

BLUE CARBON HABITATS

– a comprehensive mapping of Nordic salt marshes



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This publication is also available online in a web-accessible version at <https://pub.norden.org/temanord2022-506>.

Abstract

This report describes the results of the Blue Carbon Habitats - Pilot Study -project. It includes the methods used to generate the aquatic vegetation data layers, the generated data, and summaries of validation and carbon storage potential estimation results. A roadmap for expanding the production for the whole Baltic Sea region is also included.

1 Introduction

1.1 Background

Coastal wetlands, despite their relatively small global extent, are disproportionately important in sequestering carbon storage when compared to terrestrial ecosystems (McLeod et al. 2011, IPCC 2014, Pidgeon, 2009). Such vegetated coastal ecosystems (seagrass, salt marshes and mangroves) cover globally only 0.2% of the ocean surface but contribute 50% of the total amount of carbon buried in marine sediments (Duarte et al. 2013, Macreadie et al. 2017). For example, salt marshes and reed belts are a natural sink of carbon due to their primary production and, even more importantly, their efficiency in trapping sediments and carbon from the surrounded terrestrial and watershed areas. This makes these coastal habitats of high importance also for their climate mitigation services via their ability to sequester 'blue carbon'.

Surprisingly, in the Nordic countries, very little data on the extent and type of coastal wetlands (salt marshes in the south and, e.g., reed belts in the north) exists. The reason is the ambiguous role of coastal wetlands – they are not strictly habitats found in the sea or in the land. Underwater inventory programs may target coastal areas, but coastal wetlands are out of their scope. In similar manner, terrestrial inventories concentrate on land, not the transition zone where land meets the sea. Therefore, at present it is nearly impossible to estimate the potential carbon storage potential of coastal wetlands, although deemed important (Macreadie et al. 2021).

Habitat mapping from satellite images is cost-efficient and can cover large geographical areas, including inaccessible ones. The objective of this Blue Carbon Habitats pilot study is to develop advanced methods that harmonize and produce comparable maps of coastal salt marshes and reed belt across Nordic countries and test them in small areas in Sweden and Finland. The data on extent of coastal wetlands is then be used to calculate the potential of carbon storage in the Swedish case study areas. The produced maps and results of this pilot study are a first step towards data that will be of high importance for national and regional marine assessments tools that urgently need data on the potential of carbon storage, such as ecosystem accounting.

1.2 Purpose and scope

The project started in May 2021 and was finished in November 2021. It included three phases:

1. Generation of aquatic vegetation maps from Sentinel-2 satellite images
2. Validation of the satellite products and estimation of the carbon storage potential
3. Generation of a roadmap (a plan to expand the production to cover the whole Baltic Sea are) and dissemination

This report describes the final results of the project. In addition, the data can be interactively accessed in www.syke.fi/saltmarshstorymap.

2 EO based aquatic vegetation identification

This chapter presents a summary of the data generation method and the resulting datasets. More details are included in the internal technical report 'Probabilistic vegetated areas map for coastal interpretation: methodology' (available by request).

2.1 Basics of Earth Observation (EO)

Satellite instruments operating in the optical region of the spectrum (including near infrared or NIR) accurately record the sunlight reflected by a target (e.g., soil, vegetation, water, snow, ice, or cloud) with certain wavelength regions called bands or channels. The optical properties of the target affect the reflectance in different ways in different bands. This is why the human eye sees, e.g., vegetation as green (high reflectance in green wavelengths and low in red and blue wavelengths) and snow and clouds as white (high reflectance in all visible wavelengths).

By analyzing the observed reflectance, it is possible to estimate the optical properties and thus the characteristics of the target. The analysis methods vary from simple band indices to very complex neural networks.

2.2 Detection of aquatic vegetation

The identification of vegetated areas above water (reeds, sedges, rushes, macrophytes, other vegetation) in satellite imagery is based on the Normalized-Difference Vegetation Index (NDVI) estimated from EO images over the sea. In the peak growth season (mid-to-late summer), uniformly vegetated areas have high NDVI values, around 0.69 ± 0.18 (1σ , based on pilot areas in Sweden reported in this study). On the other hand, plain water has a relatively low NDVI, -0.17 ± 0.15 (1σ), and can thus be distinguished from vegetation in water.

The purpose here was to generate a probabilistic interpretation map from high-resolution EO images showing the location and extent of areas of aquatic vegetation along the coastlines of the Nordic countries. The primary interest is on common reed (*Phragmites australis*), as these are ubiquitous along the northern shores of the Baltic Sea, and have high carbon storage potential. However, the product is also sensitive to interpret other dense accumulations of aquatic vegetation, such as *Schoenoplectus* spp. or *Typha* spp.

The production requires the following input data:

- A satellite image or mosaic from the maximum reed biomass time (e.g., August) without cloud effects in the target area. An NDVI product is computed from this.
- Accurate shoreline data.

From these two it is possible to estimate the areas where vegetation exists in the water. These areas closer to the shore are assumed to be reed belts, salt marshes, etc.

Sentinel-2 satellite was selected as the source of satellite images due to its good coverage (global coverage every five days, full coverage of the Baltic Sea every three days), good resolution (10 m) and free and open data policy (anyone can download and utilize the images for free).

Monthly cloud free composite mosaics were generated in the Sentinel-2 Global Mosaic service (<https://apps.sentinel-hub.com/mosaic-hub/#/>). The Finnish demo areas had been processed earlier, so for this study we generated mosaics for July 2020 over the two demo sites in Sweden: one near Täby, Stockholm County (SOUTH), and another in Luleå, Norrbotten County (NORTH). The surface areas of these sites were 1,000 km² and 5,000 km², respectively. The mosaics were downloaded as GeoTIFF tiles in a spatial resolution of 10 m to the SYKE ICT environment and further processed into NDVI values based on the channel ratio $(B08 - B04) / (B08 + B04)$. Figure 1 shows an example of the NDVI values from Sweden.

As the interpretation is based on the distribution of the NDVI in the waters, a water mask was needed to represent the regions for which the indices should be computed. Such a mask was created by rasterizing the Swedish coastline layer (courtesy of SMHI) into polygons in 10 m spatial resolution. It was desired to avoid shoreline effects so that only those pixels are burned in the water mask which are completely contained within the water body.

In addition, a proximity layer was also generated from the land mask. This layer is a proximity map indicating the distance of each pixel in meters from the closest shore and becomes useful in the probabilistic interpretation as a greater weight should be put on pixels closer to the shore.

Finally, the NDVI tiles were mosaicked together over the same areas where there was water in the water mask. This was used as an input for the Bayesian interpretation together with the land and proximity masks.

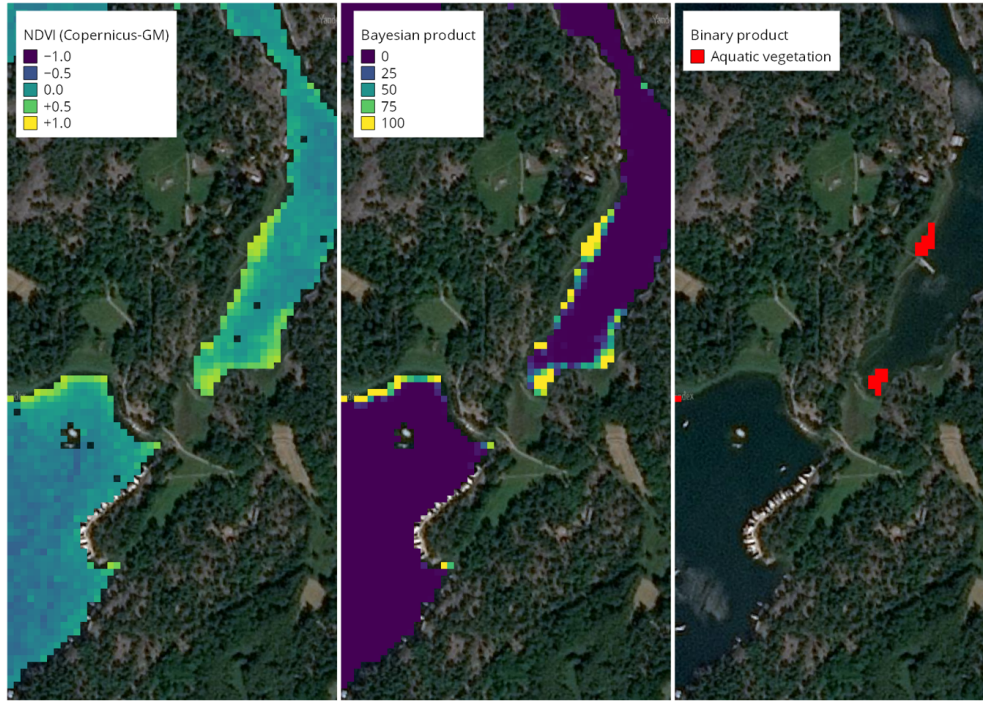


Figure 1. Left: Example NDVI monthly composite from July 2020. Yellow color indicates vegetated areas and dark blue only water. The study area is in Idholmsviken Bay in Finnhamn's nature conservation area, Stockholm County. Contains modified Copernicus Sentinel data (SYKE, 2021). Satellite orthoimagery from Yandex Maps. **The middle image:** the Bayesian aquatic vegetation product from the same area, with high probability of aquatic vegetation (in yellow). **Right:** The binary aquatic vegetation product from the same area (in red).

2.3 Probabilistic and binary datasets

A first-level approach to separating vegetated pixels from water pixels would be to use a pre-chosen NDVI threshold (e.g., 0.23) and assign all pixels with a higher NDVI than that to the vegetated class. However, choosing such a threshold is arbitrary and information is destroyed in the process. Also, this approach does not consider other factors than NDVI, for example the distance from the nearest shore, and could result in unrealistic vegetation placement outside the reasonable spatial domain.

We tested the generation of aquatic vegetation probability maps through the utilization of Bayesian methods. These can use additional information (e.g., proximity to land) in the estimation and thus give the users of the product more information than the binary (vegetation/no vegetation) version.

For a probabilistic description of the distribution of aquatic vegetation, consider the Bayesian expression

$$P(R \mid X, D) = \frac{P(X \mid D, R)P(R \mid D)}{P(X \mid D)}$$

where R is a binary variable (vegetated vs. not vegetated), X a random variable representing the observed NDVI, and D a random variable representing the proximity to shore. The probabilities in the formula above can equally well be stated in terms of probability densities for continuous random variables. The l.h.s. of the formula is proportional to the probability that the observed (X, D) pair has been sampled from

a vegetated or non-vegetated area, and therefore can be used as such as an indicator of the presence or absence of aquatic vegetation.

The likelihood tells how likely the observed NDVI value is, given that the pixel is known to represent aquatic vegetation. This can be simply represented using a parametrized distribution of typical reed NDVI values, for example in the form of a Gaussian bell curve. A set of representative vegetation edges or calibration points from near the transition between aquatic vegetation and open water were used as a reference for calibrating the Gaussian model. The process then uses bimodal distribution fitting using Gaussian Mixture Models to separate the reed component from the water component and provide the bell curve parameters necessary for likelihood estimation. An example of this is seen in Figure 2, where the rightmost component is interpreted as the 'vegetation peak' (reeds or dense aquatic vegetation). It is sufficiently well parametrized with the normal distribution. The leftmost component is distributed as $\text{Norm}(0.32, 0.74^2)$, and exhibits on average higher NDVI values than open water areas (with typical NDVIs of -0.17 ± 0.15). This may be due to turbidity effects near the shoreline, cloud errors, or sparse aquatic vegetation.

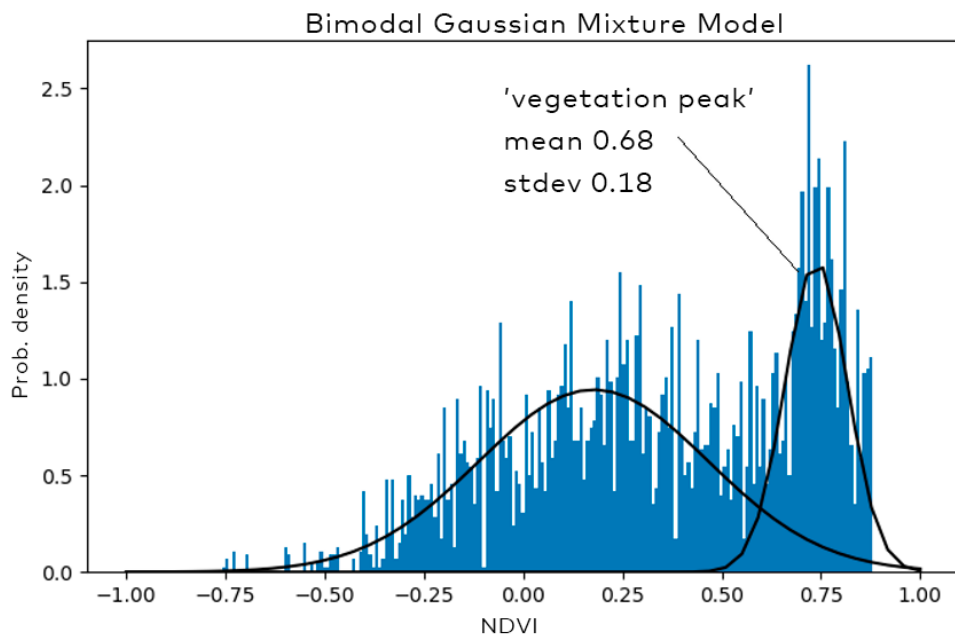


Figure 2. A bimodal mixture distribution of the NDVI values sampled at and around the representative reed edges digitized from field observations and visual comparison of satellite data and aerial orthophotos. The peak to the right is interpreted as that of concentrated aquatic vegetation, whereas the low values are interpreted as either open water or water with non-uniform aquatic vegetation.

Since the numbers resulting from the application of the Bayes formula (posterior values) are not probabilities as such but only proportional to probability, it is advantageous to scale the product so that they have consistent numeric values for comparison between different areas. One way to do this is to scale to a fixed value

(e.g., 100) a numeric threshold that gives just the right number of vegetation pixels in the binary interpretation, and then visualize the resulting product from 0 to 100. How to find this threshold is, of course, prone to subjectivism, but it may be noted that for too small thresholds, increasing numbers of pixels are (falsely) interpreted as vegetation, and for too large thresholds, hardly any pixels are interpreted as vegetation. Therefore, there is a balance or a trade-off between these two contrasting tendencies.

The trade-off can be investigated by progressively testing different threshold values for Bayesian posterior and computing the fraction of pixels that have higher posterior values. Figure 3 demonstrates the behavior of the vegetated pixel fraction as a function of the Bayesian posterior threshold. It is seen that at a posterior value of ≈ 0.17 , there is a kink in the derivative of the vegetated fraction curve. This characteristic feature can be scaled to 100 and used as an objective discriminator between reliably identified vegetation and other areas with a lesser probability to be vegetated. An example of a scaled product is seen in the middle figure of Figure 1.

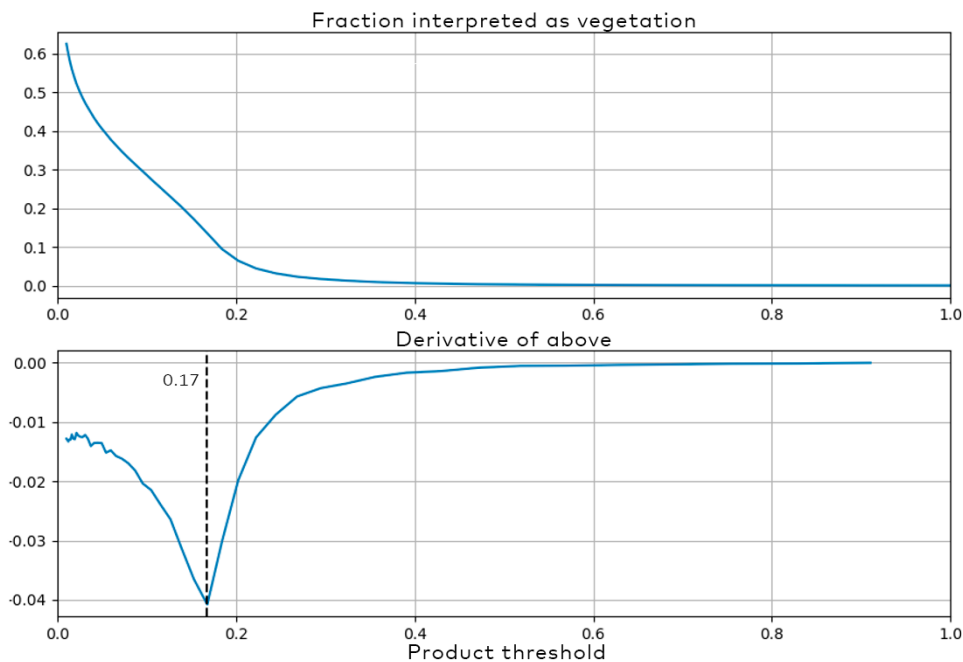


Figure 3. Objective method for choosing an appropriate threshold to scale the resulting reed interpretation maps. The line at 0.17 is close to the 'kink' in the vegetated fraction curve and is here taken as the appropriate threshold marking the upper probability limit of vegetation. If this value is scaled to be collocated with the number 100, the Bayesian posterior should be multiplied with $100/0.17 \approx 596$.

A binary product (1 = aquatic vegetation present, 0 = aquatic vegetation not present) was also generated based on the probability product using the value 100 as a threshold for aquatic vegetation. After this, small areas (< 5 connected pixels) of aquatic vegetation were filtered out of the product, and only those vegetation areas were retained that were adjacent to shorelines.

3 Validation results

The objective of validation is to determine how well the information derived from satellite images describes the actual conditions of the target. The comparison is usually done with the help of in situ 'ground truth' data. Validation can include qualitative analysis based on visual inspection by an expert and/or quantitative examination based on statistical metrics. This chapter presents a summary of the validation activities and results from the pilot areas in Finland and Sweden. More details are included in the internal technical reports (available by request).

3.1 Finland

In Finland the validation of the satellite image-based products was done qualitatively by comparing the product to aerial and satellite imagery and field measured reed outlines, and quantitatively against field observed species presence.

3.1.1 Field data

The Finnish field observations include:

1. Species observations of common reed, *Phragmites australis* (from hereon: reed) from the Finnish Inventory Programme for the Underwater Marine Diversity (VELMU). The data is mostly collected by Parks and Wildlife Finland, Metsähallitus (MH), a Finnish state-owned enterprise producing environmental services, in collaboration to VELMU. Data was selected from July and August 2019–2020. In addition, points were filtered by data collection method based on VELMU field guide, excluding dive transect and drop video survey observations, as these are collected mostly further from the shore. After filtering, 5,095 points remained. The remaining mapping methods included for instance individual dives, and inventories done with aqua scoping and harrowing. Species identities have been recorded, along with coverages as percentage (0-100%). Presence and absence was derived from this so that value 0 represents absence and all other values were considered as presence.
2. Additional data from a reed field campaign, mid-June to late August 2019. Mapping performed by MH and done by driving a boat along the outer boundary of reed belts.

3.1.2 Qualitative validation

In the qualitative validation the reed product was visually compared in QGIS software with field mapping of reeds outlines, field observations of reed coverage, and aerial photographs from National Land Survey of Finland (NLS) and satellite imagery. When comparing the field observed reed cover to the reed products, both correctly and incorrectly assigned reed presence values may be observed (Figure 4). Visual observation also shows that the exact field measured points are in many locations masked as land in the reed products.

Figure 5 shows another side-by-side comparison of aerial photography and the

binary and Bayesian product. The signal between field observations and reed products seems mixed, as reeds presence is correct at some locations which may cover only a few pixels, whereas at some locations with more continuous presence shown by the reed products the field observations show absence.

3.1.3 Quantitative validation

The quantitative validation was done by extracting values from the reed product around field observation points and then comparing the results with the field observations. With the binary product the categories of the comparison results are shown in Table 1.

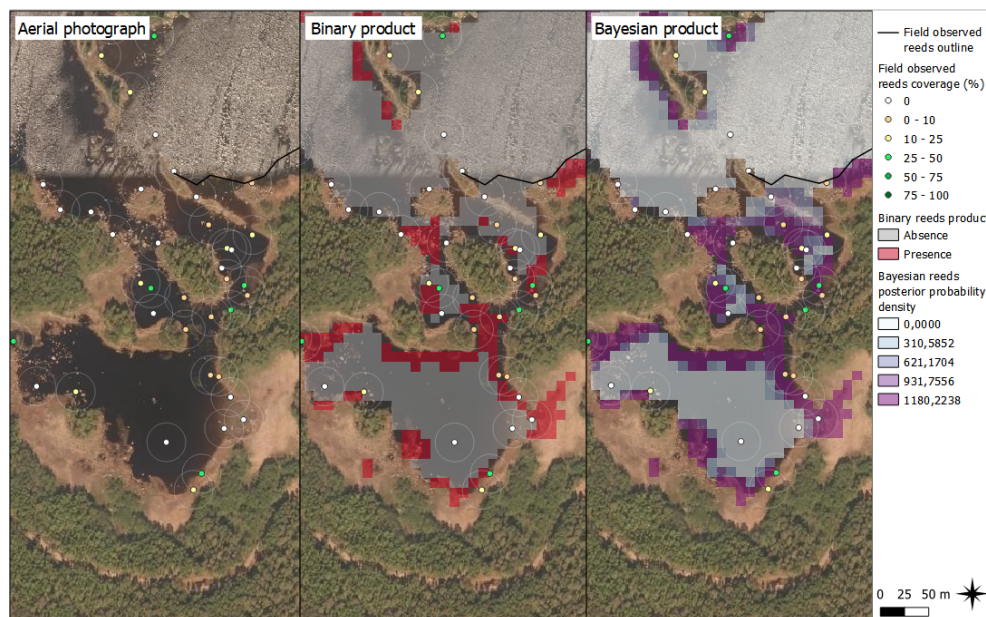


Figure 4. Example of the reeds product in Värilax, Byviken, Vaasa with VELMU observation points and Metsähallitus reeds outline mapping (line) from July 1st 2019. Circles show 20-meter radius for the points. NLS aerial photography from June 2nd 2016.

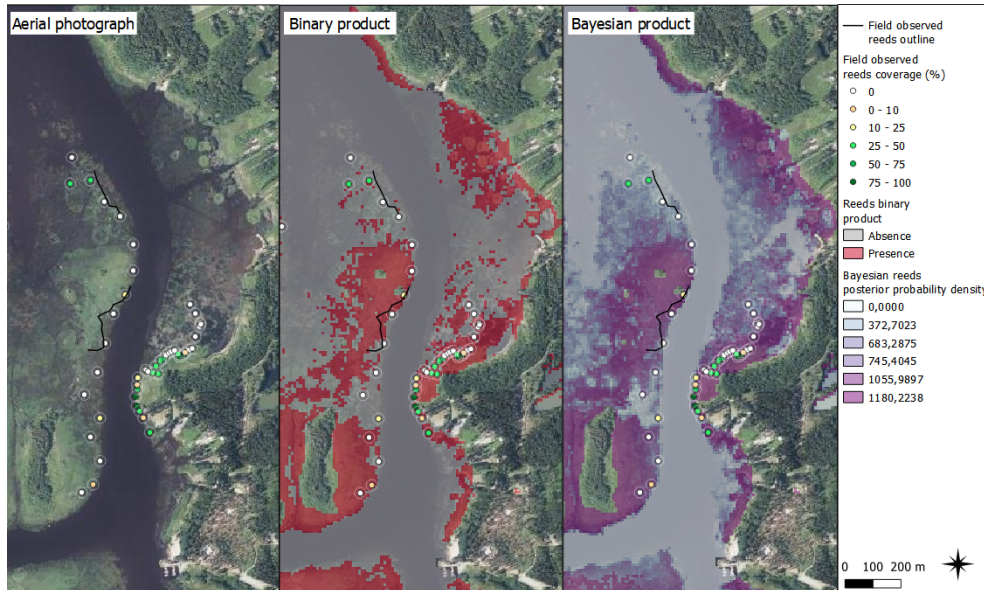


Figure 5. Söderfjärden, Vöyri. Comparison of reed products to aerial photography. NLS aerial photography from 8th to 12th September, 2016. Reeds outline mapping from 6th August, 2019. Circles indicate 20-meter radius for the points.

Table 1. Categories that resulted as point observations were compared to the reed product. Observed refers to field observations and predicted to the reed product.

Category	Explanation
Not observed, not predicted	Field observations and reeds product show absence
Not observed, predicted	Absent in field observations, present in reeds product
Not observed, NA	Absent in field observations, the pixel is masked as land
Observed, not predicted	Present in field observations, absent in reeds product
Observed, predicted	Field observations and reeds product show presence
Observed, NA	Field observations show presence, but the pixel is masked as land

The total amount of correct and incorrect matches are summarized in Figure 6 when exact point locations are used. The total high number of points with extracted NA value is because exact point easily fall outside the raster coverage near the shore as may be seen in Figure 4. Totally 69.5% of the points show correct values, 64.7% showing absence and 4.8% presence. Incorrect presence was found in 3.9% of the points and 4.7% didn't match the field observed presence.

Using a buffer with a radius of 20 meters around the field observation point reduces the number of extracted NA values as water area pixels are more likely to fall inside the buffer. In this case the total amount of correct reeds presence/absence accounts for 78.0%, 68.7% of the points showing absence and 9.3% presence. False presence

(not observed in field, present in reeds product) accounts for 14.6% of the points (Figure 7). In 5.3% of the points, observed presence is not shown in the reed product.

The field observations were also compared with the probability product (average of values within 20 m buffer around the field observation points). The average was computed from the cells that fell within the buffer. Figure 8 shows the proportions of field observed reed presence and absence for probability density values of the Bayes reeds product.

Presence observations increase with the increasing probability density value and presence accounts for roughly at least 60% of the higher end of the probability density values. The Bayes probability density doesn't seem to correlate highly with reed coverage (Figure 9). However, this may be affected by the field mapping methods of VELMU point observations as the methods concentrate on underwater mapping or mapping from boat, and may not include for example, transects through the reeds. This has the result that validation points do not cover similar geographical areas than the interpreted reeds. Inventory data is hard to obtain from the middle of dense reeds with traditional inventory methods which are not designed for such operations. Mapping the outer boundary of reeds with boats is time consuming and hard, as the environments where reeds grow are usually too shallow and impenetrable. Traditional mapping of (dense) reeds in the field is difficult, and inventories of the species living within reeds is almost impossible. Thus, satellite interpretations of the reed extent become paramount.

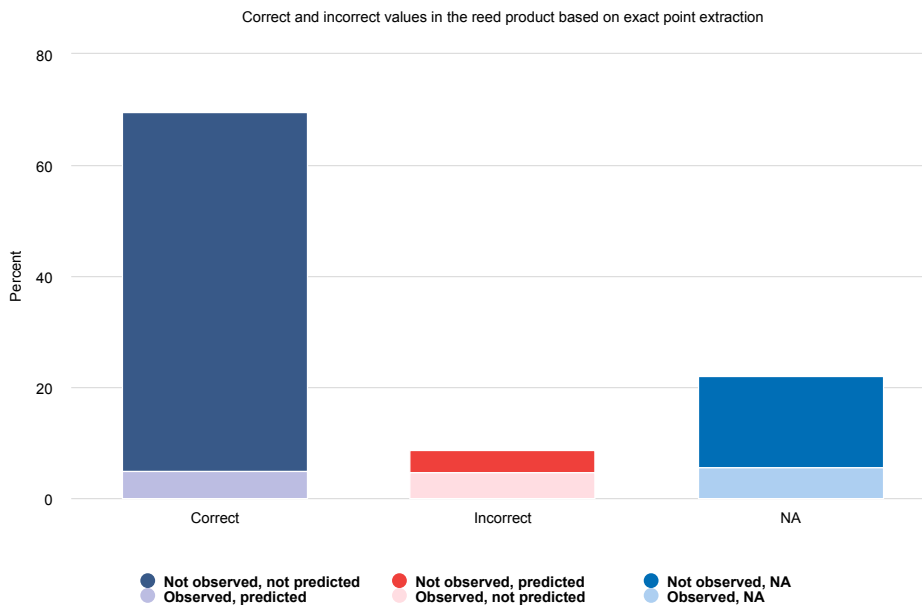


Figure 6. Summary of matches between the reed product and field observations from exact point locations.

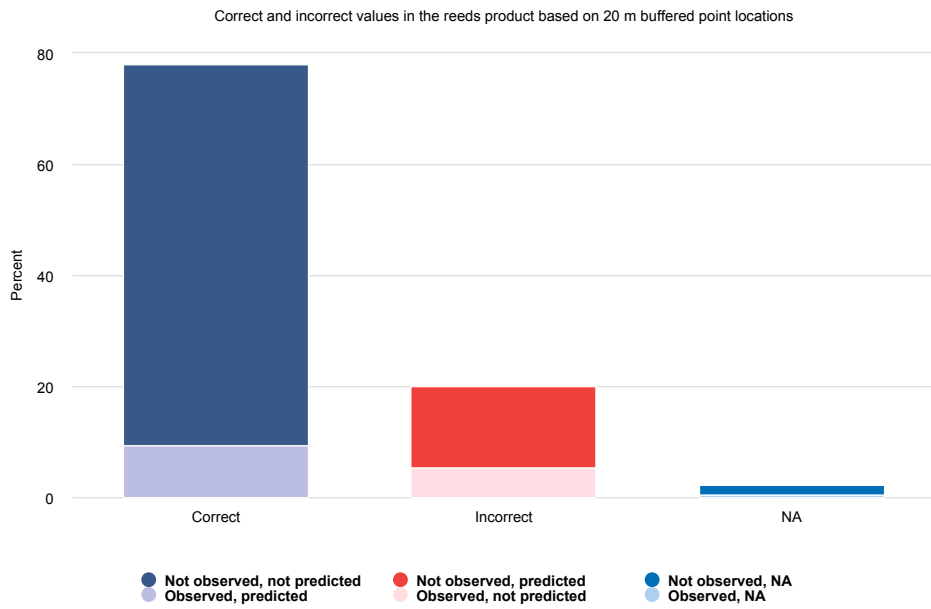


Figure 7. Summary of matches between the reed product and field observations from 20-meter buffered point locations.

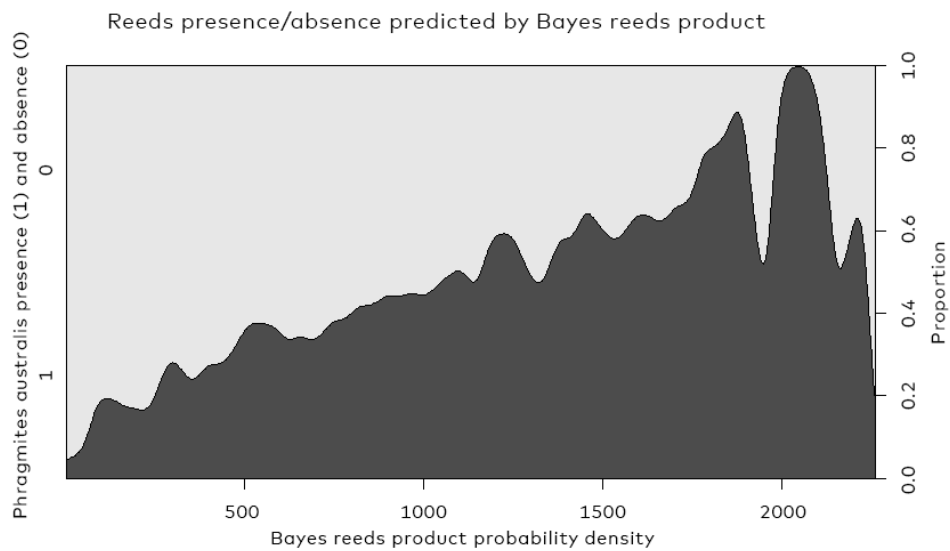


Figure 8. The proportions of reed presence (dark grey area) and absence (light grey area) as the probability density of the Bayes reeds product changes.

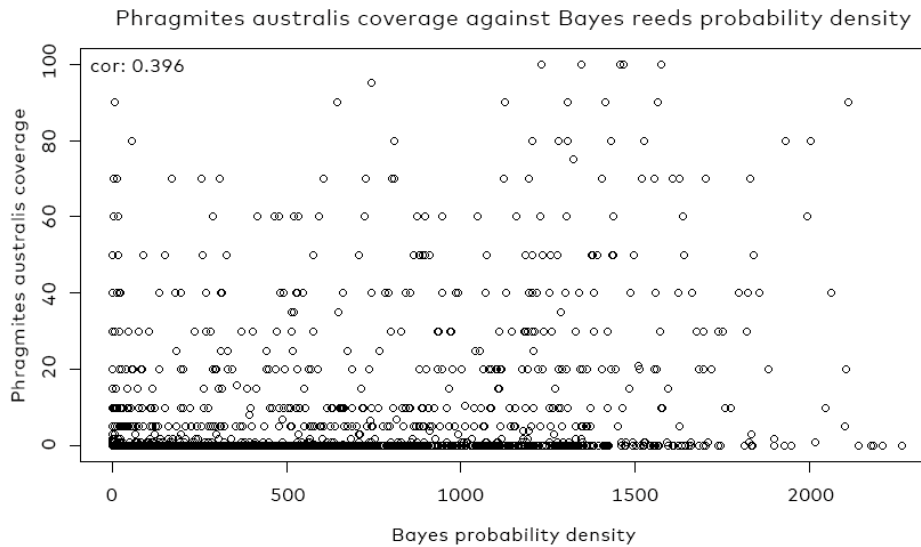


Figure 9. Reed coverage against probability density of the Bayes reeds product.

3.1.4 Conclusions

Visual comparison of the field mapped reed outlines and the reeds product seem to align in general though some variation exists partly due to the resolution (10 m) of the reed products. Limitations of the resolution are most visible near the shore, where pixels may not exactly follow the varying shoreline. In addition, defining the actual shoreline may be challenging as transition from land cover to water may not be easily interpretable in densely vegetated coastal areas or due to varying water level.

There is a 4-year time difference between the aerial images and the satellite images used in the reed product generation. Also, the aerial images are often taken in early summer when the reeds are not yet fully grown. These can explain part of the observed differences.

The large number of absence observations in the point data set may slightly skew the results of the binary comparison. However, looking at the presence observations, correctly predicted presence is slightly larger than incorrectly predicted presences (4.8% vs. 3.9% of the points, respectively) at exact point locations. Results of the buffered point comparisons imply there is some inconsistency between the predicted and observed reeds presence which is shown by the extracted values categorized as 'Not observed, predicted' and 'Observed, not predicted'.

Posterior probability density of the Bayes reeds product seems useful to predict the reed presence though was not found to be strongly linked to the species coverage. As some uncertainty remains due to the field mapping methods, more specific study would provide more detailed results. For instance, reed mapping campaign designed for validating satellite imagery would be needed.

3.2 Sweden

3.2.1 Field data

A characteristic feature of lagoons and estuaries along the coasts of the Baltic Sea is the dominance of reeds (*Phragmites spp.*). *Phragmites* stands commonly colonized many coastal meadows along the Swedish coast when cattle grazing declined 50 years ago. Reed wetlands are ecologically valuable ecosystems and play an important role for nutrient and matter cycling as well as for biodiversity (Kartens et al 2019).

In order to validate the two products, data from observations of *Phragmites spp.* were selected from the Swedish sea-shore inventory (<https://www.slu.se/centrumbildning-och-projekt/datavardskap-naturdata>). The abundance of *Phragmites* is measured along 10 meters wide transects perpendicular to the shoreline where the extent (in meters) and mean cover is registered in each transect.

The sea-shore inventory uses a balanced multi-stage sampling design that combines 3D interpretation of aerial images and field sampling. The inventory is financed by the Swedish EPA and the data is primarily used in the assessment of the European Habitats Directive, which ensures conservation of a wide range of endemic species and habitat types. In this validation we have used all surveyed field plots from 2013–2021 in the two test areas. These point locations (254) were used for reed validation following three steps:

1. manually by overlaying the points over the binary and probabilistic products;
2. automatically by checking if the raster model predicts *Phragmites* within a buffer of 20 m to the point;
3. comparing the products also with respect to the length and density of the reed belts

3.2.2 Validation of the binary product with the field observations

Observation points were overlayed to the binary products (Figure 10). As many observation points are in inland areas, buffered areas of 20 m for all observation points were calculated. Shared cells between points and rasters were extracted and the average was computed from the cells that fell within the buffer. Based on these steps, a weighted mean was calculated. For the binary products, raster cells covered by the polygons were categorized as:

- "not predicted, not observed", when both the 'length' variable and the weighted mean value of the cells is zero;
- "predicted, observed", when both the 'length' variable and the weighted mean value of the cells is more than zero;
- "predicted, not observed", when the 'length' variable is zero but the weighted mean value of the cells is more than zero;
- "not predicted, observed", when the 'length' variable is more than zero but the weighted mean value of the cells is zero

The results are shown in Figure 11 and Table 2. They indicate an overall model accuracy of 70.8% (95% confidence interval)

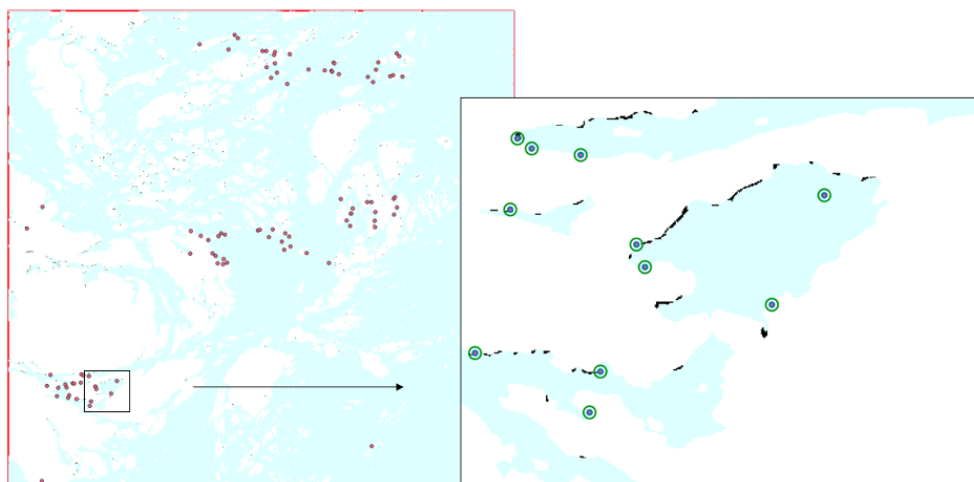


Figure 10. Close up of an area with point observations (red dots) buffered of 20m (blue circle) and 50m (green circle), overlayed to the binary product on the southern demo area (0 = no vegetation (light blue area); 1 = vegetation (small black areas). White areas are inland areas.

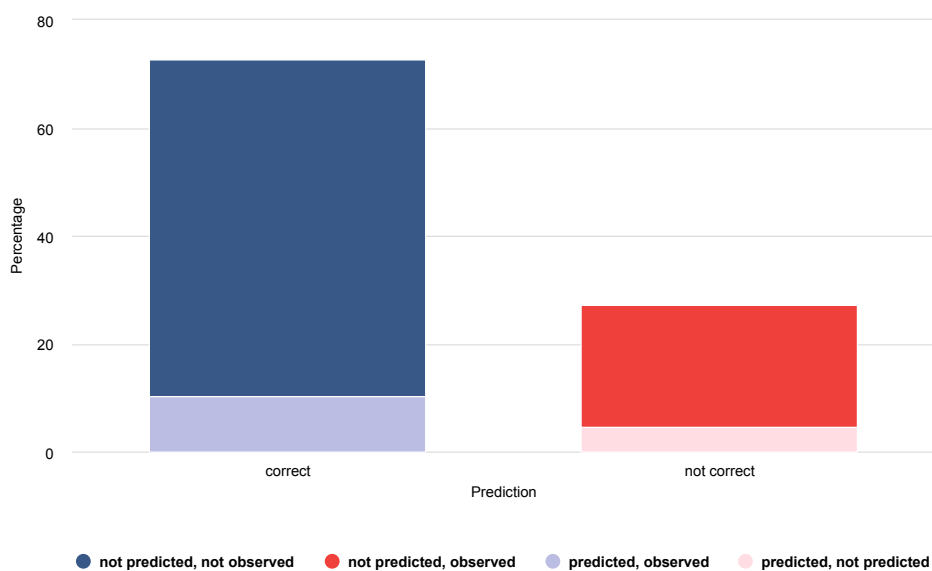


Figure 11. Percentage of observations with 20m buffer over binary products (North and South). Observed refers to field observations and predicted to the values extracted from the reed products (n = 254, of which NA = 21).

Table 2. Confusion matrix for reed area in Southern and Northern Sweden.

	Accuracy (%)	User Accuracy (%)		Producer Accuracy (%)	
		Predicted reed	Non-predicted reed	Observed reed	Non-observed reed
Sweden	70.8	74	70.3	24.6	95.3
North	72.6	68.1	73.3	31.2	92.8
South	67.8	100	65.8	15.1	100

3.2.3 Validation of the Bayes probability product with the field observations

Observation points were overlayed to the probabilistic products. As many observation points fell in inland areas, buffered areas of 20 m and 50 m for all observation points were calculated. Shared cells between points and rasters were extracted and the weighted mean was computed from the cells that fell within the buffer. The following aspects were investigated:

- Number of observations over probability range values (when length or density = 0, not observed reeds)
- Relationship between length of Phragmites along the transect (m) and the probability range values
- Relationship between density of Phragmites (%) and the probability range values

When length/density = 0, there is 'no observed' reed, which is shown in the histograms (Figure 12). However, this value does not always correspond to low probability values. Figure 13 shows the situation as a scatter plot.

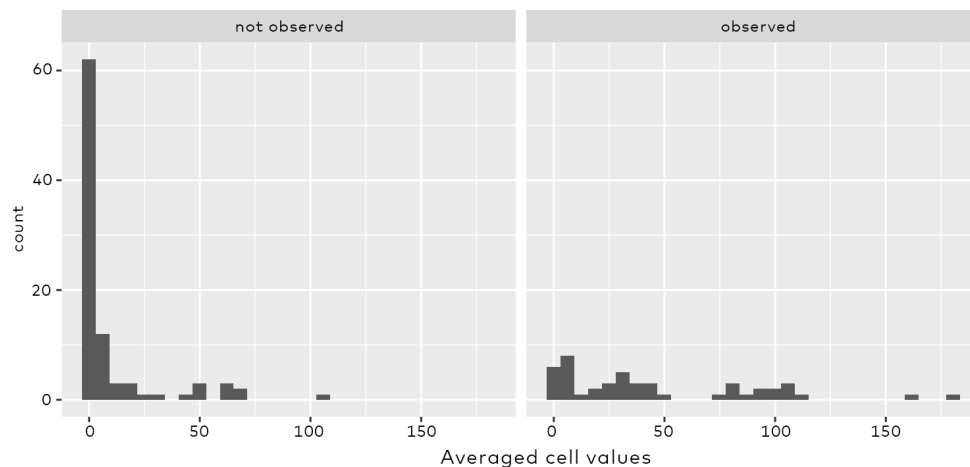


Figure 12. Observation distribution with 20m buffer over probability density (North), based on length.

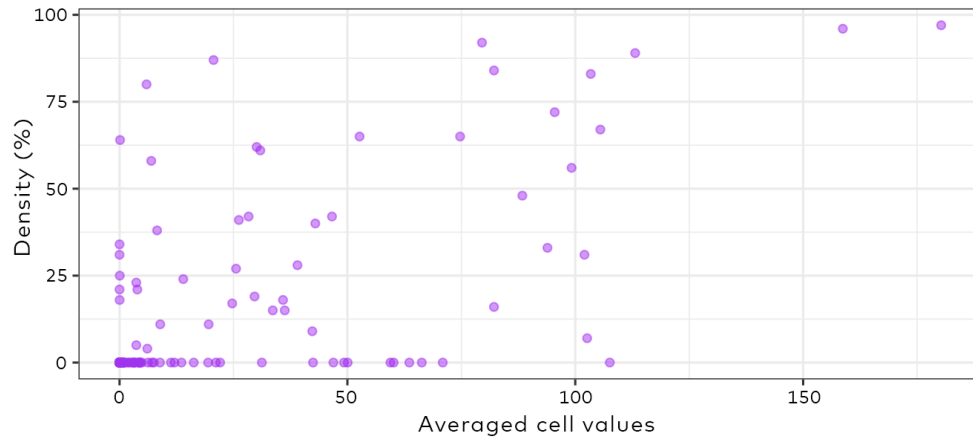


Figure 13. Relationship between reed density (%) and probability values (North, 20m buffer).

3.2.4 Conclusions

Visual comparison of the field mapped buffered reeds observations and the reeds products do not always seem to align in general, though some variation exists partly due to the resolution (10 m) of the reeds products. Limitations of the resolution are the most visible near the shore, where pixels may not exactly follow the varying shoreline. Results of the buffered point and binary product comparisons show that there is some inconsistency between the predicted and observed reeds presence which is shown by the extracted values categorized as 'Not observed, predicted' and 'Observed, not predicted'. The Bayes probability product seems useful to predict the presence of *Phragmites* spp. and compare it to the results from the binary product, though was not found to be strongly linked to the species density nor length values. Moreover, there could be some limitation when using binary products for reed validation, as these are based on NDVI which also include other type of vegetation besides *Phragmites* spp., like macrophytes. Also, to better validate the satellite products, in the case of Swedish reed belt areas, more direct field measurements would be desirable.

The about 70% prediction accuracy of the binary products seems satisfactory and as some uncertainty remains due to the field mapping methods, more specific studies about actual reed density measurements would provide more detailed results.

4 Estimation of blue carbon stock in Swedish coastal reed beds: methodology

4.1 Background

Coastal ecosystems are some of the most productive on Earth. They provide essential ecosystem services important for climate adaptation and resilience along coasts, such as coastal protection from storms, nursery grounds for fish, erosion prevention along shorelines, coastal water quality regulation, and sediment trapping (Lovelock and Duarte, 2019).

In addition, these ecosystems help mitigate climate change by sequestering and storing significant amounts of carbon, known as coastal blue carbon, from the atmosphere and oceans (Duarte et al. 2010; Lavery et al. 2013). It is estimated that carbon accumulation rate per unit area is 30–50 times higher in coastal wetlands than in terrestrial ecosystems (Mcleod et al. 2011; Kelleway et al., 2016). However, coastal ecosystems do not only capture carbon from the atmosphere but also emit it mainly in form of methane, which is produced through microbial processes in the sediments (Rosentreter et al. 2021). This underlines the importance of mapping these habitats.

In the Baltic Sea, the main blue carbon ecosystems are represented by seagrass meadows, macroalgal belts and reed beds. Some estimate of carbon sequestration and storage in Baltic coastal ecosystems have been reported mainly for seagrass meadows, wetlands and sediment (Brix et al. 2001; Jankowska et al. 2016; Rohr et al. 2016; Nilsson et al. 2019; Scheffold and Hense, 2020).

This chapter describes the estimation of blue carbon storage in reed beds dominated by *Phragmites* communities in Swedish coastal areas, based on the validation results of the binary reed products over two demonstration areas in Sweden, southern (near Stockholm) and northern (near Piteå).

4.2 Data used for blue carbon estimation

Results from the validation assessment (see Chapter 3.2) were used to estimate the carbon storage in *Phragmites* communities. In particular, the coverage of the predicted reed areas from the binary products, and the user's prediction accuracy were used.

4.3 Calculation of carbon stored in *Phragmites* spp.

Total carbon storage in reed beds was calculated by multiplying a carbon conversion factor, which represents the fraction of carbon in vegetation and varies with vegetation type, and the vegetation biomass (Howard et al. 2014). This project only considered the dominant vegetation of the estuary salt marsh communities,

Phragmites australis, for which the carbon conversion factor is 0.45 (Howard et al. 2014). Values were estimated with (and shown in Table 3):

$$C_{tot}(kg\ C) = SB(kg) \times 0.45$$

$$C_P(kg\ C/m^2) = C_{tot} / A_P (m^2)$$

where C_{tot} is the total carbon content in our estimated reed area, SB is the above-ground standing biomass of *Phragmites* in our estimated reed area, C_P is the carbon content per unit area and A_P is the area occupied by the *Phragmites* communities.

Due to lack of reed biomass data from the test areas, SB was estimated using the reed area and yield data from Southern Sweden (lital et al. 2012) as a proxy for reed biomass in our test areas as shown:

$$SB = [BM(kg) / A(m^2)] \times A_P(m^2)$$

where **BM** is the total reed above-ground standing biomass (1, 150,000 t) and A is the total reed area (230,000 ha) from lital et al. (2012).

A_P was estimated using the overall predicted reed area from the binary reed products and the user's prediction accuracy, based on the error matrix created for the validation assessment (Figure 14) (Olofsson et al. 2014).

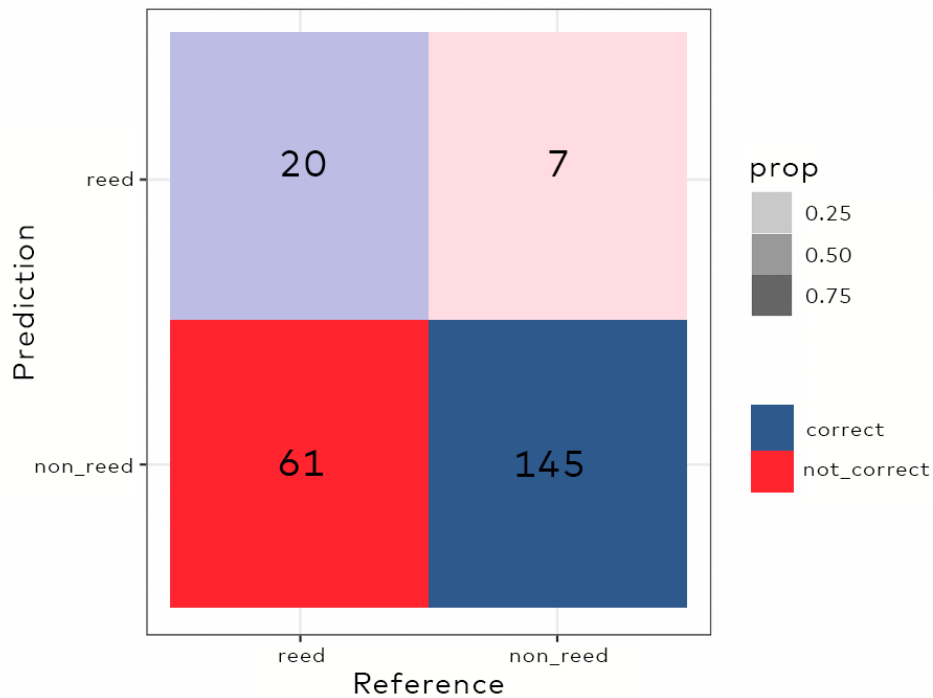


Figure 14. Confusion matrix showing field observations with 20m buffer (Reference) over modelled observations (Prediction). The proportion (prop) shows the sensitivity (true positive rate) or the specificity (true negative rate), or their complements, within each reference group. Blue = Correct prediction; Red = not correct prediction.

Table 3. Results from the reed biomass, area and carbon stock estimation. (UA = user's accuracy; V(UA) = UA variance; CI(UA) = UA confidence interval).

	Overall predicted area (m ²)	UA	V (UA)	CI (UA)	Overall estimated reed area AP (m ²)	Estimated reed biomass average (kg)	Estimated total C stock biomass (kg)	Estimated C stock average per unit area (kg C/m ²)
Values	7,120,000	0.741	0.002	0.096	5,270,000 ± 680,000	2,640,000 ± 340,000	1,190,000 ± 150,000	0.25

4.4 Conclusions

Phragmites australis wetlands can act as a sink for greenhouse gases by photosynthetic assimilation of carbon dioxide (CO₂) from the atmosphere and sequestration of the organic matter produced in the wetland soil. However, they can also act as a source for greenhouse gases by emission of sediment-produced methane (CH₄) to the atmosphere.

This study only includes estimates of blue carbon stock in *Phragmites* communities, and does not consider emissions of methane, which is important to include in blue carbon assessments as it reduces the net carbon uptake.

In fact, the balance between net CO₂-assimilation and CH₄ emission determines if a wetland can be regarded as a net sink or a net source of greenhouse gases, and hence, the function of the wetland in relation to global climate change (Brix et al. 2001; Abril and Borges, 2004).

The largest sources of uncertainty in the presented estimation of blue carbon stock in *Phragmites* communities are represented by the reed area estimation using EO, the reed biomass estimation using data from Southern Sweden (Iital et al. 2012) as a proxy, the use of the conversion factor (Howard et al. 2014), as well as the missing information on sediment recycling, burial rates, and sea/air carbon fluxes.

To reduce uncertainty in blue carbon estimated values, more information about *Phragmites* shoot density (stems/m²), dry or wet weight and stem height would have provided a more realistic estimation of the reed biomass. Moreover, more frequent and updated measurements of C stocks and C accumulation rates in sediment and vegetation – including field-based and remote sensing methods – are essential for improving estimates of C sequestration. For example, spatial mapping of normalized differential vegetation index (NDVI) and bare soil index (BSI) has proven to be an efficient way of determining soil organic carbon (SOC) distribution for different types of landscapes, which needs then to be compared with existing field SOC data (Francis et al., 2020). Such EO and field observations and maps may be used to address knowledge gaps and uncertainties to guide conservation planning and restoration efforts in reed beds and other vegetated coastal ecosystems. Moreover, blue carbon budgets may be incorporated into national

greenhouse gas inventories.

However, we still lack enough understanding of the factors that control the variability of C sequestration in vegetated coastal ecosystems. Specific field studies accounting for C sediment recycling, burial rates, and sea/air carbon fluxes are needed to improve this understanding and strengthen the case for the value of blue carbon sinks (McLeod et al. 2011). By strengthening our knowledge of the blue carbon sequestration potential and the associated biogeochemical processes, it is possible to better identify and manage priority areas for conservation and restoration.

5 Roadmap

5.1 Overall goals

The overall goal of this roadmap is to outline the steps needed for expanding the production of satellite based aquatic vegetation material and subsequent analyses into the whole Baltic Sea area. During the project the team has identified the following drivers that help define what this means in practice:

- **Start from the data needs point of view.** This means that the focus should be on what is the most useful information for different users. Thus, there must be a balance between versatility and simplicity.
- **The monitoring should be continuous.** The resulting system should be able to provide the required information e.g. once per year which is sufficient for decision making needs.

Extend the method for underwater vegetation. Emerging vegetation such as reeds are just one part of aquatic vegetation. Using satellite-based methods for biodiversity and its loss, carbon sequestration and spatial changes in habitat forming species such as Bladderwrack are important topics to keep in mind.

5.2 Satellite data processing

Chapter 2 above described how the satellite image based products were generated for the demo areas in Finland and Sweden. The provision of S2 based reed/aquatic vegetation products from the whole Baltic Sea area requires scaling up the process to cover a larger area.

The processing uses two data sources:

- Monthly cloud free composite mosaics from the Sentinel-2 Global Mosaic service
- Shoreline data from Sweden and Finland

Global Mosaic service can generate the required data from the whole Baltic Sea area. The processing time scales linearly as do the post processing phases. Using the Global Mosaic service is free of charge, so the costs are mainly due to labor needed to automatize the system to handle data flow and the post processing steps.

As mentioned above provision of annual data is sufficient for decision making. However, the optimal month can vary in different parts of the Baltic Sea. Thus, it may be necessary to produce monthly products (e.g. June, July, August) and then compute the yearly dataset from those. This further increases the processing and data handling requirements. In addition, a method that selects the optimal annual value from the monthly values for each pixel must be developed. This step still requires research.

Above we generated two kinds of products: Probabilistic and binary. The validation did not show any clear advantages for using the probabilistic product, so we propose that the binary product is generated in the large-scale data production since this simplifies the processing and is also easier to utilize.

The project has access to shoreline data from all Finnish and Swedish coastal areas so it is possible to redo the processing there. For other Baltic Sea countries who may not be willing to share the coastline data the Copernicus coastal zones data could be used. This product is available from land.copernicus.eu/local/coastal-zones and provides a detailed LC/LU dataset for areas along the coastline of the EEA39 member states.

The input data for the product includes Coastal Zones Aol, satellite image data (mainly Very High Resolution or VHR instruments), and various other datasets such as the Corine Land Cover, Urban Atlas, GIO HR Layers, National orthophoto WMS, Google Earth, Bing Maps, and numerous additional reference and in-situ data sources. The methodology used for generating the product is based on semi-automatic LC/LU classification, computer assisted visual refinement and visual interpretation. See GeoVille 2021 for more details.

The product has 71 distinct thematic classes including Salt marshes, Salines and Intertidal flats which are relevant for this project. Since Salt marshes are included in this European wide product one may wonder why this project is producing salt marsh information from S2 data. There are several reasons which are described below.

According to the documentation (GeoVille 2021) the Salt marshes category includes:

- Muddy areas covered by water in coastal salt marshes.
- Vegetated beds in salt marshes including reed coverage (basically salt-tolerant plants, but also sedges and rushes).
- Salt marshes in delta areas, estuaries, intertidal flats and coastal lagoons (with or without vegetation coverage).
- Floating aquatic vegetation.

Thus, the product includes areas that are not covered by vegetation. If the main interest of the user is to estimate the carbon storage of vegetation the product may lead to overestimations.

The Minimum Mapping Unit of the product is 0.5 ha, which is equal to 50 Sentinel-2 pixels (10 m). Thus, small salt march areas are not included in the product. The example in Figure 15 shows that the SYKE product is able to predict the outer edge of reed areas better than the CZ product. On the other hand, the CZ product is able to better follow the shape of the reed area in the shoreline. At least in this case the Finnish shoreline data goes in the middle of the reed belt and causes this underestimation. While further analysis is needed it might be beneficial to use the CZ polygons in the S2 based processing.



Figure 15. Comparison of Copernicus Coastal Zone product and SYKE reeds product near Helsinki, Finland. The image on the **left** shows a true color S2 image taken on July 13, 2021. Reeds are visible as light green areas along the shores. The **center** image shows the SYKE reed product (dark grey over the areas where the CZ product shows water and dark blue over the areas where the CZ product shows salt march) over the Coastal zone product. The image on the **right** shows the Coastal Zone product where salt marches are indicated with light blue.

The CZ product has been generated for 2012 and 2018 reference years so the update frequency is low. Users have expressed interest for annual updates and while the production schedule of the next Coastal Zones product is not clear at the moment (2024 is likely but could also be 2021) the update frequency will be too low for this goal.

Finally, at the time of writing this, the coastal zones data has not yet been validated. The documentation states the following "Overall thematic accuracy demanded is $\geq 85\%$ and class specific user and producer accuracy is $\geq 80\%$, always taking into account the relative occurrence of the LC/LU classes" but the actual accuracies need to be examined.

As a summary, we do not foresee any roadblocks that would prevent the production or require large amounts of research to take place before the production can start. The exception to this is the extension of the method for underwater vegetation. That is still a topic which requires significant amount of research before implementation.

5.3 Validation of aquatic vegetation data

The objective of validation is to assess the quality and accuracy of the satellite-based products when compared to other data sources (also called Ground Truth). As shown above in Chapter 3 the available in situ data is often not optimal for the validation of satellite-based salt march products. E.g., the characteristics of point or line type data do not allow comparison of reed areas and the number of data points remains low. This chapter concentrates on defining the kind of additional data that would be more useful for validation work in the future and streamlining the validation process so that it can be repeated in different areas of the Baltic.

As an example, in Finland the in-situ data collection usually takes place from a boat along the edge of the reed belt and observations within a dense reed belt are underrepresented. This can cause a bias to the analysis. Thus, the in-situ data

collection should include more samples within the reeds. Since this is difficult logistically, another solution is to utilize area estimates from drones or aerial imagery. Optimally, the sensor used in the image acquisition should include NIR and Red bands so that NDVI method can be used here as well. This would allow overlaying the two products in a GIS application and computation of statistics.

The timing of the image acquisition must be selected with care. The national aerial imagery in Finland is often taken in the spring or early summer (optimized for different objectives) which prevents observations of fully grown reeds. Including drone observations in in situ campaigns would have the advantage of being able to select the optimal observation time. However, collecting enough images will require a significant amount of time.

5.4 Carbon storage calculations

As shown above in chapter 4, this project estimated blue carbon storage in one of the main blue carbon ecosystems dominated by *Phragmites* communities in Swedish coastal areas, based on the validation results of the binary reed products. Also, it only included estimates of blue carbon stock in reed beds, and did not consider emissions of methane, which is important to include in blue carbon assessments as it reduces the net carbon uptake.

Total carbon storage in reed beds was calculated by multiplying a carbon conversion factor and the vegetation biomass (Howard et al. 2014). Due to lack of reed biomass data from the test areas, the reed area and yield data from Southern Sweden (Iital et al. 2012) were used as a proxy for reed biomass estimation in the test areas.

Overall, more frequent and specific studies accounting for shoot and rhizome density and weight can provide a more certain estimation of the wetland above- and below-ground biomass. Furthermore, more studies accounting for the fate of dissolved organic carbon (DOC) production from the wetlands, C sediment recycling, burial rates, and sea/air carbon and methane fluxes are needed to reduce uncertainties in blue carbon assessments and improve the understanding about the value of blue carbon sinks. For example, spatial mapping of normalized differential vegetation index (NDVI) and bare soil index (BSI) has proven to be an efficient way of determining soil organic carbon (SOC) distribution for different types of landscapes, which needs then to be compared with existing field SOC data (Francis et al., 2020). However, the rates of sediment carbon sequestration and DOC production can be difficult to determine as there is a large variation between species and ecosystems, and across seasons and water column.

In addition to this, knowing the balance between net CO₂-assimilation and CH₄ emission determines if a wetland can be regarded as a net sink or a net source of greenhouse gases, and hence, the function of the wetland in relation to global climate change, as the emissions are likely to increase with eutrophication and global warming. As a matter of fact, measurements made in the Baltic Sea during the heatwave in 2018 showed record-high levels of released methane from the coastal zone (Humborg et al., 2019).

Continuous research in the Baltic Sea could improve our understanding of blue

carbon ecosystems, for example blue carbon budgets may be incorporated into national greenhouse gas inventories. By strengthening our knowledge of the blue carbon sequestration potential and the associated biogeochemical processes, it is possible to better identify and manage priority areas for conservation and restoration. Besides, the blue carbon storage budgets can then be also added with more certainty in regional wide Baltic Sea assessments, like the Baltic Health index (Blenckner et al 2021), providing a more comprehensive view of ocean health and the benefits for humans.

6 Summary

The results show that locations of reeds (and salt marches) can be interpreted from Sentinel-2 images with the method described in Chapter 2. Thus, satellite imagery would be valuable for monitoring the extent of reed belts, their growth and removal (e.g. cutting down the reeds as required by the Marine Strategy Framework Directive).

The comparison of field data and satellite products is not straightforward due to the differences in data types and the way the field data is collected. For example, the field inventory methods are not the same in Finland and Sweden which makes it difficult to make a combined assessment. For instance, in Finland, field surveys of the reed belt cover, and of the accompanying vegetation, are not routinely done. Field data exists only for other purposes, such as surveying underwater nature, which causes bias to the validation data (e.g. sampling strategy favors water areas). Nevertheless, the results indicate that the estimation accuracy with the satellite-based method is good (>70%) both in Finland and Sweden. Visual comparison of the satellite-based reed product with aerial images shows similarities and differences. The differences between data characteristics and temporal range may explain some of the differences here also.

Sentinel-2 was chosen here as the main source of satellite imagery since it provides free data continuously with 2–3-day repeat cycle (cloud cover permitting) in the Nordic region. The continuous observations allow one to choose the time period most suitable for observing the maximum extent of salt marches and to monitor their evolution. Other option would be to utilize VHR instruments. They can provide salt march information with sub-meter resolution but are not optimal for large scale processing due to infrequent observations and cost issues. The Copernicus programme provides free VHR mosaics but only with 6-year intervals.

The estimated reed area was used in the estimation of the carbon stock in the Swedish pilot areas. The uncertainty in the estimation of the reed area is only one of the uncertainties in the carbon stock estimation process, and further work is needed to reduce the effects of all error sources.

The Roadmap in Chapter 5 outlines the steps needed to extend the production to cover the whole Baltic Sea region. These include:

- Automatization of the production system to provide Baltic Sea wide salt march coverage annually
- Promote the collection of in situ data that is more suitable for validation of EO based salt march information (e.g. timing of aerial imagery towards August, include drones in campaigns, and sampling within reed belts)
- Improve the carbon storage calculations by collecting more data about carbon conversion factors, shoot densities (stems/m²), dry or wet weights and stem heights in different areas of the Baltic Sea.

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About this publication

Blue Carbon Habitats

*a comprehensive mapping of Nordic salt marshes for estimating Blue Carbon storage potential
– a pilot study*

funded by the Nordic Council of Ministers

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ISBN 978-92-893-7243-5 (PDF)

ISBN 978-92-893-7244-2 (ONLINE)

<http://dx.doi.org/10.6027/temanord2022-506>

TemaNord 2022:506

ISSN 0908-6692

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Cover photo: Hendrick Morkel / Unsplash

Published: 24/2/2022

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