., 2007). Lower oxygen levels alter nutrient cycles limiting the removal of gaseous N_2 into the atmosphere as N is stored in the sediment during hypoxia (Jäntti & Hietanen, 2012). Under anoxic conditions sediment bound ammonia, ammonium and phosphorous may be released into the water column which can lead to more primary production and increased water column and seafloor oxygen demand (SOD) as a consequence (Havs och vattenmyndigheten, n.d.; Vahtera, et al., 2007; Diaz & Rosenberg, 2008; Diaz & Rosenberg, 1995; Chu & Tunnicliffe, 2015).

Hypoxia, defined as dissolved oxygen concentrations < 2 mℓ ℓ^{-1}, is caused by a decrease in oxygen when the supply does not meet the biogeochemical demand (Conley, et al., 2009; Chu & Tunnicliffe, 2015). Hypoxia can be episodic, periodic, or persistent, the latter defined as anoxia. Hypoxia is a natural occurring event but as the anthropogenic release of nutrients into water systems has increased, so has its spread and intensity. The most common hypoxia occurs after the spring bloom in warmer waters when stratification is the strongest in summer and autumn (Chu & Tunnicliffe, 2015). Oxygen levels in the oceans have decreased by an estimated 2% over the last 50 years as hypoxic zones have increased all over the world (Diaz & Breitburg, 2009; Breitburg, et al., 2018). Hypoxia is also strongly influenced by climate, stratification, and water circulation (Peña, et al., 2010). The major negative effects hypoxia can have on marine ecosystem includes loss of habitats and physiological stress, leading to benthic fauna and fish mortality, and changes in community assemblages (Ibid.; Wu, 2009). Studies show a gradual decrease in biodiversity during the first weeks of hypoxia before the community finally collapses (Conley, et al., 2007). As bioturbation and vertical transportation are highly influenced by species composition and abundance, changes can lead to a decrease in oxygenation of deeper waters and enhance remineralization and seafloor oxygen consumption causing longer and more severe hypoxia (Conley, et al., 2009; Breitburg, et al., 2018).

Oxygen levels naturally fluctuate in marine environments and most fish species are adapted to or can acclimatize to hypoxic events (Wu, 2009; Breitburg, et al., 2009). However, hypoxia can have a negative impact on fish abundance and distribution. Low oxygen levels may affect growth and cause reproductive and behavioural changes in individuals. Spawning can be hindered in stratified basins for species like cod, which need high salinity for their eggs to be buoyant (Diaz & Breitburg, 2009; Wu, 2009; Breitburg , et al., 2009). Loss of habitat and benthic prey can cause a shift in the predator-prey balance and a change in the community impact (Chapman & Mckenzie, 2009). Alterations in fish distribution is common as fish migrate when hypoxia occurs and return when oxygen levels have gone up again. A large part of the reduction in fish biomass during hypoxia can be explained by fish migration (Kjerulf Petersen & Pihl, 1995). During long term hypoxia, lasting for months, mass mortality and loss of almost all macrofauna often occurs (Diaz & Rosenberg, 1995).

Wetlands

Both natural and constructed wetlands have vast potential of retaining N and other nutrients and pollutions from surface water and adjoining water bodies. Studies show great variability in nutrient retention efficiency, influenced by hydraulic load and wetland size and depth (Johannesson, et al., 2015). Permanent reduction of N in wetlands can only occur through harvesting of vegetation or by emission of gaseous N_2 and N_2O, the latter in low oxygen environments, through denitrification and ANAMMOX, anaerobic ammonium oxidation (Steidl, et al., 2019; Tournebize, et al., 2017). Denitrification is highly influenced by temperature and can imply a strong seasonal variation in colder climates like Scandinavia.

Tournebize et al. (2017) found in a study looking at 34 wetlands that the average nitrate retention efficiency was 42% in a constructed wetland compared to >65% in a natural occurring one. The higher retention efficiency in a natural wetland is supposedly due to the more stable environment and higher vegetation diversity.

Implementation of costly constructions of wetlands or other beneficial landscape alternations demand financing, often from municipalities, counties, or other governments. Presenting direct and indirect links between ecosystem services and economically valuable goods, such as fish or timber, give politicians and other stakeholders a clear and simple basis to see the gain or loss of these types of investments, not only for nature but for humans and the authorities themselves.

The Öresund strait

The Öresund strait, the strait between Zealand, Denmark and Scania, Sweden, runs from the saline Kattegat Sea in the north to the brackish Baltic Sea in the south (Fig. 1). The 4,500 km^2 catchment area inhabited by 4 million people extends across Scania in the east and the eastern part of Denmark in the west (Øresundsinstituttet, 2019; Øresundsvandsamarbejdet, n.d.). The basin depth varies from about 10 m in the outer parts to 30-50 m in the middle. Strong currents caused by river inflow, wind, and atmospheric pressure transport brackish surface water from The Baltic Sea north towards Kattegat while the deep-water streams bring saline water from Kattegat southward. This gives a salinity of approximately 9 ppm in the shallower areas and a salinity up to 34 ppm in the deeper parts with a halocline at 10-12meter depth. (Øresundsvandsamarbejdet, 2018; Øresundsvandsamarbejdet, n.d.). The unique environment composed by sandy bottoms, clay filled deep holes, rock walls, eel grass (*Zostera marina)* meadows and seaweed accumulations is home to a rich sea life. The Öresund strait is an important basin for both commercial and sports fishing of e.g. Atlantic cod (*Gaus morhua*) and Atlantic herring (*Clupea harengus)* (Lunds Tekniska Högskola , 2015). Between 2008 and 2017 an average of 4,164 tonnes of fish was caught per year in the Öresund strait (ICES, 2019 (a); ICES, 2019 (b)). Bottom trawling has been forbidden in the Öresund strait since 1932 which has resulted in a higher amount of older and bigger individuals than surrounding basins, and a fish production 100 times higher than in Kattegat (Naturskyddsföreningen, 2016). The environment in the Öresund strait has been and is still physically disrupted by human activities like dredging and cities expanding beyond the shoreline (Rambøll, 2018). The total turnover from fishing, commercial and angling, in the Öresund strait amounts to an estimated 401 mil. DKK, approximately 570 mil. SEK, annually (Øresundsvandsamarbejdet, 2018). The first widespread hypoxic event in the Öresund strait and surrounding basins was reported in 1981. Changes have been seen in macroalgal distribution and an increase in drifting algae and algal blooms. Seasonal hypoxia occurs in some deep areas during late summer and autumn (Karlson, et al., 2002). 2007, the BSAP set a target of reducing N loads to the Danish straits with 15000 tonnes N, equivalent to 33% of total N input (HELCOM, 2007). A similar target was set by The Swedish environmental objectives, sub-target nr. 3 “*No eutrophication*”, to reduce N load with 30% from 1995 to 2010 (Naturvårdsverket, 2003). Both these targets have been met.

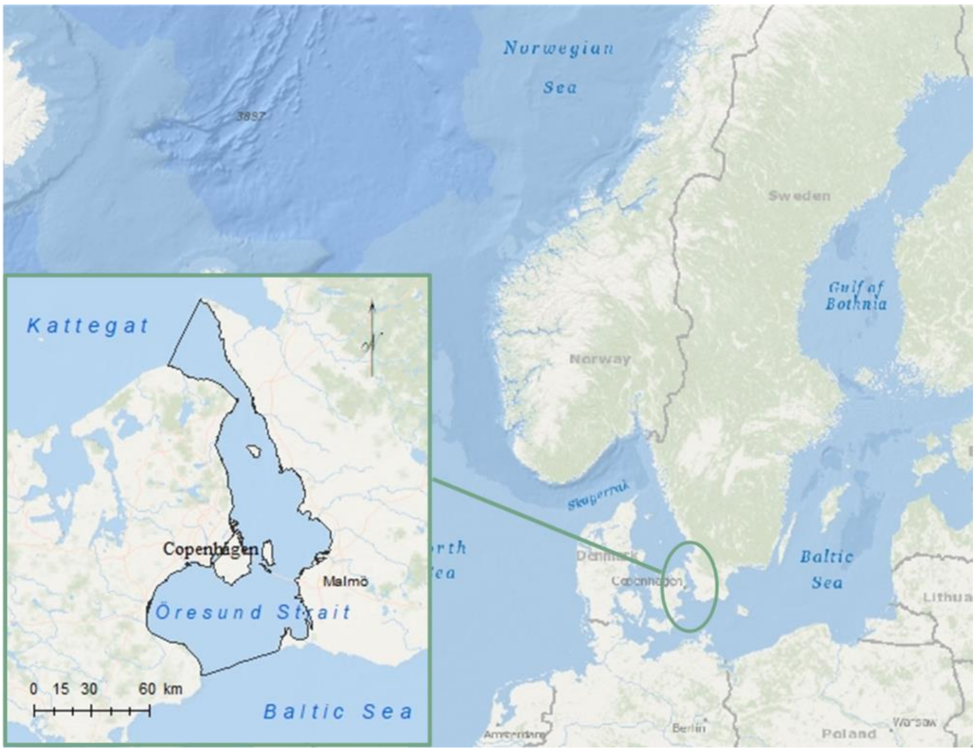

Figure 1
Map of the Öresund strait, constructed in ArcMap 10.5.1.

Purpose and research questions

This study aims to investigate the extent of N runoff to the Öresund strait in southern Scandinavia, and the potential impact this leakage has on commercial fish catch. This study will research the required areal of constructed wetlands needed to retain the N load. Since construction of wetlands imply a cost for the stakeholders, the purpose of this study is to find an indirect connection between N retention by constructed wetlands, the marine fish production, and a possible economical gain.

- How much is the current N runoff to the Öresund strait?
- What areal constructed wetland is needed to decrease N runoff with 30% and what would it cost to construct?
- How much is the SOD caused by the total amount of N runoff?
- What impact does the total amount of N runoff have on commercial catch of fish?

Demarcations

This study focuses on N impact on fish in the Öresund strait. Only data measured and registered in the Öresund strait has been processed. The calculated N input to the Öresund strait is limited to runoff from land, therefore atmospheric deposition is not included. Due to time limitations, all concentrations and quantities are based on average values for the Öresund strait as a whole unless other is stated. For this study to be applicable for Helsingborg Stad, wetland retention and costs are based on numbers from the municipality of Helsingborg.

Method

The study began with a comprehensive review of the current relevant literature, followed by the collection and compilation of relevant data from the Öresund strait. A model was then put together to determine SOD generated by N runoff. Finally, an evaluation of the relationship between catch of fish and N runoff was made.

Nitrogen runoff and wetland calculation

Concentrations of N, dissolved oxygen, and chlorophyll for the years 1997-2017 was collected from the International Council for the Exploration of the Sea (ICES) Baltic Sea monitoring data from stations listed in table 1 (ICES, 2020).

Data of annual runoff and nutrient input to the Öresund strait was retrieved from the Swedish Agency for Marine and Water Management (Havs- och vattenmyndigheten) N input to the coast statistics, (Havs och vattenmyndigheten, 2018), and the Ministry of Environment and Food of Denmark (Miljø- og Fødevareministeriet) surface water database (Miljø- og Fødevareministeriet, 2019), through the search, Stofafstrømning – Vand/stofafstrømning – Marinreference: Øresund, beregningsår: 2019.

N uptake efficiency of constructed wetlands was based on wetlands constructed by Helsingborg Stad during the period 1999 – 2002 with an average uptake efficiency of 8% and reduction of 541 kg N ha^{-1} $year^{-1}$. The wetland Bulls Måse is not included due to its large surface area and low N load, which makes it not applicable for the purpose of this study (Persson, et al., 2005).

For the purpose of this study further desirable N reduction was set to 30% of the average annual N load between 2010 and 2018. This was based on the former goals of Swedish environmental objectives, 30% reduction, and BSAP, 33% reduction due to lack of more recent numerical guidelines (Naturvårdsverket, 2003; HELCOM, 2007). The construction cost of 1 ha 10 000 m^3 wetland is estimated to be between 545,000 and 650,000 SEK, not including eventual permit costs, according to prices provided by Johan Krook[1]. The total area needed, and the

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[1] Johan Krook, Biologist, Ekologigruppen, E-mail 6 February 2020.

construction cost was then calculated according to figure 2 based on N runoff presented in figure 5.

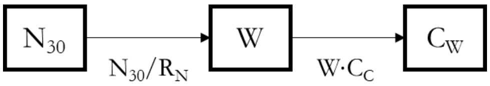

Figure 2
Model used to calculate area and cost of needed constructed wetland. N_{30} = 30% of annual total nitrogen load, R_N = average nitrogen retention for constructed wetlands per ha and year, W = wetland area, C_C = Construction cost of 1 ha wetland, C_W = Total wetland construction cost.

Table 1

HELCOM stations name, latitude degrees north, longitude degrees east and depth used to retrieve total nitrogen, chlorophyll and dissolved oxygen concentrations in the Öresund strait presented in figure 4 (ICES, 2020).

Station name	Latitude ° North	Longitude ° East	Depth (m)
171	56.1544	12.3449	25
BF27	55.9767	12.6200	22
DMU 436	55.5550	12.7550	12
FRB9070	55.9243	12.6375	31
KBH 431	55.8667	12.7500	49
KBH1723	55.5902	12.4077	6
KBK KA3	55.8322	12.5903	11
KBKSOEV	55.5697	12.7072	8
KULLEN	56.2333	12.3700	26
MCR230010	55.9682	12.5660	14
MSJ240025	55.5436	12.2558	7
N Öresund 1	56.0942	12.5903	29
N Öresund 3	56.2170	12.4079	26
N Öresund 4	56.1433	12.5016	27
N Öresund 6	56.2646	12.4446	10
NSJ230016	55.8268	12.7002	25
NSJ240022	55.5196	12.6624	12
OVF 4 9	55.7017	12.8808	16
ROS1727	55.4893	12.4207	14
Råå Hamn	55.9905	12.7455	34
Södra Öresund 2	55.8193	12.7399	53
Södra Öresund 3	55.7411	12.8877	17
Södra Öresund 4	55.7979	12.8291	20
ÖRES-2	55.5542	12.7583	11
ÖRES-4	55.6467	12.9550	15

Biogeochemical and fish catch analysis

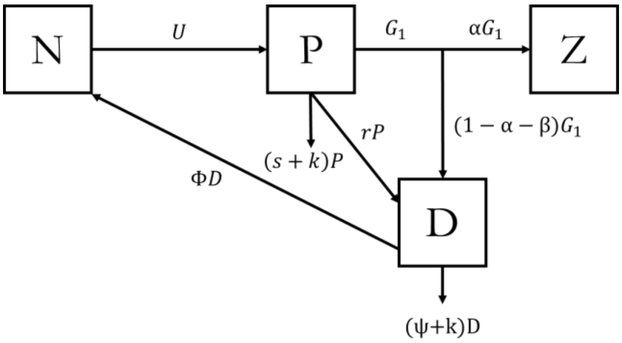

Figure 3

Transportation of nitrogen (N) through interactions of phytoplankton (P), zooplankton (Z) and detritus (D). Downward open arrows indicate loss of N to bottom layer. Remade from Edwards (2001). Used parameters are presented in table 2.

A nitrogen, a sum of Nitrate, NO_3 and Ammonium, NH_4, phytoplankton zooplankton and detritus (NPZD) model was used to demonstrate flow of N and estimate how the N loadings may influence phytoplankton growth and SOD in The Öresund strait (Fig. 3). The phytoplankton uptake, U, is calculated in equation 1 and the zooplankton grazing, G_1, in equation 2 (Edwards, 2001).

$$U = \frac{N}{k_N + N} \cdot \frac{aP}{k_w + cP} \tag{1}$$

$$G_1 = \frac{\lambda P^2}{k_Z^2 + P^2} Z \tag{2}$$

The chlorophyll (chl) to N ratio was calculated according to equation 3 where the intercepted photosynthetically active radiation, I_{PAR}, was estimated from global shortwave irradiance, I_{sw}, as $I_{PAR} = 0.43\ I_{sw}$ (Doney, et al., 1996; Möttus, et al., 2011).

$$chl{:}N = chl{:}N_*^{max} - (chl{:}N_*^{max} - chl{:}N_0)\, {}^{I_{PAR}}/_{I_*} \tag{3}$$

Mean monthly values for I_{sw} were calculated from measurements at station Lund Sol, station number 53445 for 2008-2020 retrieved from the Swedish Meteorological and Hydrological Institute (Sveriges meteorologiska och hydrologiska institut) (SMHI) meteorological observations data website (SMHI, 2020), n = 108336. The chl:N ratio was calculated for all 12 months and an average was then used in the model. Phytoplankton, zooplankton, and detritus was then calculated under the assumption of constant ratios of chlorophyll to phytoplankton 1.59, zooplankton/phytoplankton 1/10 and detritus/phytoplankton 1/1.42. All concentrations were converted into g C m^{-3} using the conversion: 1 g C ≡ 20 mg chl ≡ 10 mmol N (Edwards, 2001). The flux of detrital N was converted to SOD using the O_2/C ratio of 138/106 (Liu, et al., 2015). Used parameter values are listed in table 2. Annual SOD was then calculated using N concentration retrieved from SMHI water Webb model data (SMHI, 2020), by areas presented in table 3. Annual SOD $m\ell\ \ell^{-1}$ was calculated using the annual total water runoff presented in figure 5. Concentration data could only be retrieved with one common value for Nitrite and Nitrate, thus only data from Swedish inputs have been used in the model.

A regression analysis was made using Microsoft Excel (version 12430.20184) to identify a possible relationship between annual N loadings and fish catch in the Öresund strait. Fish catch statistics were retrieved from ICES database “Catch Statistics” for FAO are 27.3.b.23 and log. transformed. All <0.5 values have been counted as 0.5 and species with only one <0.5 from 1997-2005 have been excluded (ICES, 2019 (a); ICES, 2019 (b)). Only demersal, benthopelagic, pelagic and pelagic-neritic fish species have been used in this study. Pelagic and pelagic-neritic species will from here on in be collectively referred to as “pelagic”. The species classification was made using fishBase (FishBase, 2019). Species and classifications are listed in table 4 appendix 1.

Table 2

Parameter values used in the NPZD model.

Parameter	Description	Value	Reference
I^*	Critical irradiance for photoadaptation	90 W m^{-2}	(Doney, et al., 1996)
$chl{:}N_0$	Non-limited growth chl:N ratio	1 mg chl (mmol N)$^{-1}$	(Doney, et al., 1996)
$chl{:}N_*^{Max}$	Maximum photoadapted chl:N ratio	2.5 mg chl (mmol N)$^{-1}$	(Doney, et al., 1996)
k_N	Half-saturation constant for N uptake	0.003 g C m^{-3}	(Edwards, 2001)
a	a/b gives maximum P growth rate	0.2 m^{-1} day^{-1}	(Edwards, 2001)
k_W	Light attenuation by water	0.2 m^{-1}	(Edwards, 2001)
c	P self-shading coefficient	0.4 m^2 (g C)$^{-1}$	(Edwards, 2001)
r	P respiration rate	0.15 day^{-1}	(Edwards, 2001)
s	P sinking loss rate	0.04 day^{-1}	(Edwards, 2001)
μ	Cross-thermocline exchange rate	0.005 day^{-1}	(Edwards, 2001)
λ	Maximum Z grazing rate	0.6 day^{-1}	(Edwards, 2001)
k_Z	Z grazing half-saturation coefficient	0.035 g C m^{-3}	(Edwards, 2001)
α	Z growth efficiency	0.25	(Edwards, 2001)
β	Z excretion fraction	0.33	(Edwards, 2001)
Φ	D remineralization rate	0.1 day^{-1}	(Edwards, 2001)
ψ	D sinking loss rate	0.08 day^{-1}	(Edwards, 2001)

Table 3

Waterbody name, midpoint coordinates, maximum depth (m), area size (km^2) and volume (km^3) of the Öresund strait (SMHI, 2020). Used to compile NO_3 and NH_4 concentration runoff to the Öresund strait presented in figure 6.

Waterbody name	Midpoint coordinates	Depth (m)	Area (km^2)	Volume (km^3)
S Öresunds kustvatten	N55°28' E12°51'	9	59.41	0.29
S m Öresunds kustvatten	N55°44' E12°50'	34	141.09	2.13
Höllviken	N55°28' E12°55'	8	55.81	0.14
Lommabukten	N55°40' E12°58'	18	112.27	1.15
Lundåkrabukten	N55°49' E12°53'	20	49.92	0.35
Helsingborgsområdet	N56°2' E12°40'	39	19.34	0.40
N m Öresunds kustvatten	N55°55' E12°44'	52	128.29	2.35
N Öresunds kustvatten	N56°11' E12°30'	44	169.22	3.25

Ethical reflection

When performing scientific studies such as this one, it is important to maintain an ethical reflection throughout to highlight possible conflicts and issues that can arise from the outcome of the research. For example, when working with humans as the study or interview subject it is important to mediate clear information regarding the study and the objectives of the study. It is also crucial to present the result in a way that protects the integrity of the people involved.

For studies like this, which do not have a direct personal impact, conflicts of interest could manifest between stakeholders and other parties. The promise of financial gain can drive implementation of projects where other non-financial values can be lost. When conducting research for a client, e.g. a corporation or an organization, ethical conflicts can arise if the result does not suit the agenda of the paying party. It is then important to maintain scientific integrity and not interpret the results to suit a specific interest.

Nutrient retention efficiency in a wetland is influenced by placement and formation. A constructed wetland optimised for N retention is often not the optimum for biodiversity or other ecosystem services, which could lead to conflicts of environmental interests.

The risk of derived ethical conflicts is assessed to be relatively small and should not arise during this project or as a direct consequence of the results.

Results

Nitrogen runoff and wetland retention

The monthly average concentrations of dissolved oxygen, total nitrogen (tot-N), and chlorophyll from 1997 to 2017 is shown in figure 4. The oxygen level fluctuates throughout each year with a few episodically hypoxic events, dissolved oxygen conc. <2.0 mℓ $ℓ^{-1}$, occurring in deeper areas. Tot-N levels reached two minor peaks in March 2010 and May 2011 with a max. value of 25.6 µmol $ℓ^{-1}$. Between 2012 and 2017 the annual average N concentration increased by 3.6 µmol $ℓ^{-1}$.

N runoff from land to the Öresund strait has decreased from 12,514 tonnes in 1995 to 5,829 tonnes in 2018. Of the total N input about 82% is nitrate and 4% ammonium. 64% of total N input comes from Swedish grounds and 36% from Danish grounds. The annual N loads fluctuates with the surface water runoff (fig. 5, 6). Agriculture is responsible for 86% of the Swedish N runoff to the Öresund strait (fig. 7). Agriculture is also the largest source of N loading from Denmark, followed by industries (Baaner & Tegner Anker, 2013).

The cost per kg reduced N was calculated to 50-60 SEK with a deprecation of 20 years and the retention efficiency of 514 kg N ha^{-1} $year^{-1}$ (Persson, et al., 2005). The total area of constructed wetland needed to retain 30% of the annual average N load between 2010 and 2018 would be 2.63 ha from Sweden and 1.27 ha from Denmark and would cost 1,709,000 and 826,000 SEK respectively. A total cost of 2.53 mil. SEK. The calculation is based on the higher cost mentioned above. The input numbers are based on the average annual input from 2010 to 2018 shown in figure 5.

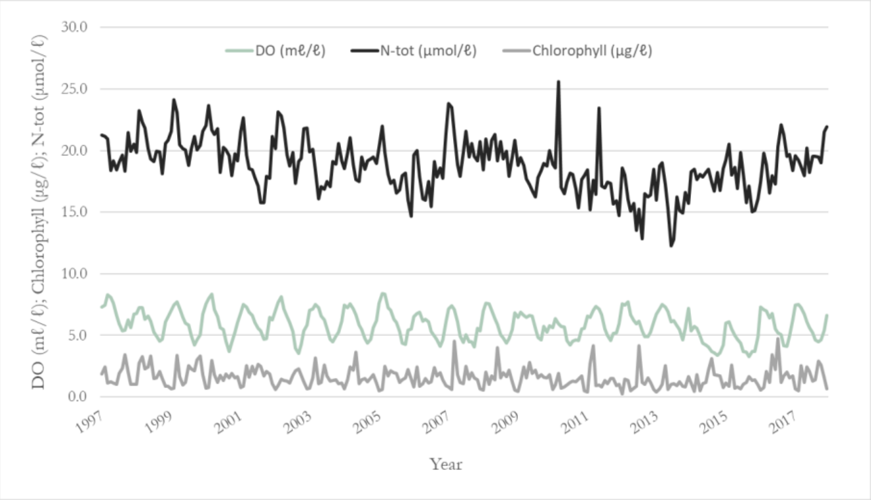

Figure 4
Monthly average concentrations from bottom samples, from top to bottom, of total nitrogen (µmol/ℓ) n = 10199, dissolved oxygen (mℓ/ℓ) n = 24751, and chlorophyll (µg/ℓ) n = 8070 in the Öresund strait from 1997 to 2017 (ICES, 2020).

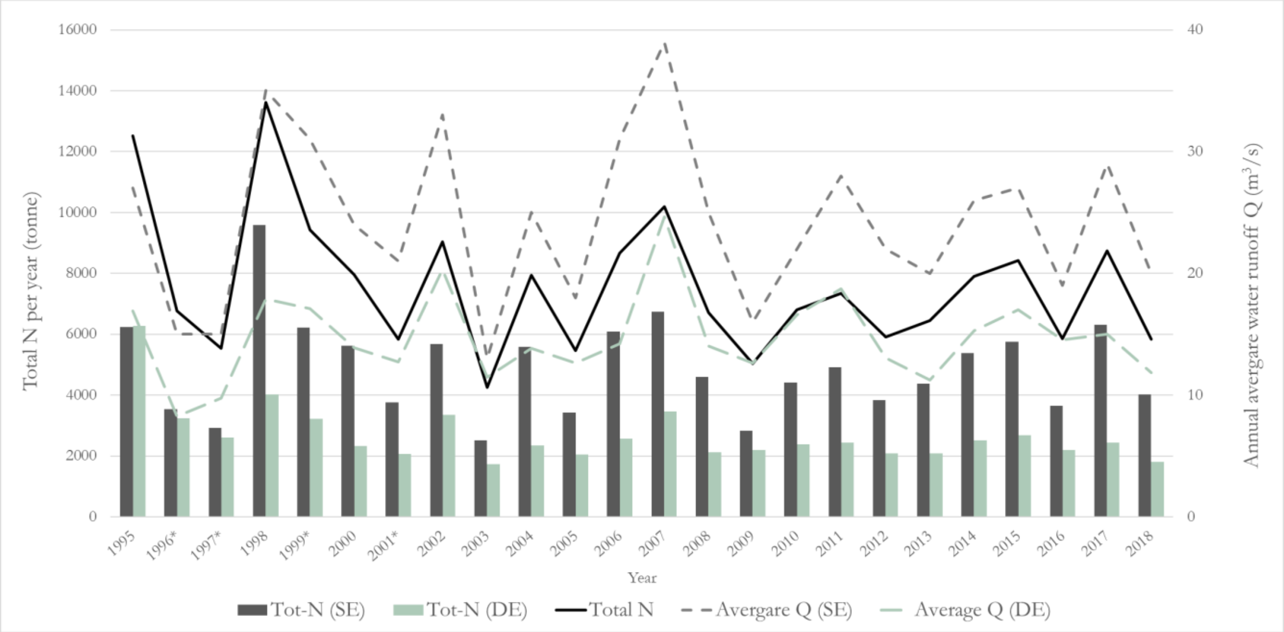

Figure 5
Annual total nitrogen loading (Tot-N) and average water runoff (average Q) to the Öresund strait from Denmark (DE) and Sweden (SE). No data is available for Tot-N (SE) from industries and wastewater treatment plants for 1996, 1997, 1999 and 2001. Average Q (DE) is calculated by total annual water flow m^3/31536000, 31622400 for leap years. (Havs och vattenmyndigheten, 2018; Miljø- og Fødevareministeriet, 2019)

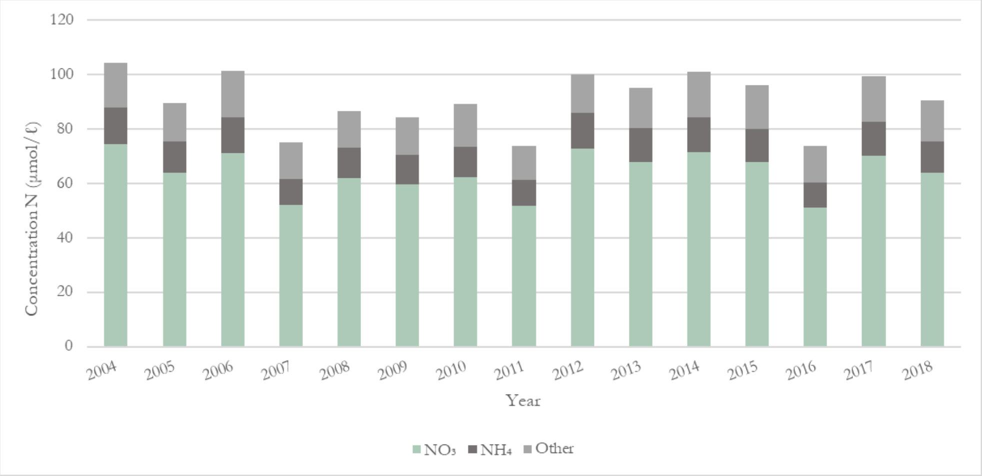

Figure 6

Total nitrogen concentration input from Sweden to the Öresund strait 2004-2018, presented fom bottom to top in NO_3, NH_4 and other (µmol/ℓ) (SMHI, 2020 (a)).

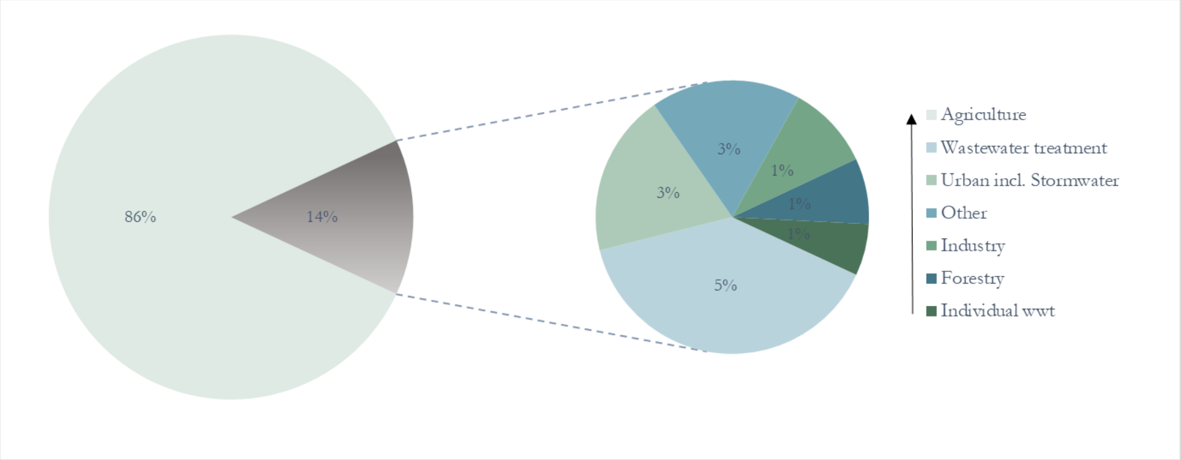

Figure 7

Source of nitrogen input to the Öresund strait from Sweden. Compiled with data from Sveriges meteorologiska och hydrologiska institut (2020 (a)).

Biogeochemical and fish catch analysis

The SOD for the years 2004-2017 calculated as mmol O_2 ℓ^{-1} is shown in figure 8. The annual average oxygen demand produced by N loadings is 0.37 $m\ell\ \ell^{-1}$ $year^{-1}$, which is equivalent to a consumption of 7 ± 3 percent of annual average dissolved oxygen concentration in the Öresund strait.

Catch of fish between 1997 and 2017 peaked in 1998 when 33,945 tonnes of fish were caught in the Öresund strait. Catch of fish has seen a major decrease for demersal e.g. European flounder (*Platichthys flesus*), benthopelagic e.g. Atlantic herring (*Clupea harengus)* and pelagic e.g. European sprat (*Sprattus sprattus*) species, 60%, 79% and 84% respectively (fig. 9).

The regression analysis shows a statistically significant positive relationship between annual tot-N loads and annual benthopelagic catch (linear regression p = 0.04 F_{17} = 4.80), and total catch (Linear regression p = 0.05 F_{17} = 4.56), where annual catch increase with increasing N loads. No statistically significant relationship can be seen for demersal or pelagic fish catch (fig. 10). Looking at the two most important species, the nonmigratory species Atlantic cod (linear regression P = 0.05 F_{17} = 4.39) and the migratory species Atlantic herring, Atlantic cod shows a statistically significant positive relationship with annual tot-N loads (fig. 11).

Figure 8

Dissolved oxygen (DO) concentrations, n = 14954, in the Öresund strait from bottom samples between 2004 and 2017 (ICES, 2020). Dashed sections mark annual seafloor oxygen consumption from nitrogen loadings. The solid line shows nitrogen produced oxygen consumption percentage of total dissolved oxygen

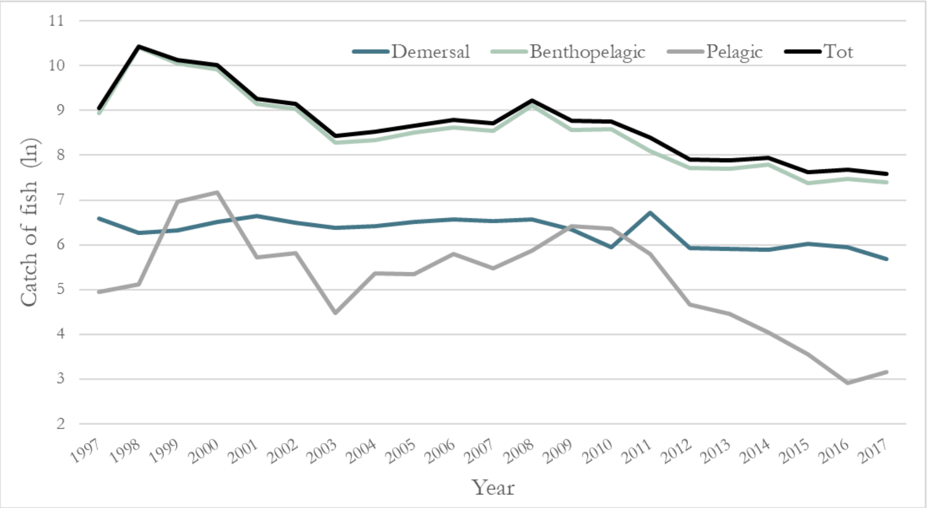

Figure 9
Log. Scale of tonnes catch of fish in the Öresund satrit, ICES area 27.3.b.23, 1997-2017. Presented by milieu, demersal, benthopelagic, pelagic species and total catch (ICES, 2019 (a); ICES, 2019 (b)).

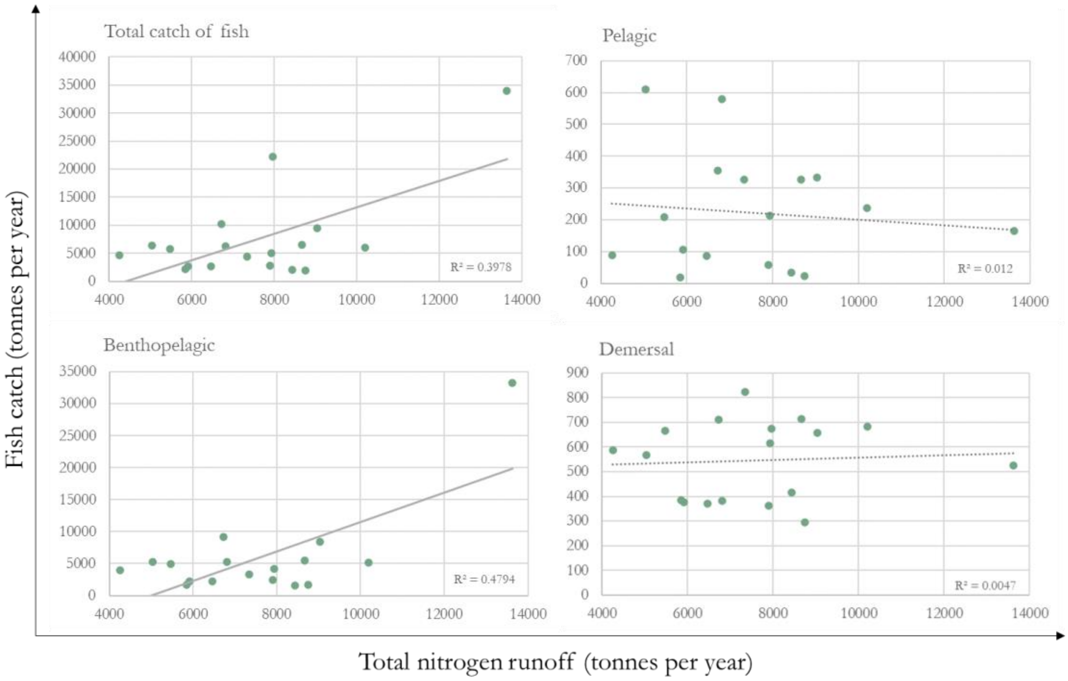

Figure 10
Linear regression between catch of fish by milieu, demersal, benthopelagic, pelagic and total catch, and total nitrogen input in the Öresund strait 1998-2017. Solid line indicate statistical significant correlation. (1999 and 2001 are excluded due to data deficienscy) (Havs och vattenmyndigheten, 2018; Miljø- og Fødevareministeriet, 2019; ICES, 2019 (a); ICES, 2019 (b)).

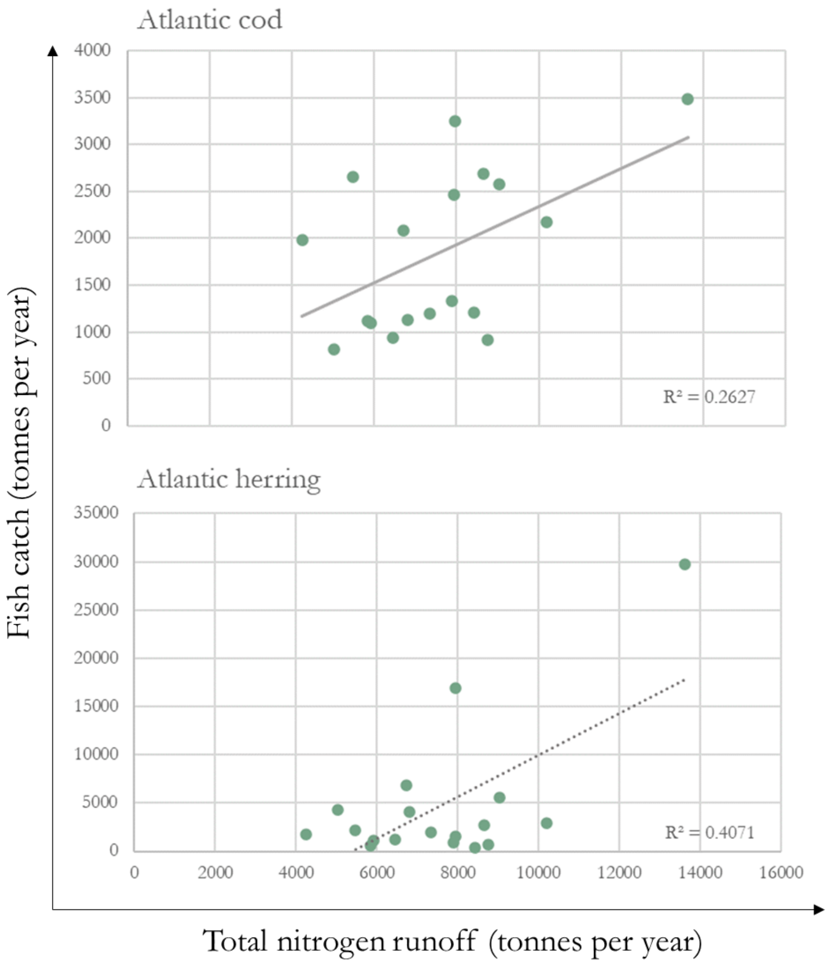

Figure 11
Linear regression between catch of Atlantic cod (*Gadus morhua*) and Atlantic herring (*Clupea harengus*), and total nitrogen input in the Öresund strait 1998-2017. (1999 and 2001 are excluded due to data deficienscy). Solid line indicate statistical significant correlation. (Havs och vattenmyndigheten, 2018; Miljø- og Fødevareministeriet, 2019; ICES, 2019 (a); ICES, 2019 (b)).

Discussion

The results suggest that current N runoff does not have a negative effect on catch of fish. Instead, the analysis shows a significant positive relationship between annual N runoff and total catch. The calculated SOD generated by N runoff is equivalent to a consumption of 7% of annual average dissolved oxygen concentration in the Öresund strait.

Annual N runoff have decreased in the last two decades to an average of about 7000 tonnes per year with the implementations of the BSAP and national regulations through construction of wetlands, more efficient wastewater treatment plants and controlled agricultural fertilization (Jordbruksverket, 2019; HELCOM, 2007). With actions taken by both Denmark and Sweden, N runoff has decreased sufficiently to meet the reduction goals set by the Helsinki commission (HELCOM) in the BSAP 2007 (HELCOM, 2007). N concentrations in the Öresund strait decreased during the early 2010s but rose to previous levels again during 2016 which can be due to higher atmospheric temperatures with N influx from other basins and atmospheric loads. Although anthropogenic N loads have decreased, sediment bound N is released from the sea floor adding to the sea concentrations (Havs och vattenmyndigheten, 2019).

To further decrease N runoff to the Öresund strait, 3.90 ha of additional constructed wetland is needed, adding up to a cost of 2.53 mil. SEK. The constructed wetlands used in this study have a relative low N retention efficiency compared to the average nitrate reduction found by Tournebize, et al (2017). Higher N-retention is more likely to occur in warmer regions and are not reasonable to achieve in Scandinavian climate. An explanation for the lower retention efficiency is that the highest N load occurs during winter when low temperatures reduce microbial activity and thus N retention (Steidl, et al., 2019).

The findings in this study show no declining effect of N loads on fish catch, which follows the findings of Breitburg et al. (2009). As is the case with the Öresund strait, ibid. also found that benthopelagic species increased with increasing N loads. With Benthopelagic species being a large part of the total fish catch from the Öresund strait, overall catch also increased with increasing N loads. A slight but statistically significant positive relationship was found between N loads and Atlantic cod catch but there was no statistically significant relationship between N loads and Atlantic herring. This is to be expected as Atlantic herring migrates to the Öresund strait from Kattegat only staying a few months in the fall before migrating further south in the Baltic Sea. Atlantic cod on the other hand, lives their whole life in the Öresund strait and are therefore directly affected by the close surrounding environment in the Öresund strait. Although N loads do not have a declining effect on fish catch in the Öresund strait, overall fish catch has declined with 77% from 1997 to 2017. Sustained hypoxia has shown to reduce fish catch due to loss of benthic flora and fauna, thus causing the loss of prey, and refuge from predators (Kemp, et al., 2005). Breitburg et al. (2009) found in their study that hypoxia has a negative effect on fishing systems in basins with hypoxia exceeding 40% of the area. The annual average added SOD of 0.37 $m\ell\ \ell^{-1}$ due to N loads cannot be concluded to have an apparent effect on the benthic ecosystem as it would take over 8 years with no oxygen influx to the Öresund strait to reach extensive hypoxic levels of dissolved oxygen. As sea temperatures rise, oxygen get less soluble and future hypoxic events could be more widespread and severe. Potential hypoxia due to rising sea temperatures should be monitored going forward.

Hypoxic events are still relatively uncommon in most of the Öresund strait. And as strong currents create a constant inflow of oxygenated saline bottom water from Kattegat, it is not feasible to assume that the decline in fish catch is caused by hypoxic events from N input nor that it will occur in the Öresund strait unless N loads increase extensively. A main reason for the decreased fish catch is the reduction in fishing quotas in the Baltic Sea region. Atlantic cod (*Gaus morhua)* and Atlantic herring (*Clupea harengus)* combined make up approximately 80% of the total fish catch in the Öresund strait. The quotas for these two species have decreased considerably, 82% and 85% respectively, in the western Baltic Sea, ICES area 22-24, since 2012 (Havs och vattenmyndigheten, 2017). Catch of the two species from the Öresund strait has gone down 83% respectively 68% from 1997 to 2017 (ICES, 2019 (a); ICES, 2019 (b)). The current ecological situation in the Baltic Sea and the collapsed cod stock has called for a drastic reduction in cod quotas in Scandinavian waters to retain a sustainable fish stock.

Another cause of decrease is the loss of habitat through dredging and cities expanding beyond the coastal line. Dredging leaves deep holes in the sea floor where organic material accumulates which through low waterflow can cause seasonal hypoxia (Olsson, 1993). The activity has been forbidden in Sweden since 1982 but is still legal and performed in Denmark. Cities expanding out beyond the coastline replace shallow sandbanks with fast increasing depths. These shallow areas are key eel grass (*Zostera marina)* habitats and important nurseries for many marine species.

To further evaluate N runoff impact on the marine productivity in the Öresund strait, research should be made on coastal environments in connection to N runoff where N loads might have a direct effect on the ecosystem.

Method evaluation

This study has been made to give an idea of the effect of N runoff on marine production and fish catch. Parameters used in the NPZD model (table 2) are uncertain standardized parameters thus, SOD calculated in this study is a rough estimate and conclusions drawn from the results must be done with careful consideration. For better results, the parameter values need to be measured and calculated specifically for the basin in question.

Since fish catch is highly affected by politics and regulations, spawning stock biomass (SSB) would have been a more accurate and effective way of estimating the relationship between N load and fish productivity. SSB data is not available for the Öresund strait as an isolated basin. While available data of N load stems from HELCOM and national data bases, available SSB data stems from ICES. Since these organisations/authorities use different area divisions, the SSB data for the Öresund strait would have to be calculated using a different method and this was not feasible due to time limitations. Therefore, the catch statistics have been used in this paper.

Conclusions

The N runoff to the Öresund strait has decreased substantially during the last two decades. Current N runoff cannot be concluded to have any negative effect on neither SOD nor catch of fish. A slight positive relationship can instead be seen between N runoff and catch of fish. Further studies are needed to analyse the effect of N runoff on the ecosystem in the Öresund strait.

- Decrease of N runoff has already met current national and international goals.
- Current N runoff are estimated to make little effect on bottom dissolved oxygen concentrations.
- The decrease in fish catch is highly unlikely due to N load from land. It is more likely to be a consequence of lowered fish quotas due to declining fish populations in adjoining basins.
- A first step to further lower N loads to the Öresund strait would be to decrease effluent from wastewater treatment plants and leakage from agricultural soil.
- In addition, constructed wetlands are a studied and functional way of retaining the leakage that cannot be avoided. By carefully planning location, size and form of the constructed wetland, nutrient retention can be enhanced while ensuring biodiversity and recreational values.
- Care and conservation of the already existing and, generally more efficient, natural wetlands can be a highly cost-efficient way to preserve ecosystems both in the water and on land.
- To further evaluate N runoff impact, studies should be made on coastal ecosystem e.g. Seagrass meadows.

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Appendix 1. Fish classification

Table 4
Fish species used in this study; name, classification, and total catch in tonnes for the period 1997-2017 in the Öresund strait. * species not included elsewhere (ICES, 2019 (a); ICES, 2019 (b)).

Species	Common name	Milieu classification	Total catch (tonnes)
Lophius piscatorius	Angler	Demersal	4.03
Gadus morhua	Atlantic cod	Benthopelagic	45072.34
Hippoglossus hippoglossus	Atlantic halibut	Demersal	3.03
Clupea harengus	Atlantic herring	Benthopelagic	113616.65
Trachurus trachurus	Atlantic horse mackerel	Pelagic	31.01
Scomber scombrus	Atlantic mackerel	Pelagic	102.53
Salmo salar	Atlantic salmon	Benthopelagic	6.74
Anarhichas lupus	Atlantic wolffish	Demersal	9.31
Scophthalmus rhombus	Brill	Demersal	134.05
Blenniidae	Combtooth blennies	Benthopelagic	0.08
Cyprinus carpio	Common carp	Benthopelagic	2.01
Limanda limanda	Common dab	Demersal	549.46
Solea solea	Common sole	Demersal	284.32
Zoarces viviparus	Eelpout	Demersal	4.69
Anguilla anguilla	European eel	Demersal	3653.17
Platichthys flesus	European flounder	Demersal	3693.96
Merluccius merluccius	European hake	Demersal	4.2
Perca fluviatilis	European perch	Demersal	30.85
Pleuronectes platessa	European plaice	Demersal	2506.23
Dicentrarchus labrax	European seabass	Demersal	1.55
Sprattus sprattus	European sprat	Pelagic	4759.48
Coregonus lavaretus	European whitefish	Demersal	61
Osteichthyes	Finfishes*	Pelagic	131.4
Abramis brama	Freshwater bream	Benthopelagic	0.02
Abramis spp	Freshwater breams*	Benthopelagic	6.01
	Freshwater fishes*	Pelagic	62

Belone belone	Garfish	Pelagic	1405.25
Trachinus draco	Greater weever	Demersal	40.03
Reinhardtius hippoglossoides	Greenland halibut	Benthopelagic	1.03
Eutrigla gurnardus	Grey gurnard	Demersal	5.73
Osteichthyes	Groundfishes*	Demersal	0.3
Triglidae	Gurnards, searobins*	Demersal	0.52
Melanogrammus aeglefinus	Haddock	Demersal	117.9
Microstomus kitt	Lemon sole	Demersal	51.56
Molva molva	Ling	Demersal	9.12
Cyclopterus lumpus	Lumpfish	Benthopelagic	2100.6
Osteichthyes	Marine fishes*	Pelagic	3.4
Mugilidae	Mullets*	Demersal	16.02
Esox lucius	Northern pike	Demersal	7.3
Leuciscus idus	Orfe	Benthopelagic	0.63
Squalus acanthias	Picked dogfish	Benthopelagic	5.62
Sander lucioperca	Pike-perch	Pelagic	3.76
Pollachius pollachius	Pollack	Benthopelagic	7.66
Trisopterus luscus	Pouting	Benthopelagic	0.02
Oncorhynchus mykiss	Rainbow trout	Benthopelagic	2.3
Raja spp	Raja rays*	Demersal	2.54
Rutilus rutilus	Roach	Benthopelagic	4.56
Pollachius virens	Saithe	Demersal	20.09
Ammodytes spp	Sandeels*	Demersal	457.67
Salmo trutta	Sea trout	Pelagic	82.57
Tinca tinca	Tench	Demersal	1.01
Chelon labrosus	Thicklip grey mullet	Demersal	0.91
Psetta maxima	Turbot	Demersal	173.46
Merlangius merlangus	Whiting	Benthopelagic	101.41
Glyptocephalus cynoglossus	Witch flounder	Demersal	5.05
Anarhichas spp	Wolffishes*	Demersal	9.09