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Mussel farming along the south-Swedish coasts

A possible solution to eutrophication?

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Musselodling kring sydsvenska kuster - *en möjlig lösning mot övergödning?*

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Bachelor thesis, 15 credits, in Physical Geography and Ecosystem Analysis

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Abstract

The concept of mussel farming as a mitigator to nutrient pollution is steadily spreading. The southernmost part of Sweden borders the Baltic Sea where the water quality differs between the costs, however, all are affected by eutrophication. The study presents a suitability analysis using GIS to find potential locations for blue-mussel farm establishment, and the outcome was produced as maps. A multi-criteria analysis (MCA) was done based on the environmental conditions needed for mussel growth (chlorophyll a, salinity, dissolved oxygen, temperature, currents, and water depth), possible disturbances (pipelines, cables, shipping, and nature reserves) and a short discussion on the spatial availability considering potential variations of eutrophication levels in the water based on adjacent land cover. The difference in salinity had a great effect on the location suitability, and adjustments showed that with lower salinity, the area availability increased, marginally along the west coast but to a pronounced degree along the east coast.

Keywords

Mussel farming, Aquaculture, Spatial suitability analysis, Eutrophication, Baltic Sea

1. Introduction

Eutrophication is a major environmental issue affecting many coastal areas and water bodies worldwide. It is mostly pronounced in lakes, semi-enclosed and landlocked seas (Kotta et al., 2020). One of the main contributors to eutrophication is the large excess of nutrients, particularly nitrogen [N] and phosphorus [P] (Conley et al., 2009). The excessive amount of pollutants facilitates the environmental conditions for large-scale algal blooms and consequently oxygen depletion (Lindahl et al., 2005). The main source of the continued nutrient output is due to anthropogenic activities such as the discharge and runoff water from settlements, industries, and agriculture. The Baltic Sea fits the given descriptions and is therefore a suitable site to investigate eutrophication-related research. With an overflow of nutrients and an absence of deep water mixing or ventilation, the stratified Baltic Sea can be regarded as a subject opposed with a two-folded threat (Andersen et al., 2015).

One of the potential solutions to mitigate eutrophication is the aquaculture of marine bivalves such as shellfish, clams, and mussels. As these molluscs are filter feeders that can remove excess nutrients from the water, farming would be considered a pollution mitigator that has a positive effect on water quality and gives a production of biomass (Kotta et al., 2020; Maar et al., 2023). Mussel communities have also been shown to prove beneficial for aquatic ecosystems suffering from eutrophication and algal blooms. As the mussels filter the water for nourishment, they mitigate the abundance of phytoplankton and consequently absorb nutrients stored in these microbes. This results in lower availability for algae blooms and by less photosynthesis, which further enables more free dissolved oxygen and clearer water. Mussels that are released have also shown to function as nourishment for species living on the seabed (Maar et al., 2023; Kotta et al., 2020; von Thenen et al., 2020).

Mussel farming shows potential socioeconomic as well as environmental benefits. With commercial farming, the fishing industry is diversified, which enables the market for new work opportunities and solutions. A direct consequence is the increase in food stock and biomass that the mussels contribute (Hamilton et al., 2013). The biomass production can be regarded as a recycler of nutrients, and the harvested mussels can be further used as food stock for animals such as poultry and fish farms, as soil fertilizer, as bioenergy production, and in a future perspective, as a supplement for food production (Kotta et al., 2020; Hamilton et al., 2013).

However, in order to establish a mussel farm certain environmental requirements must be met. The six requirements that are needed for mussel growth each play a key importance and will be further investigated; however, the most important one is salinity (Hamilton et al., 2013). A mussel needs certain levels of salinity in order to increase the production of shell formation, where an optimal salinity ratio is about 12-30 psu. If the conditions of the other environmental requirements are optimal, the enhanced shell production results in faster growth (Hedberg et al., 2018). Mussels are however able to adapt when the environmental conditions are suboptimal, but it causes stress which consequently reduces the growth rate. An example of this is the comparison of blue mussels found on both the saline west side and the brackish waters on the east side, where there is a substantial difference in size; east coast being much smaller (Hedberg et al., 2018; Hamilton et al., 2013).

Aim

This study aims to assess the potential of using mussel farming as a sustainable solution for mitigating eutrophication around the coast of Scania, a strategy that is uncommon in waters around the southern Swedish coast. These waters are known to suffer from eutrophication. They are also known to have a varying degree of salinity, with the waters along the eastern coast being brackish. As salinity has a key importance for mussel growth, it is assumed that salinity will have a substantial influence on the possibilities to allocate suitable areas for mussel farm establishments in these waters. The aim can be structured into the following objectives:

1. Is it possible to identify suitable locations for establishing mussel farms based on a combination of knowledge about how mussels grow and develop and more site-specific disturbance factors? If so, to what extent and where? How are suitable locations distributed in space?

2. One of the most dominating factors that prevents mussel farming within the study area is known to be the degree of salinity, the Eastern waters being brackish. How would the allowance of a lower salinity affect the extent of suitable areas in this region?

The methodology will be carried out in a step-wise approach, beginning with a literature research where the most dominant environmental parameters for growing mussels will be identified, continuing with a spatial analysis in order to determine how well the conditions within the study site meet-up with these criteria, and ending with a brief discussion on how any identified locations for growing mussels meet-up with areas that may suffer particularly from eutrophication and nutrient leaching.

2. Background

2.1 Nutrients

There is a continuous input of nutrients into marine environments. This pollution is transported to the waters mainly by surface runoff and through water streams from adjacent land, fuel emission by ship traffic, and atmospheric sinks (Gupta et al., 2011; Raudsepp et al., 2019).

Agricultural runoff is one of the major contributors to marine pollution, where added fertilizers containing Phosphorus [P] and Nitrogen [N] are leached through runoff to nearby water bodies and rivers (Djodjic et al., 2021; Kotta et al.,2020).

The two most important nutrients in the marine ecosystem are Phosphorus [P] and Nitrogen [N] (Conley et al., 2009). The two pollutants together with oxygen and sunlight are required for the photosynthesis and growth of phytoplankton, which plays a crucial role in the ecosystem. However if the water column is not frequently mixed or stratified, and the availability of nutrients becomes abundant eutrophication occurs. This causes phytoplankton to grow at faster rates than the food web can handle (Karlson et al., 2021). This abundance of Phosphorus [P] and Nitrogen [N] enhances algae blooms, which can be harmful to the ecosystem. The imbalanced photosynthesizing of the large-scale algae blooms alters the water column, resulting in oxygen depletion and preventing light from entering lower levels (Vaquer-Sunyer & Duarte, 2008; Kotta et al.,2020).

Nitrogen [N] is easily transported as it is soluble in water. However, besides loading through discharge and runoff water, the atmospheric sink through N fixation and direct input fuel emittance from ship traffic are other common pathways of the pollution input (Raudsepp et al., 2019). Phosphorus [P] is an insoluble nutrient, meaning that it has to be biologically fixed or bound to different compounds (for example as a fertilizer compound or soil particles) which therefore makes it less mobile (Djodjic et al., 2021).

What also has to be taken into consideration is that, even though the continuous input of nutrients into the sea can be mitigated, the phosphorus footprint from past pollution is sedimented into the seabed, and can therefore be seen as a debt or over-storage (Thomas et al., 2021).

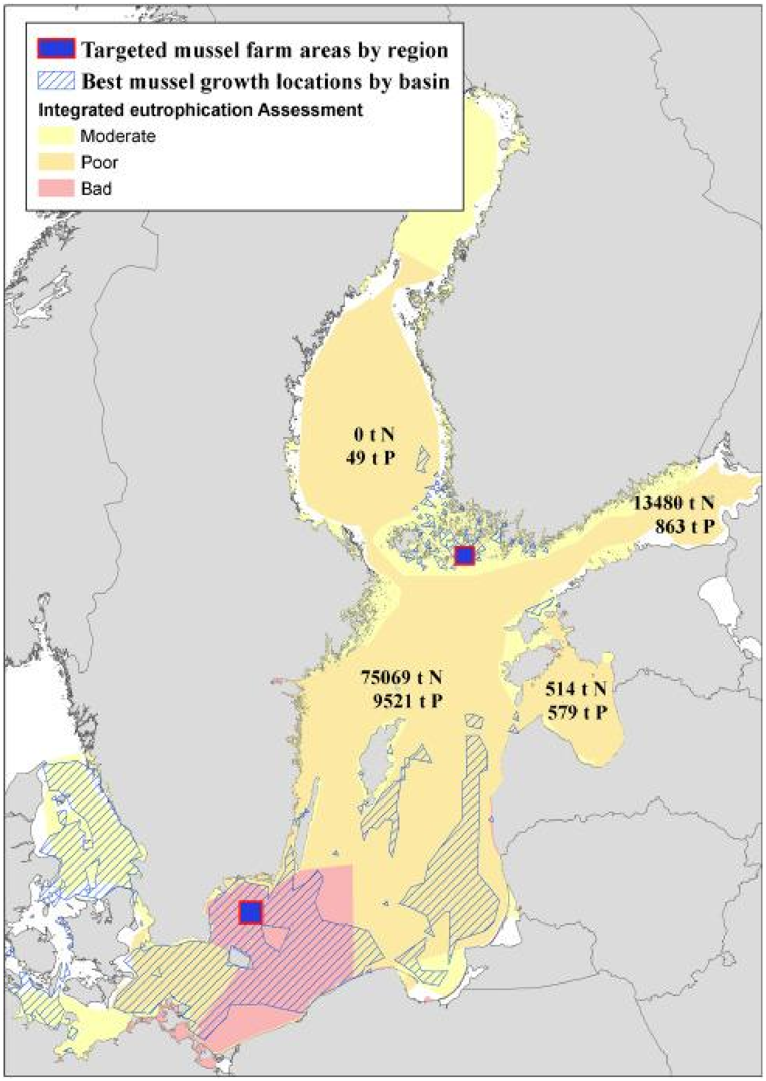

Figure 1: Areas of the Baltic Sea with further classification of estimated annual amounts of phosphorus and nitrogen in tonnes, as well as the measured annual eutrophication rate with regards to the goals of emissions set by the HELCOM Ministerial Meeting 2013.

Kotta et al., 2020

2.2 Mussel physiology

The suspension-feeding which is done by the blue mussel plays a large role in the ecosystem. They filter the water column for seston which refers to suspended particles such as plankton, dissolved organic material, and minerals. The filtering and absorption of phytoplankton can be regarded as a mitigation to algae blooms which consequently results in more free oxygen in the water column and clearer water (Hamilton et al., 2013).

The filter-feeding is done through pumping of water through a set of gills (Steeves et al., 2022). The pumping is triggered when the food concentration reaches the minimum level, this varies according to the species and environmental prerequisites. The feeding rate for a mussel is measured in liters per hour (Lh-1) and the normal filtering range for the blue mussel is approximately from 1-5 L h-1 where 1 is very low and 5 is very high, and the normal seston absorption is measured in mg L-1 and ranges from ~1-3 μg L-1 (but can reach both much lower as well as much higher values) (Steeves et al., 2022).

2.3 The blue mussel

There are several types of mussels found in the Swedish waters, one of the most common is the blue mussel (Mytilus edulis). The name blue mussel comes after the blue-colored shell but can vary between brown and black as well (Havet.nu., 2022). The trait that differentiates the blue mussel from many other mussel types is that it can be found both in the saline waters of the Atlantic Ocean and in the brackish waters of the Baltic Sea (Hedberg et al., 2018). The reason why the blue mussel is able to thrive along both the saline west coast and the brackish east coast of Sweden is the ability to adapt to lower saline levels. The lowest optimal saline level is around 11-12 psu which is found on the west coast; however, the blue mussel can lower the tolerance as far as 4.5 psu. This stress does however consequently result in a slower growth rate (Hedberg et al., 2018; Filippelli et al., 2020). Furthermore, the faster growth rate on the west side makes farming more profitable from a commercial standpoint. The size of the blue mussel varies depending on multiple conditions, such as food availability, salinity levels, and age. Under optimal conditions on the west coast, the blue mussel grows up to 8 centimeters in size, but can under very optimal conditions grow up to 20 centimeters (Havet.nu., 2022). While the normal size found on the east coast (under stress) is about 4 centimeters (Andersson et al., 2013).

There have been projects using the Zebra mussel (Dreissena polymorpha) in the Baltic Sea (off the coast of Germany). However, some studies have shown that this species can prove to be invasive and will therefore be disregarded (von Thenen et al., 2020; Burlakova et al., 2014).

Picture 1: Blue mussels (*Mytilus edulis*)

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2.4 Mussel farm description

Mussel farms can take many shapes and sizes, from small private farms to commercial large-scale farms. A common practice is to use fibrillated polypropylene ropes or ribbons called "fuzzy ropes", they have a high surface area per unit length to increase efficiency; and the carbon black dye promotes high rates of mussel larval settlement (Kotta et al., 2020; Tortell, 1976). An example of a farm structure would be an area over 1x1 hectares, with several horizontal lines; each containing multiple vertical suspended fuzzy ropes, that have a recommendation maximum of 10 meters in depth. A farm establishment is bound by only space and depth; however, the distance between each horizontal line should be about 10 meters apart to prevent competition over food. (Kotta et al., 2020; Hamilton et al., 2013; von Thenen et al).

2.5 Geographical location

The potential location for a mussel farm differs depending on the size of the farm. This paper follows the recommendations of Hedberg et al., (2018) and will therefore mainly focus on farms with a preferable scale of 1-4 hectares. However, with size comes more restrictions, the location of the farm must be chosen so that it is not accidentally disturbed by coast-based activities. It also has to follow certain conditions, such as no harm or disturbance to protected land (Natura). Lastly, it is also to avoid possible disturbances such as shipping paths. A delimiting factor may therefore be the space availability for suitable locations. By conducting a spatial analysis using GIS, both suitable areas and their sizes can be found.

3. Method

3.1 Study site

Scania is the most southern county of Sweden with an area of approximately 11,030 square kilometers and a coastline of 500 kilometers. The coastlines consist of three parts, one facing west at Kattegat, one facing south, and one facing east which both are found in the center of the Baltic Sea. (Region skåne, 2022; Kulturmiljöprogram: Kustens Landskap, 2003; Baltic Sea, 2023).

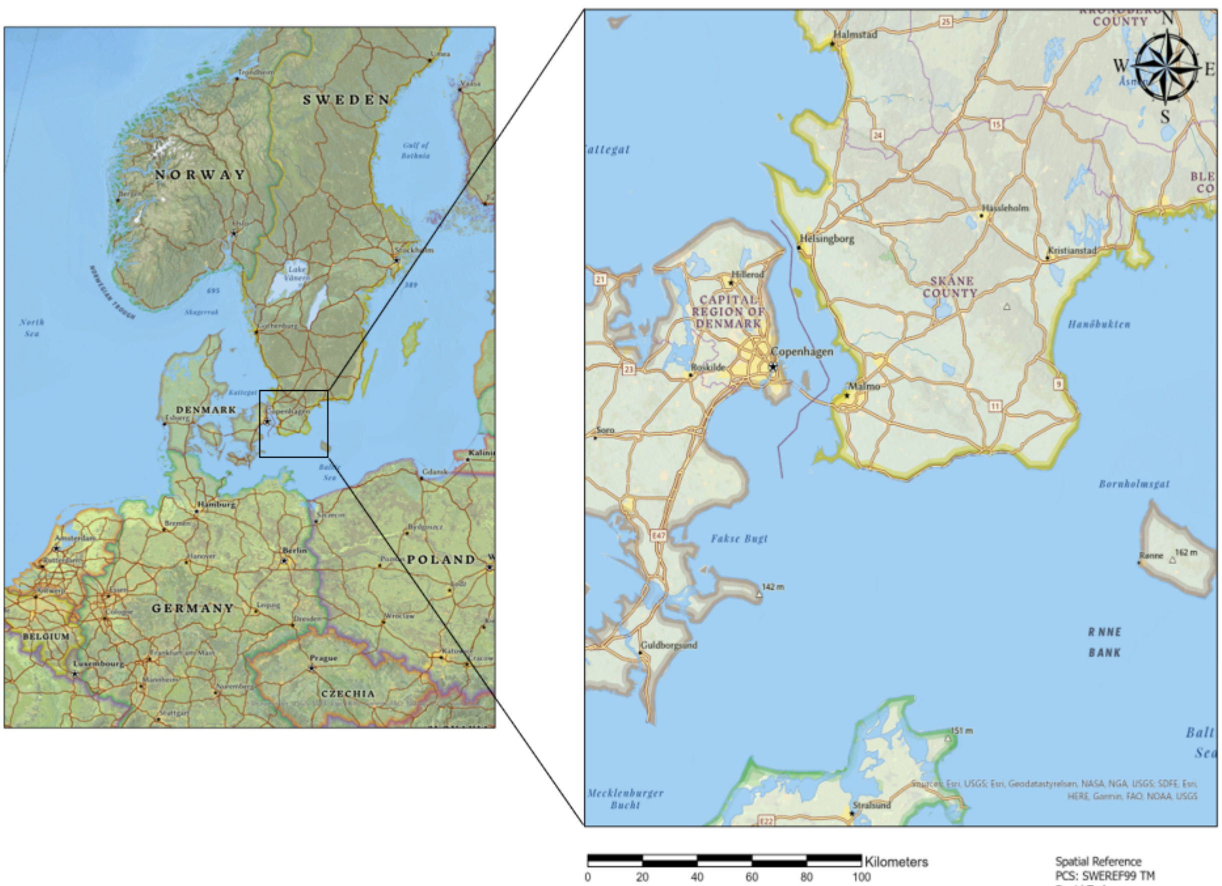

Figure 2: The county of Scania as well as the three coastlines to the Baltic Sea.

ArcGIS pro National Geographic Style basemap

The geographical difference in regards to direction means that the water composition varies in qualities such as salinity, dissolved oxygen, and temperature. Another difference is the location and size of the water body outside of the corresponding coastline. The western side toward Kattegat is fairly mixed with the saline water from the Atlantic Ocean, it is however rather small in size and due to its geographical position of being the only entrance and exit to the Baltic Sea is heavily trafficked (Meyer, 2016). The southern side is a mixture of the saline water coming through Kattegat and the brackish water from the Baltic Sea (almost fully brackish), it is also fairly small and heavily trafficked. Lastly, the eastern side is brackish and has the largest water availability of the three and also less traffic (Andersson. T, 2015; Kotta et al., 2020; von Thenen et al., 2020).

Regarding the present aquaculture of mussels in Scania the main commercial harvest comes from the west coast (Hamilton et al., 2013). The biodiversity and growth rate are greater there. This is due to the water quality and the active mixing of the water column. Although the mussels thrive when there are a lot of nutrients and chlorophyll a the salinity level enables a faster growth rate (von Thenen et al., 2020; Kotta et al., 2020).

The study site was based on socioeconomic interests such as the dominant agricultural practices that can be found in Scania. Scania is one of the leading counties in agriculture, with almost 45% of the land use consisting of farmland (Olsson, 2020). Furthermore, a number of river catchments can be found running through the farmland, enabling nutrient transportation (Gupta et al., 2011). Consequently, continued high productivity of the cropland will require fertilization, where excess nutrients may be transported to the Baltic Sea causing possible eutrophication (Rosenberg et al., 1990; Ezzati et al., 2023). Another interest is the lack of data regarding mussel establishment around the whole coast of southern Sweden. In order to find suitable locations, a suitability analysis was conducted to find both the environmental suitability and spatial availability using GIS.

3.2 Study site land cover and nutrient storage

In order to investigate how and where the nutrient-dominating pollution and eutrophication manifest around the coast Scania factors such as land use cover, nutrient transportation possibilities, and present storage and leakage in the county must be taken into consideration (Gupta et al., 2011; Djodjic et al., 2021; Ezzati et al., 2023). The land cover consists of multiple land classes in the form of raster data, however in order to narrow down the parameters a selection of the three major pollution classes was chosen; cropland, woodland, and urban settlement (Gupta et al., 2011; Rosenberg et al., 1990).

The present storage of nutrients is also a relevant consideration as it shows the potentiality of leaching. This storage is presented in three different classes, agricultural which represents the nutrient input from cropland and farming, background which represents the natural (non-anthropogenic) storage and output and lastly diffusion which is the direct linkage of anthropogenic emission (Figure 3-5) (Djodjic et al., 2021; Ezzati et al., 2023; Helcom, 2023).

Finally, the last factor of interest in this analysis is the river catchments, where a possible correlation between river positioning and distribution, and land use/storage can be found (Wit, 2001). All the data was sampled from Helcom (Helcom, 2023).

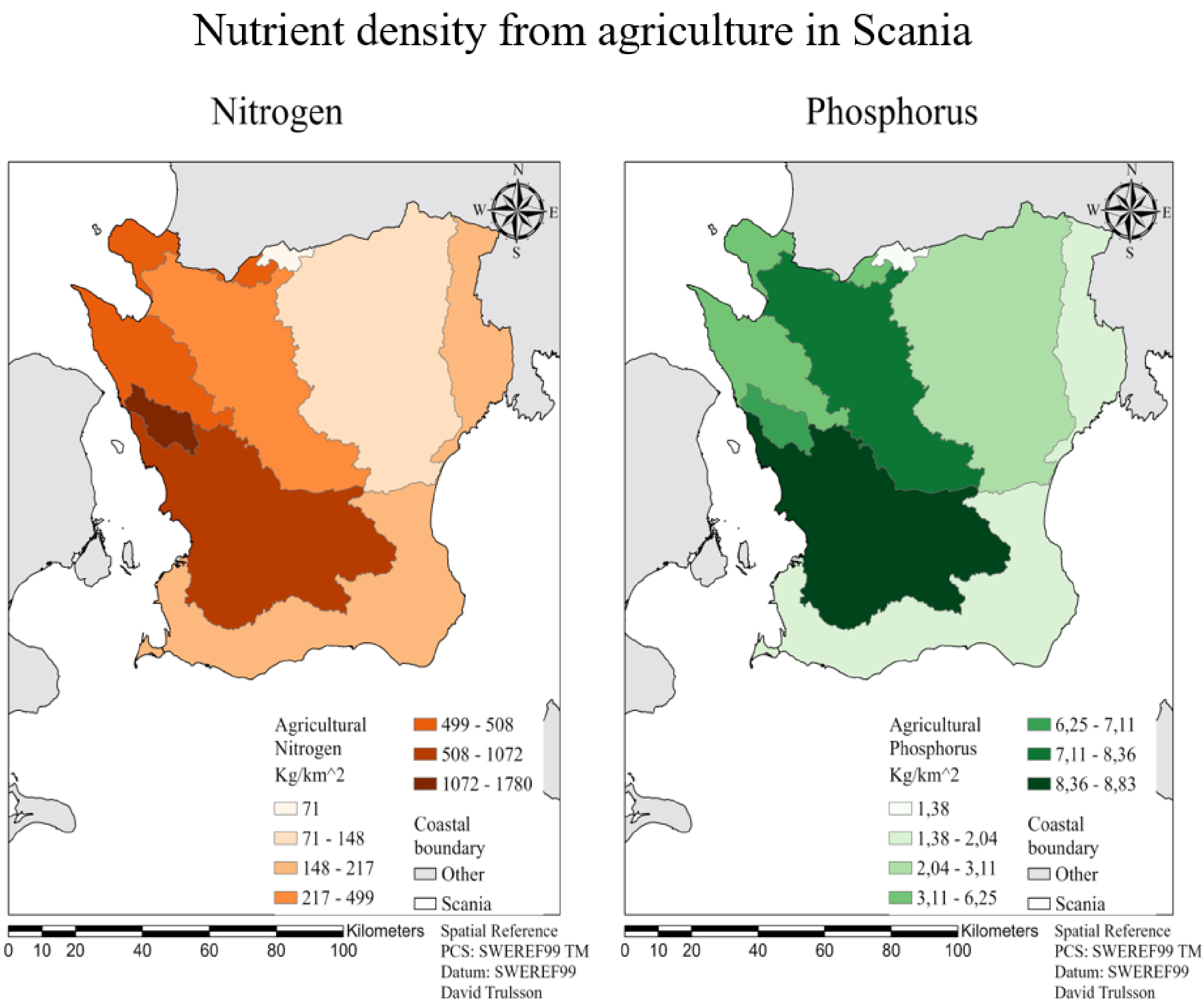

Figure 3: The nutrient density (Nitrogen, red, and Phosphor green) in kilogram per square kilometer in regards to agriculture in the county of Scania.

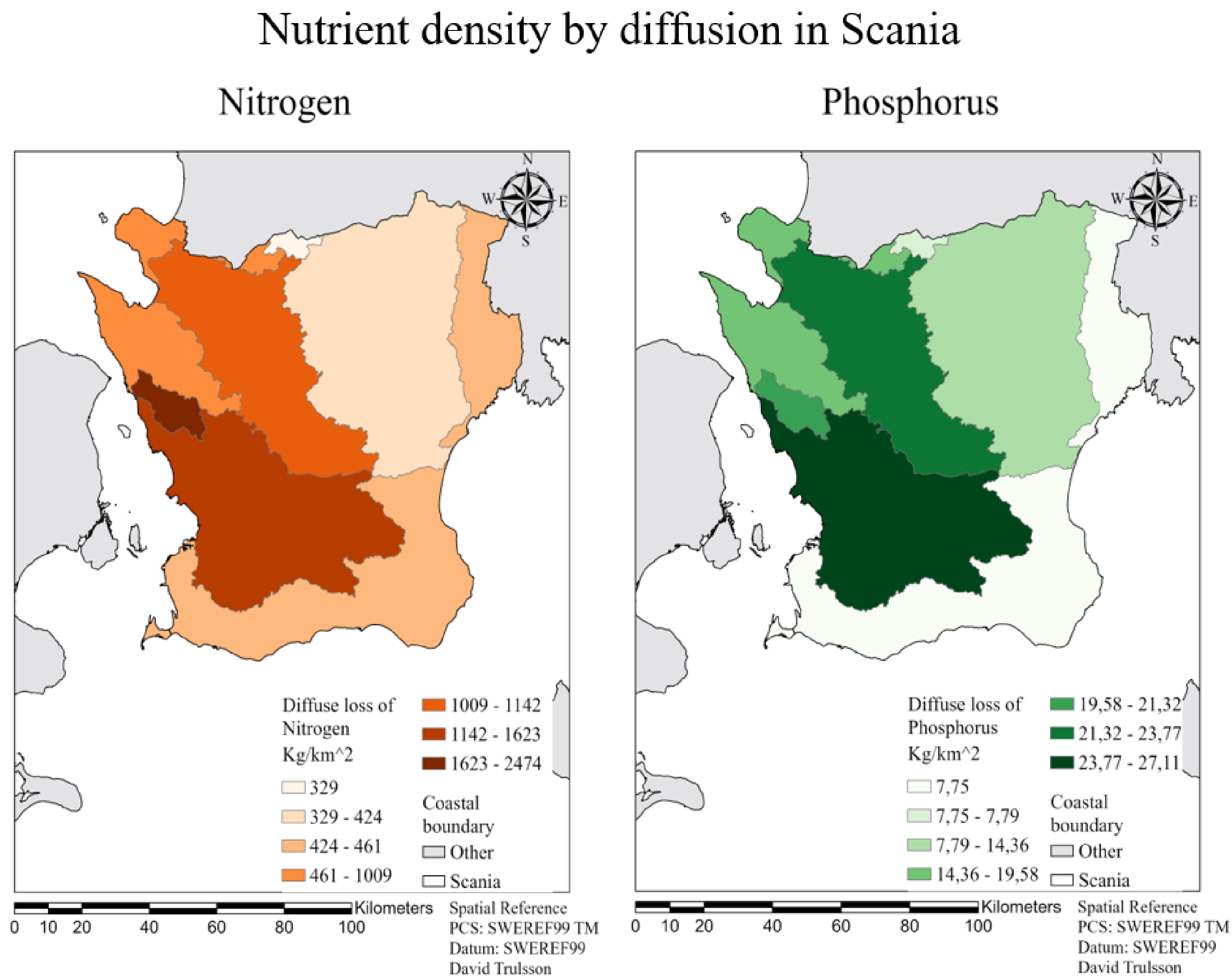

Figure 4: The nutrient density (Nitrogen, red, and Phosphor green) in kilogram per square kilometer in regards to urban diffusion loss in the county of Scania.

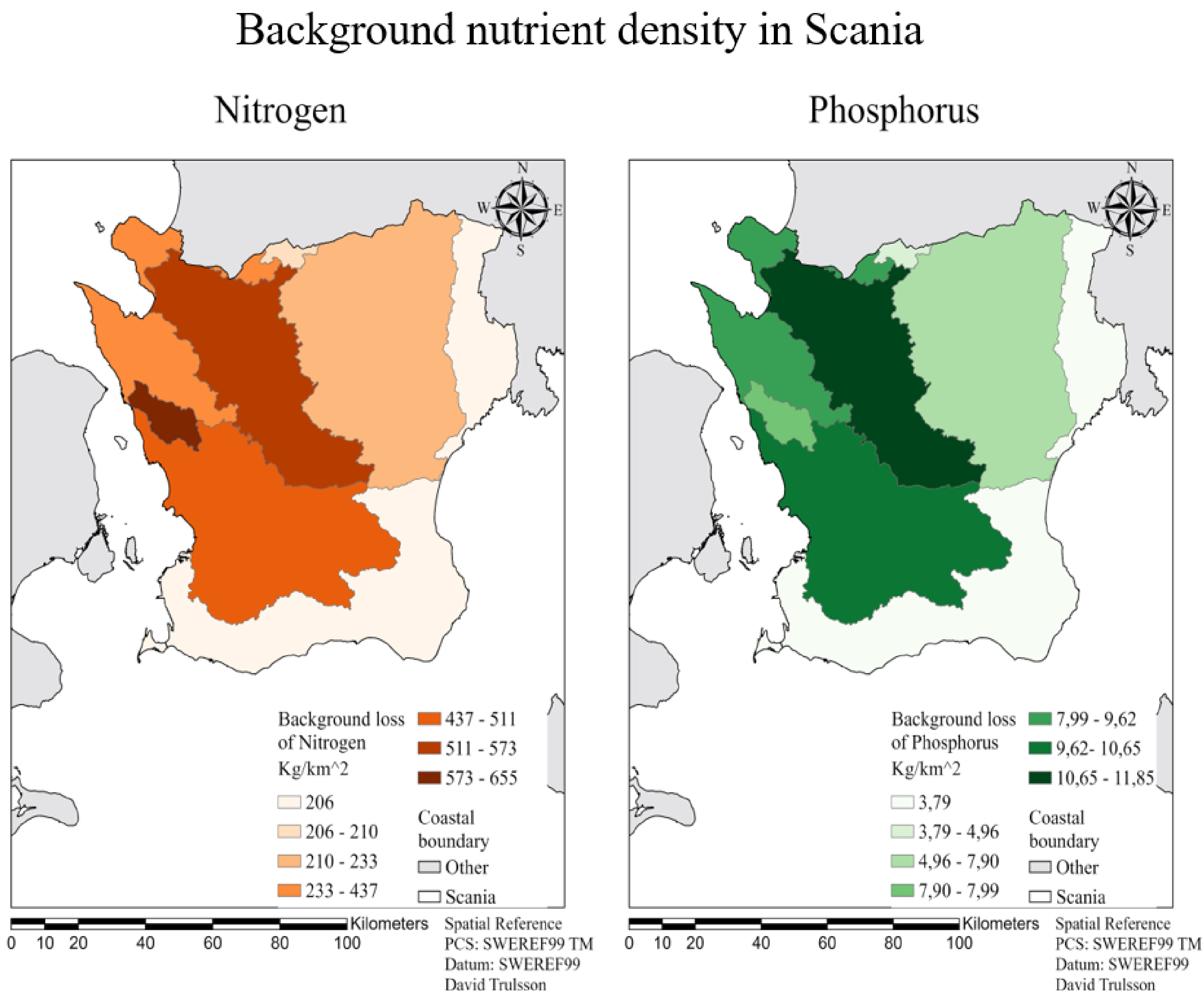

Figure 5: The nutrient density (Nitrogen, red, and Phosphor green) in kilogram per square kilometer in regards to background loss in the county of Scania.

3.3 Environmental requirements of blue mussels

The overall method used in this section is aligned with the one used by (von Thenen et al., 2020).

In order for the blue mussel to grow there are some critical factors that need to be taken into consideration, such as chlorophyll a, salinity, dissolved oxygen, temperature, currents, and water depth, these environmental requirements are based on the literature from Andersson T, (2015) and Davaasuren et al., (2010) and their recommended threshold values are summarized in Table 1. They all carry a key importance in order for mussel flourishment however, they are not weighed equally. Weighting factors were obtained from Davaasuren et al. (2010), according to Equation 1:

$$E = D(10S + 5T + O + C + Ch) \tag{1}$$

Where E = Recommended requirements of blue mussel, D = Water depth (meters), S = Salinity (‰, psu), T = Temperature (℃), O = Dissolved oxygen (mg/l), C = Currents (ms^{-1}), Ch = Chlorophyll *a* (mg/l).

Currents are the determiner of whether or not the mussels receive an approximate food level or not. A strong current; but not strong enough to harm the mussels, can transport larger quantities of chlorophyll and distribute it throughout the farm. A slow current can on the other hand lead to food depletion, where the center of the farm would suffer the most. The threshold of suitability for this paper is based on (Valdemarsen et al., 2015a), where a binary 1 for current speeds higher than 0.02 ms^{-1} and 0 for values below 0.02 ms^{-1}.

Chlorophyll plays a very important role as it functions as a mussel food availability estimation. It is used in the photosynthetic growth of phytoplankton, which is considered to be a large part of the mussel diet. The availability of phytoplankton is however hard to measure, but chlorophyll on the other hand reflects photosynthetic pigments which makes it easier to measure (Doering et al., 2006). Based on the literature of Hamilton et al., 2013 and von Thenen et al., 2020 the optimal minimum is 3 $\mu g\ l^{-1}$ (range 2 - 4 $\mu g\ l^{-1}$), however, this minimum resulted in very few data points and so the minimum was set to a lower value of 2 $\mu g\ l^{-1}$ which still reaches within their range of the environmental requirements. The chlorophyll data were, therefore, classified binary-wise where values equal or above 2 $\mu g\ l^{-1}$ is 1 and everything below is 0.

Another factor that varies with location is the dissolved oxygen concentration. However, a threshold was based on the literature (Vaquer-Sunyer & Duarte, 2008) with a determiner of $5\ mg\ l^{-1}$. This value is considered the margin of oxygen deficiency, where values below $5\ mg\ l^{-1}$ are considered as hypoxic conditions. The data that was collected from (Helcom, 2023) "Oxygen frequency" was based on station data, i.e. point vector data. In order to convert it into raster data a kriging interpolation was conducted. This resulted in an approximate estimation of the dissolved oxygen level over the area based on the weighted data points.

Temperature and salinity were also collected from Helcom and were classified based on the environmental condition ranges recommended by Hamilton et al. (2013) and von Thenen et al. (2020). The data is in a raster format where the temperature is measured in degrees Celsius (℃) and the threshold was set to 5-20 (℃). The salinity is measured in particle salinity units (psu) or parts per million and was set to the primary threshold of 11-30 psu, a second lower threshold of 7.5-30 psu. These two factors are the most heavily weighted in Equation 1 by Davaasuren et al., 2010, where salinity is the most relevant of the two. This is due to the fact that the temperature in the study area normally does not fluctuate below 0 or higher than 20 (℃) (Smhi, 2014). The temperature will therefore be disregarded as a determining factor.

Bathymetry is in this perspective solely regarded as a depth parameter. The suitable depth differs depending on the location and environmental factors such as currents and wave patterns. Based on the literature of Andersson et al. (2013) recommendation consists of a range from 5m-30m, where everything lower than 5 meters is considered too shallow and everything above 30 meters is too deep.

Table 1: The Environmental condition ranges needed for Mussels to thrive, based on the given literature.

Parameter	**Range**	**Reference**
Salinity ‰ (psu)	11-30 (primary) 7.5-30 (secondary)	Hamilton et al. (2013)
Temperature ℃	5-20	Hamilton et al. (2013)
Depth m	5-30	Andersson et al. (2013)
Current ms^{-1}	> 0.02	Valdemarsen et al. (2015)
Chlorophyll mg/l	≥ 2	Hamilton et al. (2013) von Thenen et al. (2020)
Dissolved oxygen mg/l	> 5	Vaquer-Sunyer & Duarte. (2008)

3.4 Disturbances

The Baltic Sea is a fairly active sea in regard to marine activities such as traffic, cable, and pipelines. The spatial availability for a mussel farm is therefore constrained to areas where disturbances are set to a minimum. Buffer zones were therefore calculated around the disturbance parameters, this was in regard to literature cited by (von Thenen et al., 2020).

Pipelines are a construction found at several locations in the Baltic Sea, the establishment as well as maintenance is a cause of disturbance. A buffer zone of 200 meters is therefore considered based on Danish Maritime Authority (1992). The pipeline data consists of two data sets, they separately contain valuable information. They were collected from Helcom (HOLAS 2 & 3). There are some cable establishments in the Baltic Sea, they are also considered a potential disturbance and thus a similar buffer zone is made. This data was also collected from Helcom 2023 (HOLAS 2 2015-2016).

The density shipping map is a collection of the trips by all IMO registered ships over a grid net with a cell size of 1x 1 km, i.e. transportation, shipping, maintenance, fisheries, and private. The data was collected from (Helcom, 2023) and dates over the year 2021. In order to prevent disturbances from ship traffic a safety margin is created, it applies to the area adjacent to the traffic pathway. These buffer zones were created according to Equation 2, based on the literature (Andersson T, 2015)

$$B = D \times 2Ls \times L \tag{2}$$

where B = the estimated buffer safety margin (buffer zone around the traffic path), D = the density (number of ships), Ls = Length ships domain (ships overtaking) and L = Length of standard ship (size of the ship).

The difference in ship traffic density resulted in the buffer zones; 1600 meters for annual traffic of fewer than 4400 vessels per year with an estimated 2 vessels side by side (overtaking), 2400 meters for annual traffic greater than 4400 but lower than 18000 vessels per year with an estimated 3 vessels side by side and lastly 3200 meters for annual traffic greater than 18000 vessels per year with an estimated 4 vessels side by side.

There are some protected areas around the coast of Sweden, this layer is classified as Nature reserves and consists of polygon data over areas that are considered necessary to protect. Regardless of the fact that some studies such as (Gatti et al., 2023) argue that mussel farms do not cause any bigger threats or negative impact on the environment but rather the opposite, these areas are treated as non-applicable locations (von Thenen et al., 2020).

Table 2: Potential disturbances and the given buffer zone required i.e. the distance that has to be given from disturbance to farm, based on the given literature.

Potential disturbances	**Buffer zones**	**Reference**
Shipping	1600m - 2400m - 3200m	Andersson T, (2015)
Pipelines 1	200 m	Danish Maritime Authority (1992)
Pipelines 2	200 m	Danish Maritime Authority (1992)
Cables	200 m	Danish Maritime Authority (1992)
Nature reserves	-	

3.5 Suitability analysis

For the selection of suitable mussel farm areas, a Multi-criteria analysis (MCA) was chosen. The primary suitability analysis was based on raster data from (Helcom, 2023), which was then implemented and formatted in GIS. The environmental requirement thresholds were further classified into binary (0/1) based on the range in Table 1, 1 as suitable, and 0 as not suitable, and the potential disturbance vector data were given the recommended buffer zone area based on the ranges in Table 2. The environmental analysis and the disturbance analysis were combined to find the overall suitability and the specific areas where a mussel farm could be established. The steps of the GIS analysis are shown in Figure 6.

With regards to different factorization (weighing) in equation 1, a second suitability analysis was done with a less strict requirement range for salinity; set at 7.5-30 psu. This was done in order to see how much of a determiner salinity is for the overall farm suitability and how an alteration of lowering the threshold affects the total suitable locations.

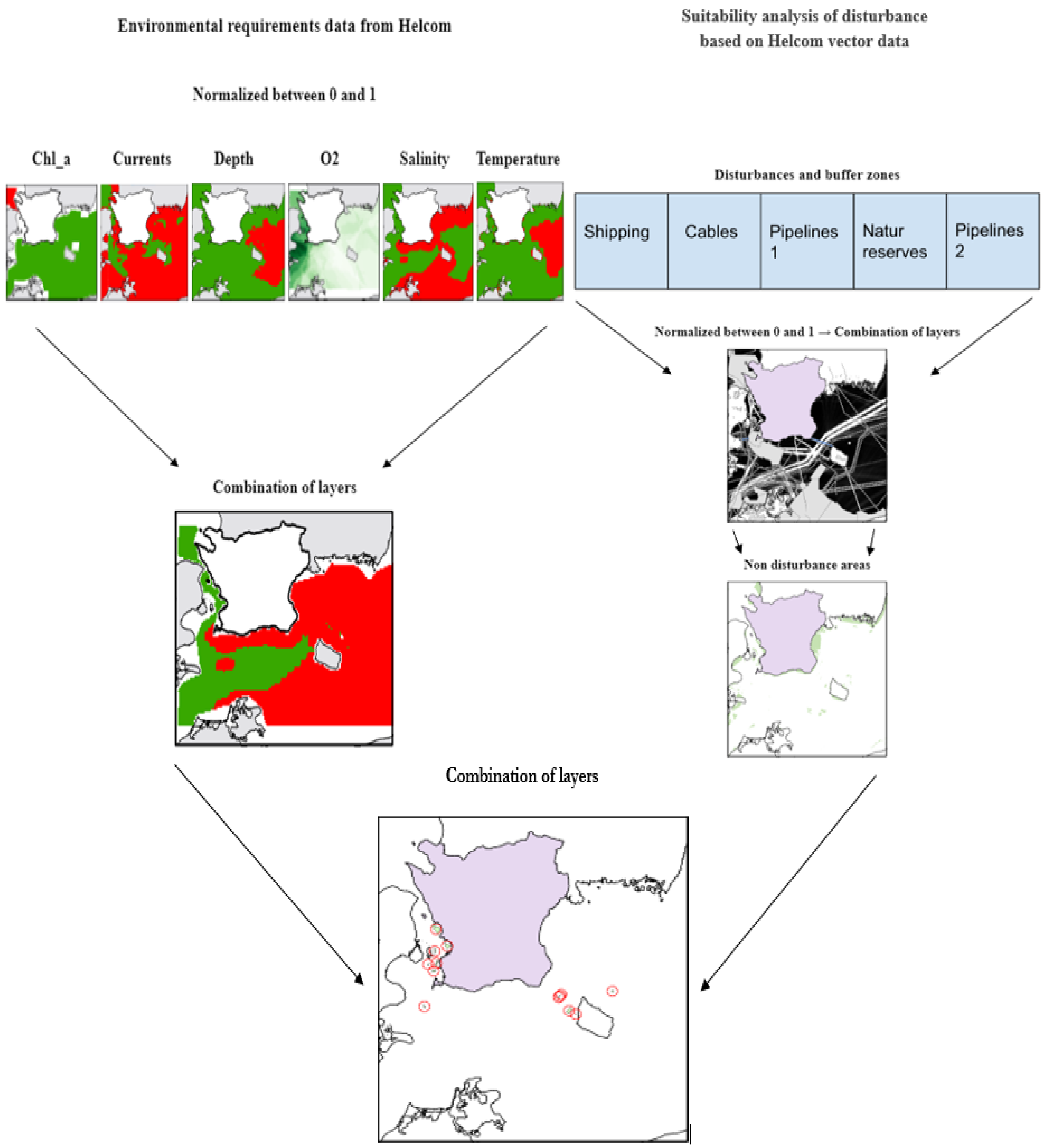

Figure 6: The method used in ArcGIS to find the suitable areas to establish a mussel farm. The left side represents the environmental recommendation analysis, where green represents value 1 i.e. areas where the prerequisites are fulfilled. Red represents a value of 0 i.e. non suitable areas. The right side represents the disturbance analysis where the disturbance rasters are colored in white (disturbance) and black (no disturbance). The final combination layer represents the suitable areas (encircled) as polygons.

4. Results

4.1 Suitable areas for mussel farming based on the multi criteria analysis

The primary suitability analysis showed that with the relatively strict conditions of requirements from Tables 2 and 3, and the removal of all the potential disturbances; 17 suitable locations with an area larger than 1-4 hectares were found. Ten were found on the west/southwest coast (Figure 7A), and seven were found on the southeastern side outside the island of Bornholm (figure 7B). Figure 8 shows the size of the suitable locations numbered 1-17 which can also be found in Table 3.

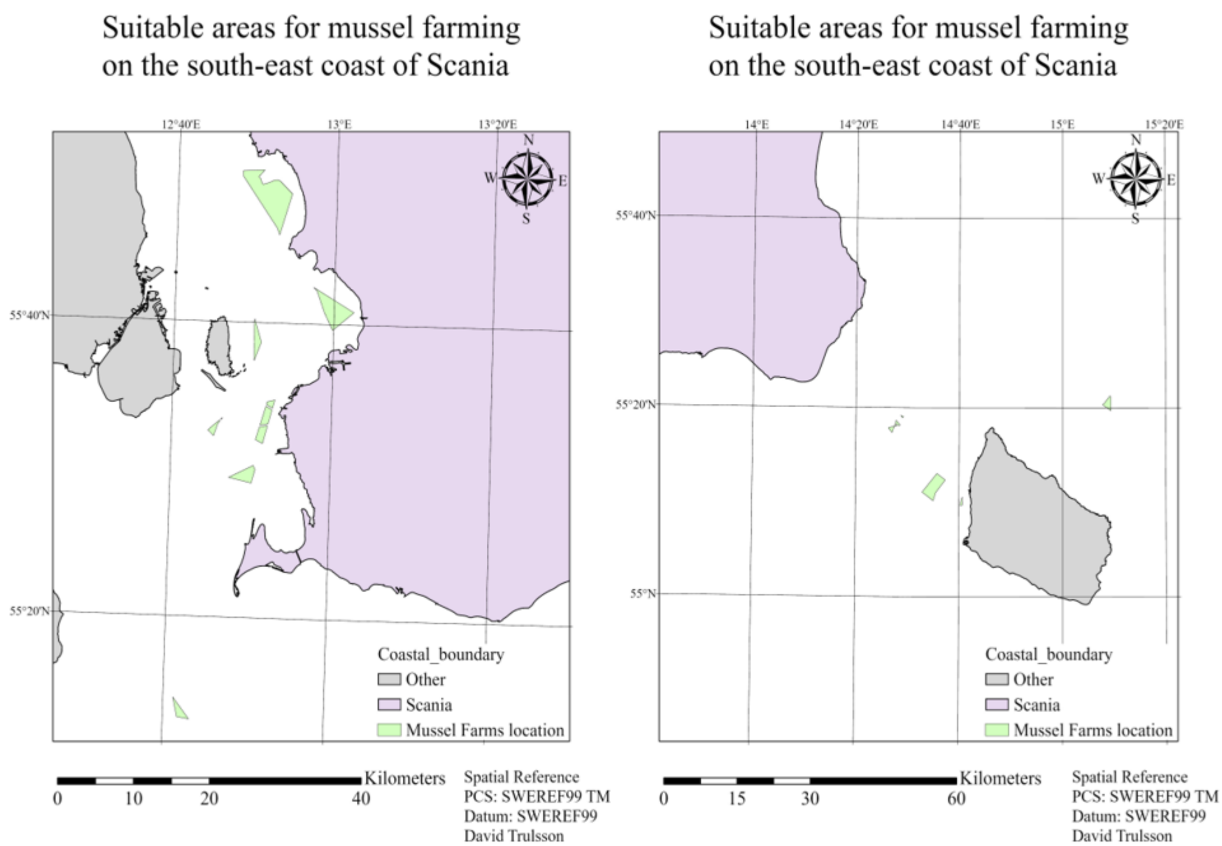

Figure 7: Suitable areas to establish a mussel farm, the left side (A) represents the west/south-west coast of Scania where ten polygons can be found, and the right side (B) represents the south-eastern side where seven polygons can be found outside the island of Bornholm.

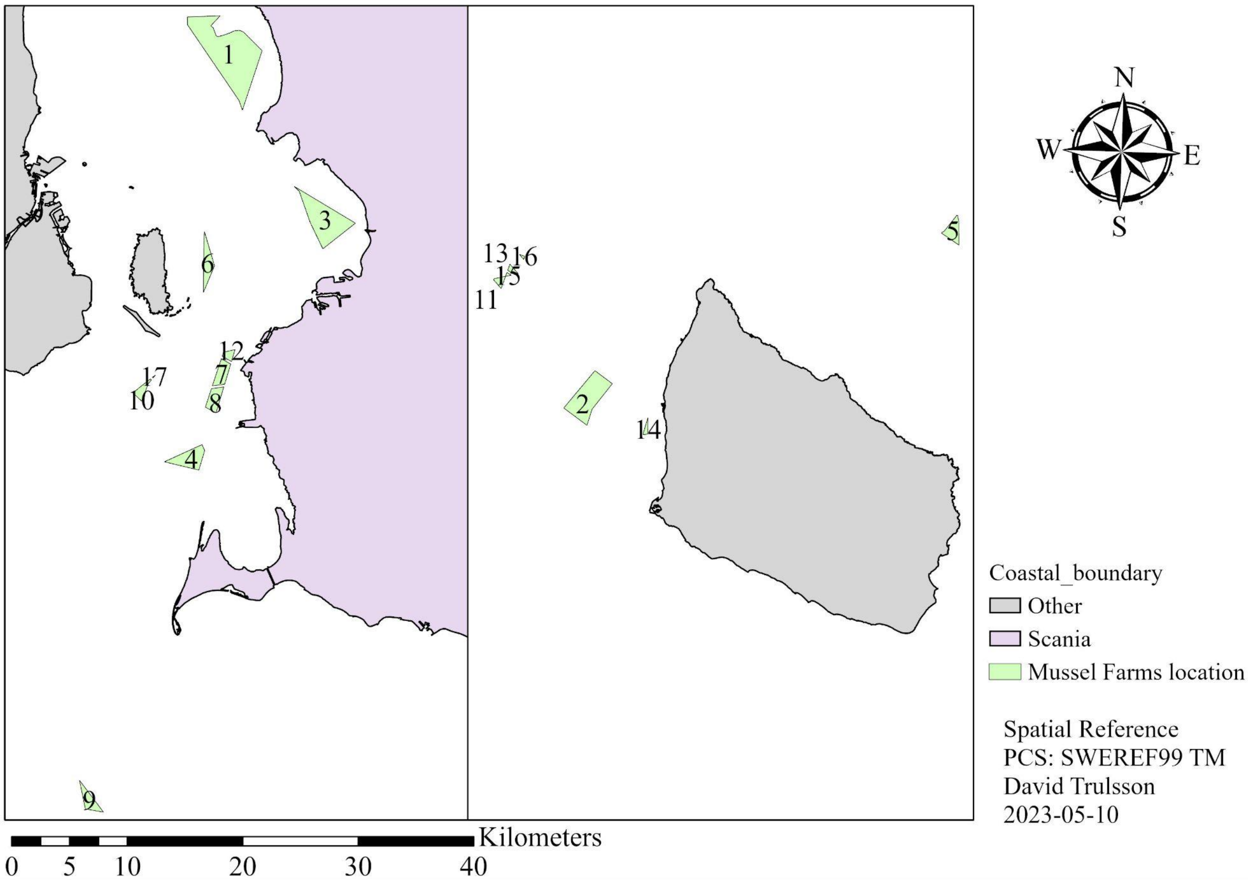

Figure 8: Of the seventeen suitable arrears to establish a mussel farm, ten are located on the western/south-western side (A) and seven on the south-eastern side (B).

Table 3: Corresponds to Figure 5 and represents the total area in square meters of a polygon based on the Identification number and position to the coastline of Scania.

Id	**Area (m^2) (rounded)**	**Coast side**
1	22 400 000	West
2	10 850 000	South-east
3	10 100 000	West
4	3 700 000	West
5	2 530 000	South-east
6	2 520 000	West
7	2 020 000	West
8	2 020 000	West
9	1 870 000	South-west
10	1 000 000	West
11	680 000	South-east
12	640 000	West
13	440 000	South-east
14	400 000	South-east
15	96 000	South-east
16	88 000	South-east
17	12 000	West

4.2 Suitable areas for mussel farming based on a lower salinity level

When the second suitability analysis was redone but with a lower salinity threshold (7.5-30 psu) the result showed substantial difference. This can be seen in Figure 9, where the left side shows the primary result of the original value of (11-30 psu) and the right side shows the secondary result. Furthermore, the final output after the readjustment of salinity, resulted in 53 new polygons that reached the scale requirement of 1-4 hectares. The output showed that there were several new areas, both close to the coast border but also a few more remote; however, the biggest difference was the new availability on the east coast where large homogeneous areas of suitability were found. These can be seen in Figure 10.

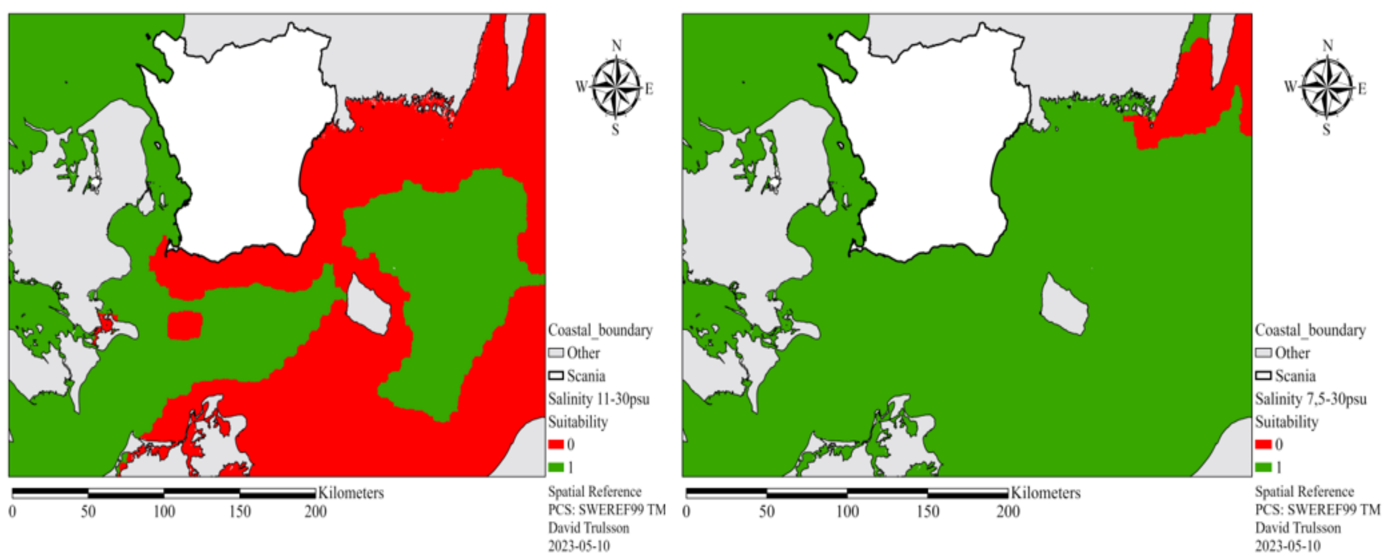

Figure 9: The suitability of around Scania based on salinity level, where red is unsuitable and green is suitable. The left figure corresponds to a requirement threshold of 11-30 psu, whereas the right figure corresponds to a requirement threshold of 7.5-30 psu.

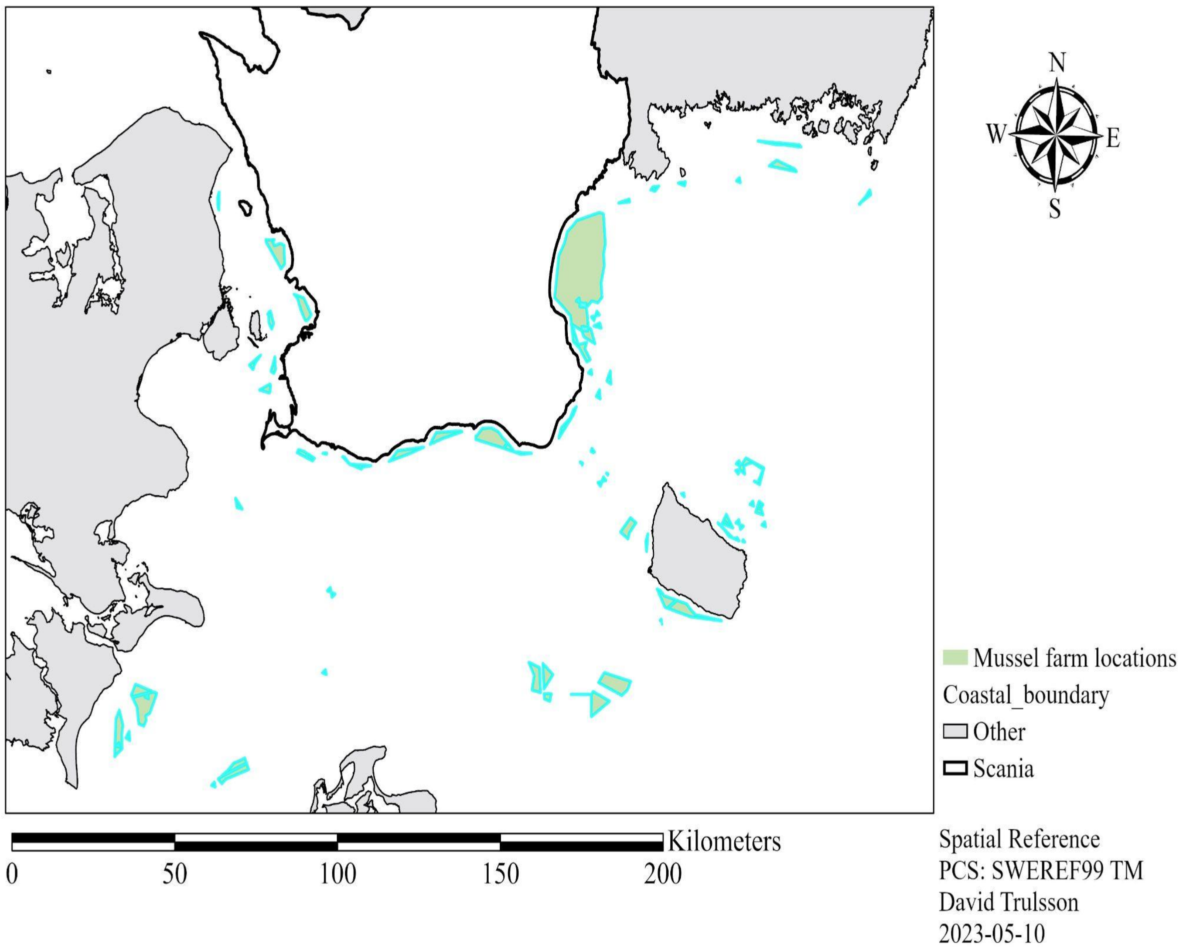

Figure 10: Suitable areas to establish a mussel farm around Scania based on the second suitability analysis with a lower salinity requirement. The figure shows the highlighted 70 polygons which fulfill the scale requirement of 1-4 hectares. Note the large suitable area on the east coast.

4.3 Land based nutrient leakage analysis

The nutrient leakage analysis resulted in two figures (11-12). The first figure (11) shows the nutrient leakage measured from the stations. The two nutrient maps showing nitrogen and phosphorus in µmol per liter, show similar trends due to the lack of available stations or stations that recorded any data. The second figure (12) shows the recorded data points from measuring stations around the coastline of Scania. The point data is estimated eutrophication frequency ranges from 1-24 and corresponds to the number of occurrences per year that a station measurement reached the threshold level of eutrophication, set by the Helcom HEAT 3.0 model (Zweifel et al., 2015).

The first three are displaying the present nutrient storage and loss of nitrogen and phosphorus in kg/km2 from different sources such as agriculture, urban diffusion, and background. A dominant trend throughout all of the six first figures is the intense storage and loss that can be found on the west side of the county.

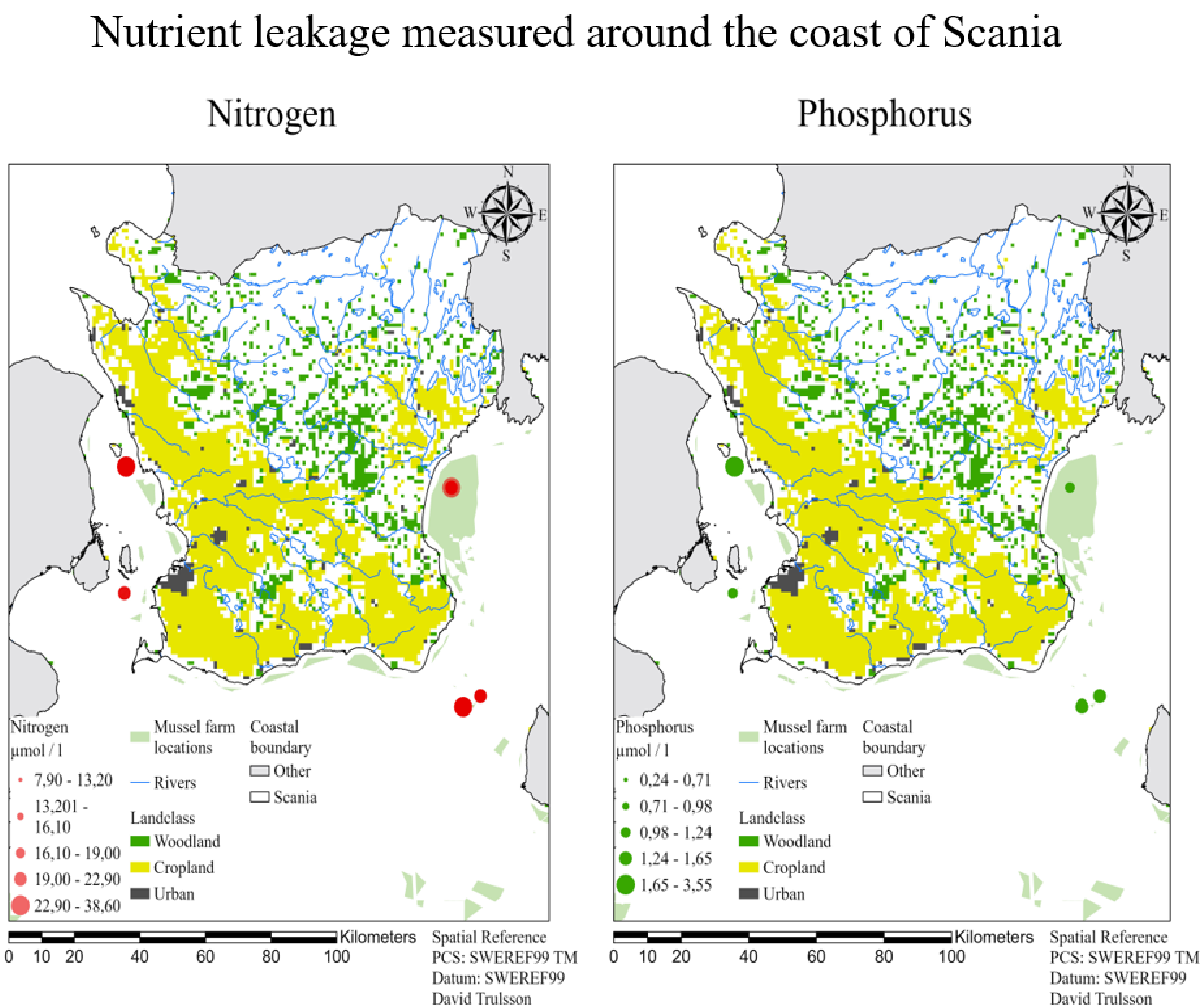

Figure 11: The amount of nutrient leakage in µmol per liter recorded by stations around the coast of Scania (Nitrogen, red and Phosphor, green). Land cover classes of woodland (green), cropland (yellow), and urban settlement (gray) as well as river catchment across the county. Potential mussel farm areas on the cost sides (light-green).

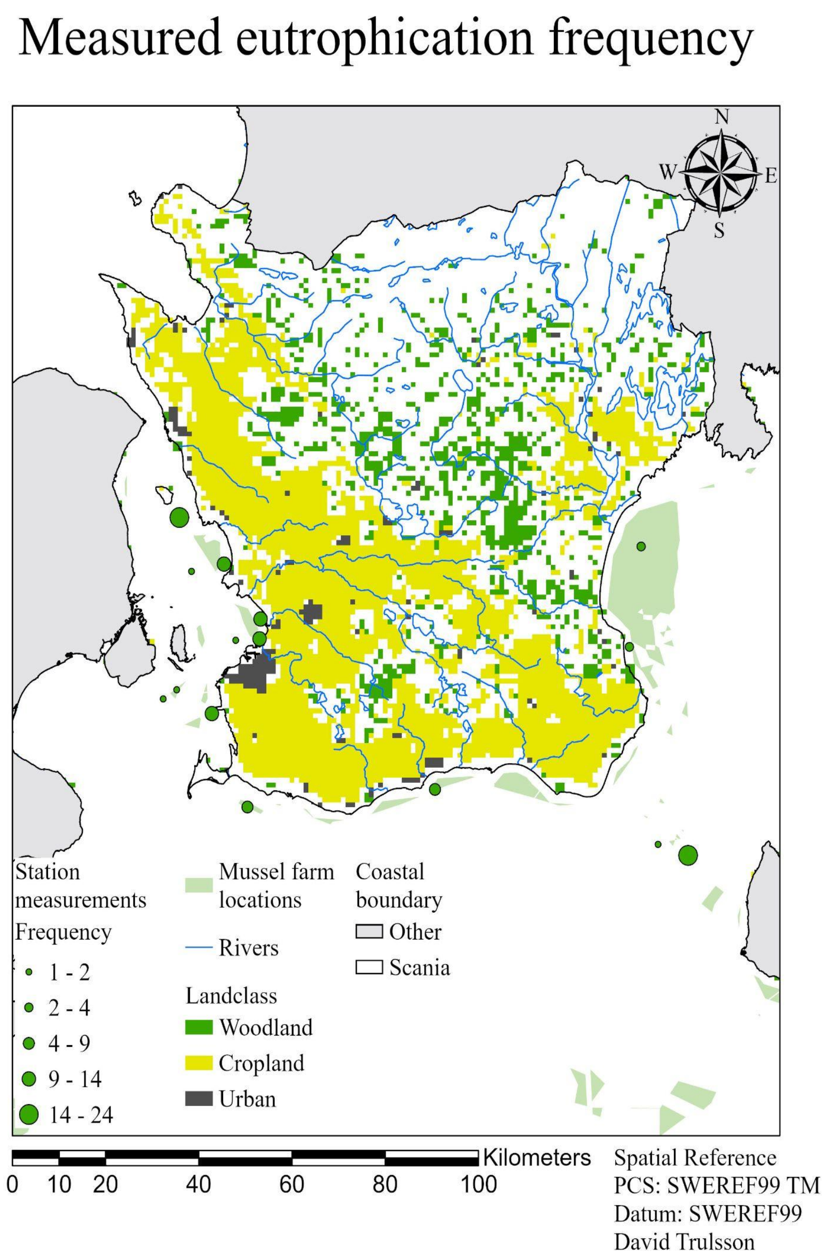

Figure 12: The recorded eutrophication frequency (green) by stations around the coast of Scania. Land cover classes of woodland (green), cropland (yellow), and urban settlement (gray) as well as river catchment across the county. Potential mussel farm areas on the cost sides (light-green).

The result of the two suitability analyses displayed suitable locations on all coast sides of Scania (figure 10), however when including the nutrient leakage analysis, there was a predominance of suitable areas in contrast to pollution and nutrient leakage on the west and a few on the east coast.

5. Discussion

When comparing the efficiency of mussel absorption and growth rates between the west coast and the east coast based on literature by Hedberg et al. (2018) there is a clear difference. They found that nitrogen absorption in µmol per mussel was approximately 10 times higher on the west coast compared to the east coast, whereas phosphorus absorption in µmol per mussel was about 5 times the difference in the same direction. The reason for this is due to the inflicted stress that comes with lowering the salinity level below optimal conditions, limiting the overall productivity of mussel growth (Hedberg et al., 2018). This would imply that the estimation of the saline west coast mussel filtering rate (~1-3 µg L^{-1}) found by Steeves et al. (2022), would result in one-tenth respectively on fifth in difference in nitrogen and phosphorus when situated on the east coast. However, this is approximated and may vary depending on how well the environmental conditions are met and if they fulfill the optimal conditions recommended by the literature (Hamilton et al., 2013; Andersson et al., 2013; Valdemarsen et al., 2015; Vaquer-Sunyer & Duarte, 2008; von Thenen et al., 2020).

The environmental requirements that were factored in the equation by Davaasuren, N et al. (2010) for the Baltic Sea, weighted salinity and temperature as more important than the others. When investigating the two parameters only salinity proved to be the determining factor, This was due to the low fluctuation rate of temperature in the Baltic Sea (Smhi, 2014). The suitability analysis showed a clear difference between the primary and secondary run. The difference of 11-30 psu and 7.5-30 psu (i.e. 3.5 psu difference) resulted in an increase from 17 to 70 suitable areas. However, as has been previously stated, the salinity level has a large effect on the growth rate (Andersson et al., 2013; Hamilton et al., 2013), which could argue that the 17 primary locations may result in a better yield than the additional 53 that was found in the second run.

The overall assessment that can be drawn from the nutrient leakage analysis, is that the dominant storage and leakage is located on the west side of the county resulting in more pollution. The result showed a clear dominance of agricultural land use, with the majority located on the west-south/western side of Scania. What also needs to be taken into consideration is the availability of nutrient transportation (Djodjic et al., 2021). Several river catchments were found in the west side county, where the majority runs through agricultural lands and finally mouths out on the west coast. The nutrients transported by the river catchment result in a trend that can be seen in the measure station data. Some of the highest measured nutrient leakage data is found in direct or nearby linkage at the end of a river catchment.

A relevant question from the county's perspective is where the best location for a mussel farm would be placed if possible. With regards to the two analysis data together with literature such as Hedberg et al. (2018) Hamilton et al. (2013) and Kotta et al. (2020) the strategically best and most efficient placement would be around the center west coast. If the main focus is to improve the water quality in the Baltic Sea, however, a better choice would be to place a farm on the east or southeastern side (Kotta et al., 2020; Maar et al., 2023). What also needs to be taken into consideration is that some of the available locations found in this study are located outside of Swedish borders. This can consequently make these areas non-applicable, but it could also open a discussion for potential collaboration between countries. Danish and Swedish borders are very close; especially in the waters of Kattegat (i.e. the west coast of Scania). As some of the pollution-measuring stations are located in between the two countries it is hard to differentiate who causes the most pollution in these areas. Cross-border collaborations are at times sponsored by the EU, and considering the present state of the Baltic Sea joined mussel farming as a mitigation to the eutrophication would be an excellent project (Baltic Sea, 2023).

5.1 Improvements and future

The data that contained the measured station data was limited by the low number of active stations found around the coast. This consequently affects the decision of the best suitability location, where more stations would presumably increase the number of possible locations.

Another factor that strictly regulated the opportunity of a farm is the criteria of environment and disturbances. In the primary suitability analysis, the criteria were chosen to be very strict as it would guarantee the prerequisites needed for the mussels and a farm. An improvement that could be done for the suitability classification of the environmental requirements, would be to treat them as fuzzy logic parameters. This would probably increase the total suitable areas as well as give the overall suitability weight of the areas; ranking areas depending on their suitability fit. A second improvement that would increase the suitable areas is the classification of disturbances; specifically shipping. Shipping was set to all kinds of ship traffic, it includes non-frequent traffic such as private boats crossing the area. If this parameter would be set to only larger and more frequent ship traffic many more available areas around the coast would be suitable in the analysis.

The usage of the mussels produced by the farms may vary depending on where they are located. The center part of the Baltic Sea is considered unhealthy in regards to the fishery of food consumption as it may contain Dioxins and PCB:s (Livsmedelsverket, 2022). It can however fill other functions such as fuel for bioenergy production, food stock for animals such as poultry and fish farms, or soil fertilizer. The production in the center part of the Baltic Sea can be regarded as a recycler of nutrients where aquaculture absorbs parts of the continuous output which is then returned to land-based agriculture (Kotta et al., 2020; Hamilton et al., 2013).

From a future perspective, this could lower the present usage of imported fertilizers and maybe even as a supplement for food production.

6. Conclusion

The overall assessment of this study is that there is potential for mussel farm establishment in the ocean waters that surrounds Scania. The maps produced from the spatial analysis based on the multi-criteria analysis (MCA) found 11 suitable polygons forming an approximated total area of 5966 hectares within the study area. The spatial distributions of these polygons were found to be skewed between the two coast sides, where 7 polygons of about 4628 hectares) was found on the western side, while only 4 (2 larger and 2 miners) polygons of about (1338 hectares) on the eastern side. As expected this skewness was found to be caused by the difference in water salinity between the coast sides. The suitability is heavily dependent on the environmental requirement ranges of salinity, where a decrease from 11 psu to 7.5 psu resulted in a polygon increase of 63 new suitable areas. When looking at the selection of the suitable area in regards to eutrophication and pollution, the analysis favored the west coast as it had a higher degree of leaching from the land catchment areas; predominantly from agricultural and urban settlements. Hence, considering both the potential of mitigating the ongoing nutrient emittance and benefitting the commercial aspect, the study suggests that the waters along the western coast are the most optimal choice. However, if the aim is to improve the water quality in the more central regions of the Baltic Sea, locations suitable for mussel farms on the east/south-east coast would be a plausible option if the salinity minimum is allowed to be set at a lower threshold, having the consequence of a slower mussel growth rate in the brackish water.

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