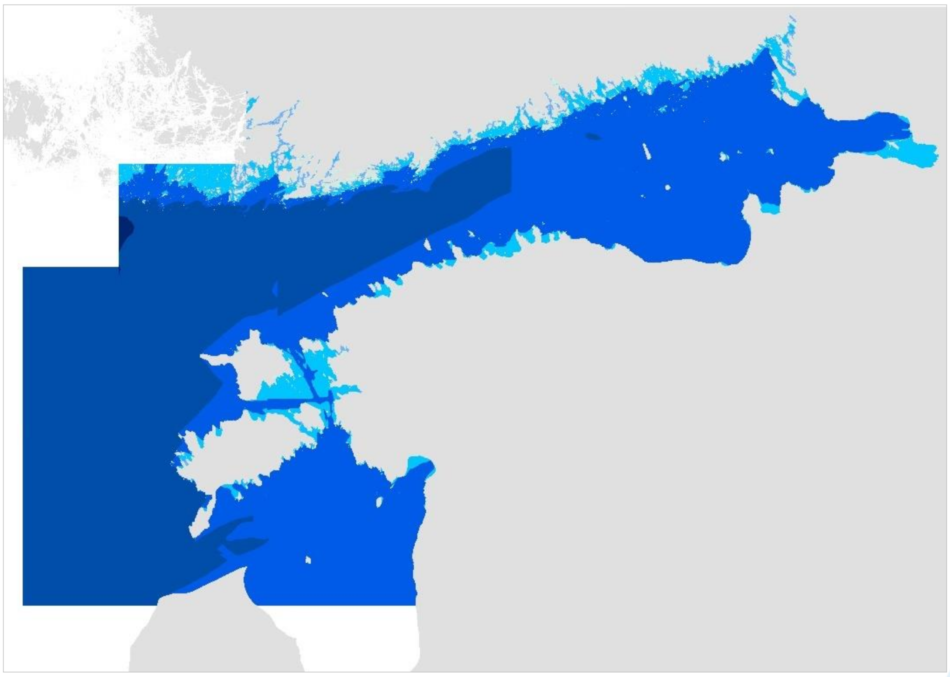
Wave exposure calculations for the Gulf of Finland

Felix van der Meijs and Martin Isaeus
AquaBiota Water Research



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S T O C K H O L M , D e c e m b e r 2 0 2 0

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CONTENTS

SUMMARY

Wave exposure is one of the major factors structuring the coastal environment and is an important parameter in both coastal research and management.

The aim of this project was to construct wave exposure grids covering the entire Gulf of Finland and the Estonian coast, using the Simplified Wave Model method SWM (Isaeus 2004). The wave exposure was calculated for mean wind conditions represented by the seventeen-year period between January 1, 2003 and December 31, 2019, using wind data correlating with 'current' or 'future' environmental conditions.

A nested-grids technique was used to ensure long distance effects on the local wave exposure regime, and the resulting grids have a resolution of 25 m. The methods used and described in this report incorporate the division of the shoreline into suitable calculation areas, the selection of wind stations and processing of wind data, the calculation of fetch and wave exposure grids, and subsequently the integration of the separate grids into a seamless description of wave exposure along the Gulf of Finland.

The digital versions of the merged grids were delivered to the Estonian Marine Institute at the University of Tartu in December 2020, and a printed version of the 'current'-scenario is found here in Appendix.

1. INTRODUCTION

Geographic Information systems (GIS) have become an important tool for management as well as for research. This development has raised a demand for maps or models describing the environment to be used as input layers for the GIS analyses. Wave exposure is one of the major factors structuring the coastal environment, and the aim of this project was to construct wave exposure grids covering the entire Gulf of Finland and the Estonian coast.

Wave exposure can be estimated in many ways and the method chosen for this project was the Simplified Wave Model (SWM), calculated with the software WaveImpact 1.0, which is fully described in the thesis by Isæus (2004). The method is called simplified since it uses the shoreline and not the bathymetry as input for describing the coastal shape. This is an adoption to the fact that bathymetry data of sufficient spatial resolution is often unavailable or confidential and therefore of restricted use. The method has been tested successfully in the Stockholm archipelago and it was also found to be the most ecologically relevant method in a comparison with three other wave exposure methods along the Norwegian coast (FWM, STWAVE, Norsk Standard; Bekkby et al., in prep; Sundblad et al., 2014).

SWM has earlier been used for wave exposure calculations of the entire Swedish, Norwegian, and all Baltic coasts. The use of the same method for describing the physical environment facilitates the comparison between all these coasts, and the implementation of common classification systems, such as EUNIS.

2. METHODS AND MATERIALS

2.1. Land/Sea grids

In order to include large areas in the model, but still deliver high-resolution grids, SWM uses a nested-grids technique. In this case a coarse grid (500 m cellsize) covering the major part of the Baltic Sea, was used to support a finer grid (100 m cellsize) with input fetch values, see **Figure 1**. This 100 m grid further provided input values for the final 25 m grids. The extent of the 25 m grids was set to fulfil the criteria:

1. Include coastline features that affect the fetch locally.
2. Together cover the national coastline with an overlap between each grid pair.

This resulted in nine grids simply named grid 1-9 (see the red rectangles in **Figure 2**).

Further, one coarse grid with 100 m cell size was created with an extent large enough to include each 25 m grid together with surrounding coastline features of importance for the fetch calculations, see the blue rectangle in **Figure 2**. The extent of the coarse 500 m grid was set to include all land shapes that possibly could affect the fetch measured from the Estonian coast. Since this grid was not limited by computation capacity it was created to include most of the Baltic Sea (green rectangle in **Figure 1**).

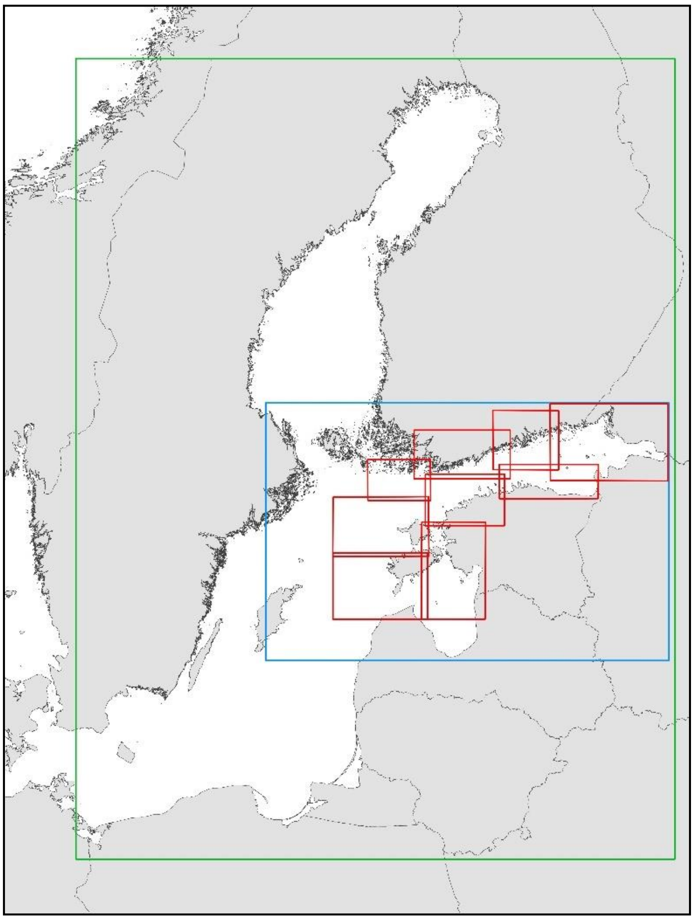

Figure 1. *The extent of the grids used for the nested wave exposure calculations. The green rectangle shows the grid with 500 m resolution, the blue rectangle shows the 100 m grid, and the red rectangles the 25 m grids.*

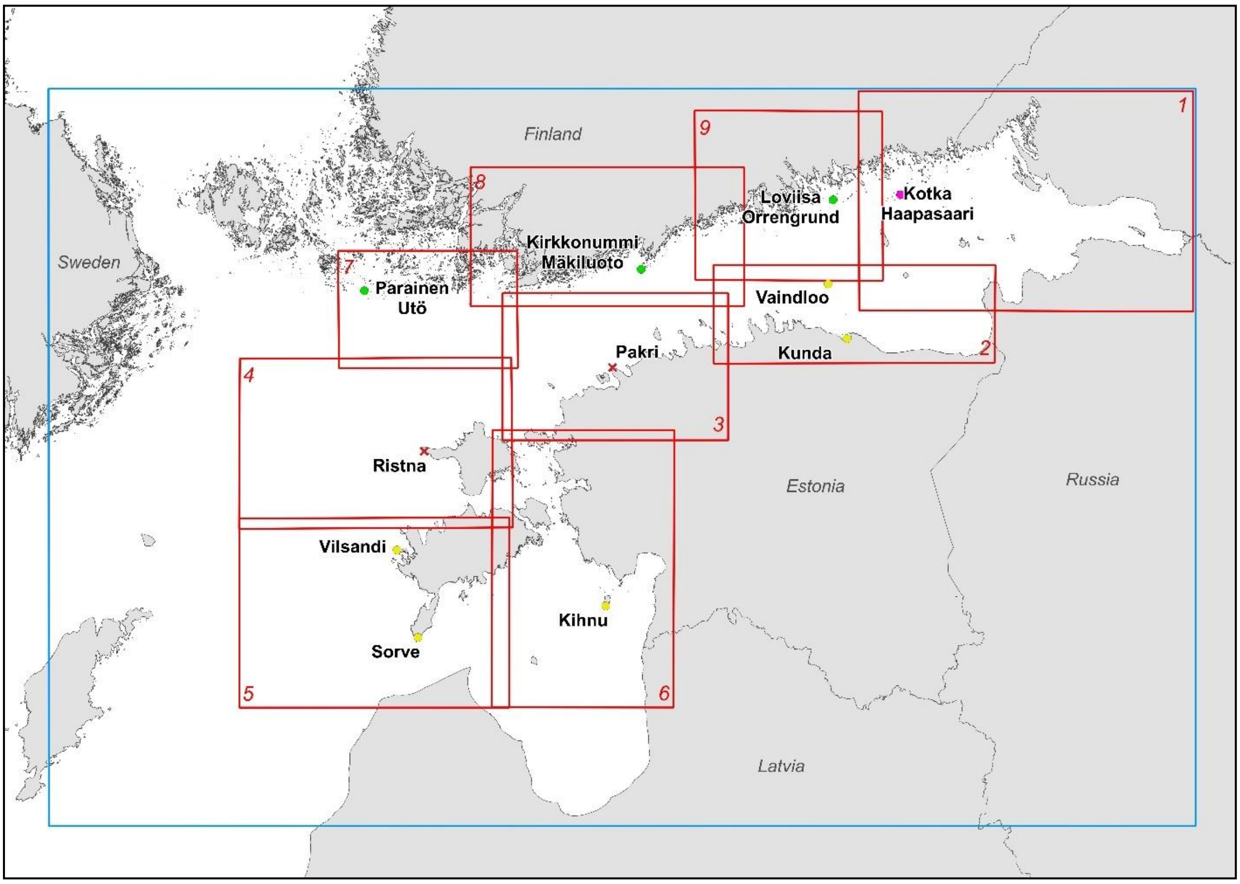

Figure 2. *The location of the utilized wind stations (marked by their names, and colored dots based on the country they represent) together with the extent of the land/sea grids with a grid resolution of 100 m (blue) and 25 m (red), respectively. Estonian wind stations in yellow, Finnish stations in green and the Russian-represented station as pink. Red crosses marking Estonian wind stations exchanged for other more suitable stations.*

The land/sea grids were constructed from two coastline maps of different degree of detail. The shoreline of countries bordering the Gulf of Finland in the ESRI software map *country.shp*, was substituted by a more detailed coastline provided from the Estonian Maritime Administration and Estonian Marine Institute database. Hence, the 25-m and the 100-m grids are composed mainly by high-resolution coastlines from the surrounding countries The map projection for the project was the Lambert Conformal Conic projection *Estonian Coordinate System of 1997*.

2.2. Fetch calculations

The wave exposure estimates were computed in a geographic information system (GIS) with the software WaveImpact 1.0, which has been particularly developed for this purpose. Grids with only two classes, *Land* and *Sea*, were used for the calculations. WaveImpact uses ASCII grids (text files) of the format that can be exported and imported into the GIS softwares ArcView and ArcMap.

The wave exposure values are based on fetch, i.e. the distance of open water over which the wind can act upon the sea surface and waves can develop. The fetch is calculated for every sea grid cell of the map. Basically, this is done by starting at the map edge of the incident –wind direction and increasing the grid cell values by the size of one cell (in meters) for each sea grid cell in the propagation direction, until land is reached (**Figure 3a**). The procedure starts over again from zero if there are more sea cells on the other side of the land cells.

An advantage of using such a grid solution is that the values of adjacent cells can be used as input data, which facilitates the simulation of the patterns of refraction and diffraction. Instead of adding the cell size to the source-cell value straight behind, the cells behind-to-the-right and behind-to-the-left were used. The procedure is illustrated by an example for a southerly wind in **Figure 3b-c**.

The formula used for calculating a southerly wind/wave direction, when no land pixels obstructed (**Figure 3b**), was:

Formula 1.

OutputMatris(i, J) =
OutputMatris(i + 1, J - 1) * (0.5 - Ref)
+ OutputMatris(i + 1, J + 1) * (0.5 - Ref)
+ OutputMatris(i + 1, J - 2) * Ref
+ OutputMatris(i + 1, J + 2) * Ref
+ Cellsize,

where *OutputMatris(i, J)* is the current cell position in the grid, *i* is increased downwards (southwards) in the grid relative to the current position, *J* is increased to the right (eastwards) in the same way, *Ref* is the calibration value of the refraction/diffraction effect (set to 0.35), and *Cellsize* is the cell size in meters.

In the case when the adjacent grid cell on the left (western) side of the current grid cell was *Land* only cell values from behind and from behind-to-the-right were used (**Figure 3c**):

Formula 2.

OutputMatris(i, J) =
OutputMatris(i + 1, J) * (0.5 - Ref)
+ OutputMatris(i + 1, J + 1) * (0.5 + Ref)
+ Cellsize.

Corresponding formulas were used for land obstacles to the right (east), and for all sixteen wind directions (see **Section 2.3** below).

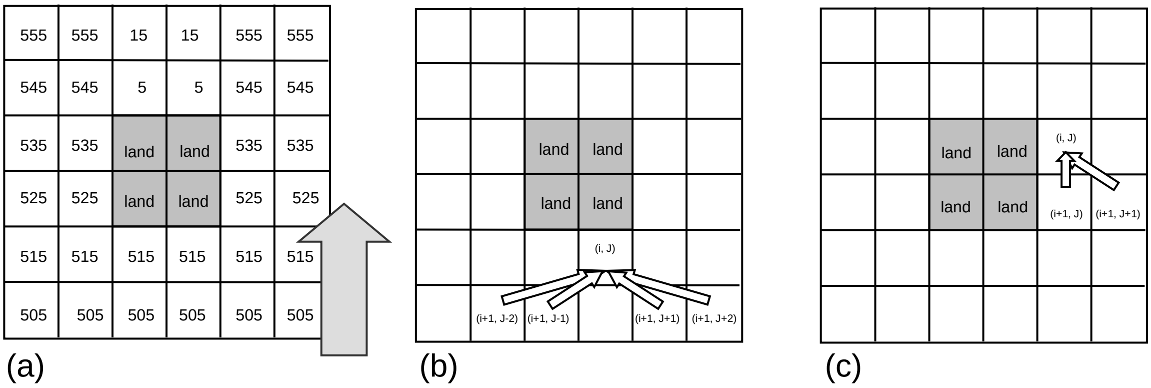

Figure 3. *Examples illustrating the calculation of the fetch values in a land/sea grid, for a southerly wind. a) The basic principle of increasing the fetch values by adding one cellsize (here 10 m) for each new cell. b) Values from the cells adjacent to the source cell are used instead of the source cell itself, in order to simulate refraction/diffraction patterns. c) Calculations when an island limits the use of values from all adjacent cells.*

This method results in a pattern where the fetch values are smoothed out to the sides, and around island and skerries in a similar way that refraction and diffraction make waves deflect around islands. Aerial photographs of wave crests deflected around islands were used to coarsely calibrate the simulation of refraction/diffraction during the construction of the method.

The fetch values were calculated for each 25-m grid with input from the coarser grids in the nested procedure described above (see Section 2.1).

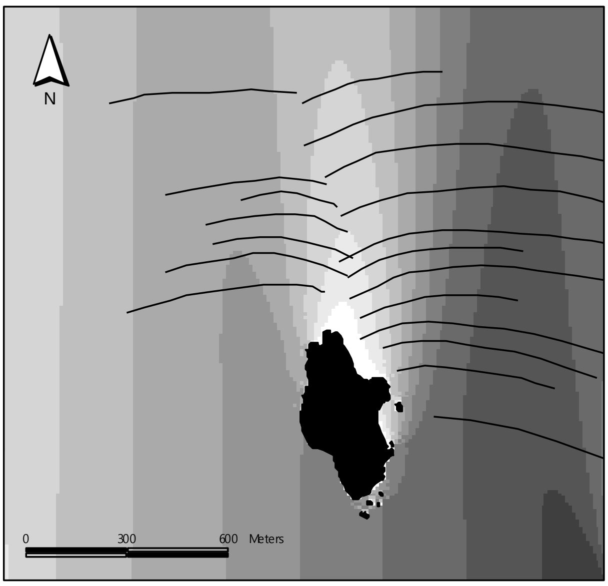

Figure 4. *Aerial photographs of wave crests (black lines) were used to calibrate the refraction/diffraction simulation during construction of SWM.*

2.3. Wind Data

The wind data used was 'average wind speed' (m/s), obtained from 9 weather stations located inside the study area, see (**Table 1**).
The measurements were provided for the period between January 1, 2003 and December 31, 2019. From Estonian weather stations, data was utilized from every third hour (00, 03, 06, 09, 12, 15, 18, and 21 GMT) between the first of January 2003 and the first of November 2003, thence data from every hour was used. For the Finnish stations (including the Russian represented station) data was used from every hour from the start until the end of the study.

The station Parainen Utö had no data from august 4th 2009 until September 28th 2011. Station Loviisa Orrengrund had no data from January 1st 2003 until October 3rd 2006. The start date for this station was therefore set to January 1st, 2007. Station Vaindloo had no data from January 1st 2003 until October 10th 2012. The start date for this station was therefore set to October 11th 2012.

Station Ristna had been obstructed by houses and forest, and station Pakri had been relocated several times throughout the study period. The data from these stations were therefore unrepresentable to the locations and wind data was instead sourced from nearby wind-stations. Pakri was replaced with data from Vaindloo, and Ristna was replaced with data from Vilsandi.

Wind data had been divided into two categories: current and future. This classification was based on long-term resemblance to 'normal' climate and IPCC RCP6.0 future scenarios.

For the calculations, the wind data were divided in sixteen compass directions (N, NNE, NE, ENE etc.), each representing an angular sector of 22.5°. For each sector we further computed the mean value of all available wind-velocity measurements for further use in the exposure calculations.

Table 1. *The utilized wind stations with positions and the number of the associated land/sea grid. The wind was measured at 10 m height at all locations.*

Station Name	Latitude (dg, WGS84)	Longitude (dg, WGS84)	Grid No
Kotka Haapasaari	60.28676	27.18482	1
Kunda	59.52139	26.54139	2
Vaindloo/Pakri	58.82034	26.36000	3
Vilsandi/Ristna	58.38277	21.81416	4
Sorve	57.91361	22.05805	5
Kihnu	58.09861	22.06638	6
Parainen Utö	59.77909	21.37597	7
Kirkkonummi Mäkiluoto	59.91981	24.35023	8
Loviisa Orrengrund	60.27476	26.44759	9

2.4. Wave exposure calculations

For each wind direction sector, the value of each cell in the corresponding fetch grid was multiplied by the mean wind speed. In this case this resulted in sixteen new grids. The mean value of all grids was calculated in an overlay analysis, which can be summarized by the formula:

Formula 3.

$$E_{SWM} = \frac{\sum_{i=1}^{16}(F_i * W_i)}{16},$$

where E_{SWM} is the wave exposure value, F_i is the adjusted fetch value for the direction *i*, and W_i is the mean wind speed in direction *i*.

This was repeated for each grid of the five sub regions along the Estonian coast (the red rectangles in **Figure 2**).

3. RESULTS AND DISCUSSION

Since the separate wave exposure grids are calculated from different wind data, it leads to somewhat different wave exposure values in areas where the grids overlap. To avoid two different wave exposure values in cells of overlapping grids, and to level out the differences between adjacent grids, the grids were merged and then clipped again. The grids were merged using the script MosaicToNewRaster within the ESRI ArcGIS 9.2 Data Management toolbox. The operator for the script was 'Blend' which uses a distance-weighted algorithm to create a seamless grid and smooth transition in overlapping areas.

The use of two wind stations (Ristna and Pakri) generated very low values, as the two stations were obstructed from several directions. The wind data from stations were therefore excluded, and data for their respecting grids were exchanged for nearby wind stations (Vilsandi and Vaindloo, respectively).

An overview of all wave exposure grids along the Gulf of Finland for the scenarios 'current' and 'future' is shown in **Figure 5** and **Figure 6**. The colours indicate preliminary EUNIS classes according to the legend. The two merged grids for scenario 'current' and 'future', were delivered digitally to the Estonian Marine Institute at the University of Tartu.

The gridcell resolution of 25 m was a compromise between the need for high resolution and manageable amounts of data. However, in a study by the Swedish Board of Fisheries on the effects of scale on wave exposure values calculated with the same method as in this study (WaveImpact, method SWM) it was concluded that the results for a 25 m resolution differed only little from those of finer resolution, but 50 m and coarser differed significantly (Göran Sundblad, pers. comm.). The 25 m resolution seems then to be an acceptable compromise even though studies of the narrowest bays might benefit from a higher resolution.

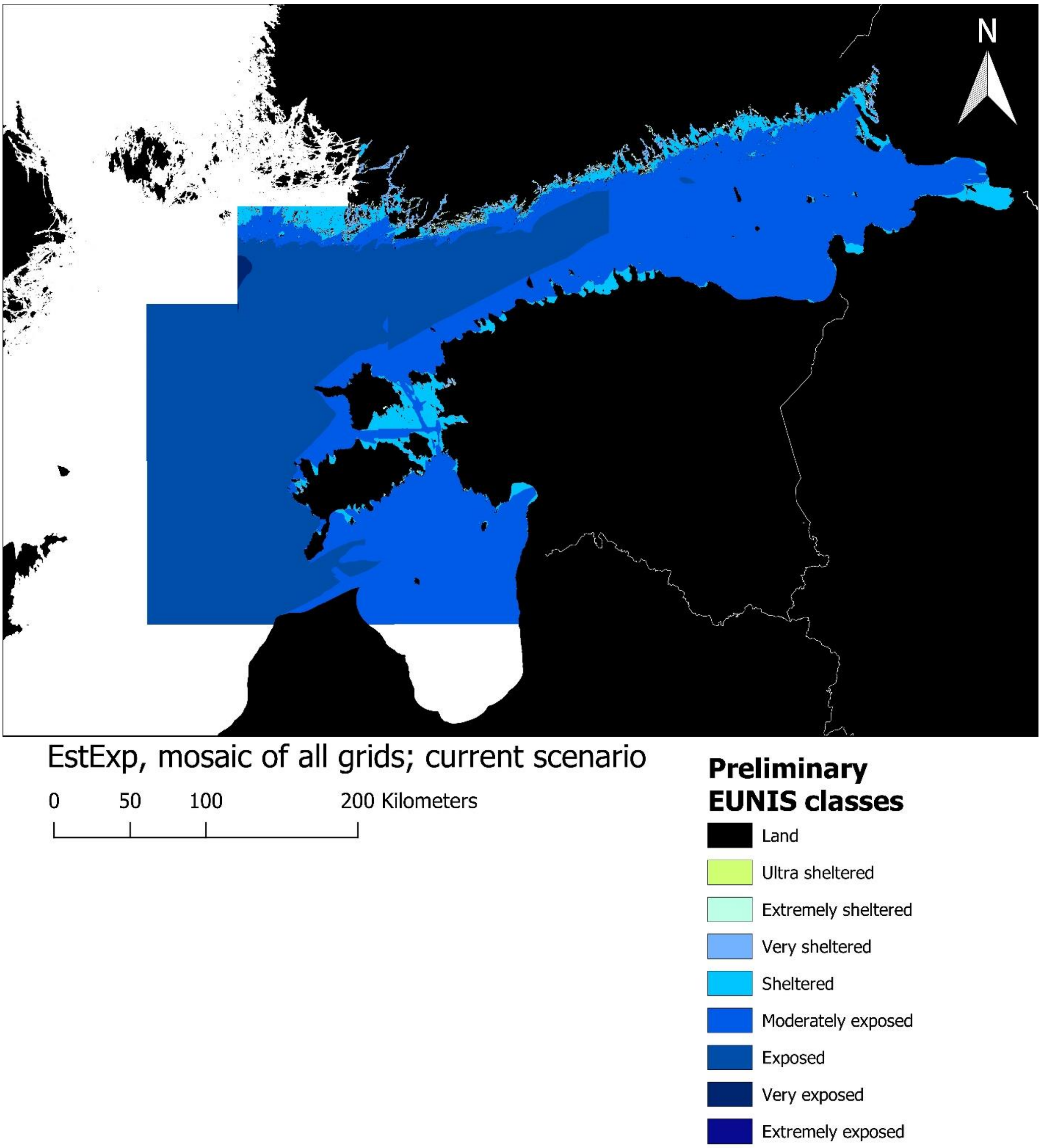

Figure 5. *An overview of the Gulf of Finland showing a mosaic of the calculated nine wave exposure grids for the '<u>current</u>' scenario. The colors indicate preliminary EUNIS classes according to the legend. Each grid is shown separately in Appendix.*

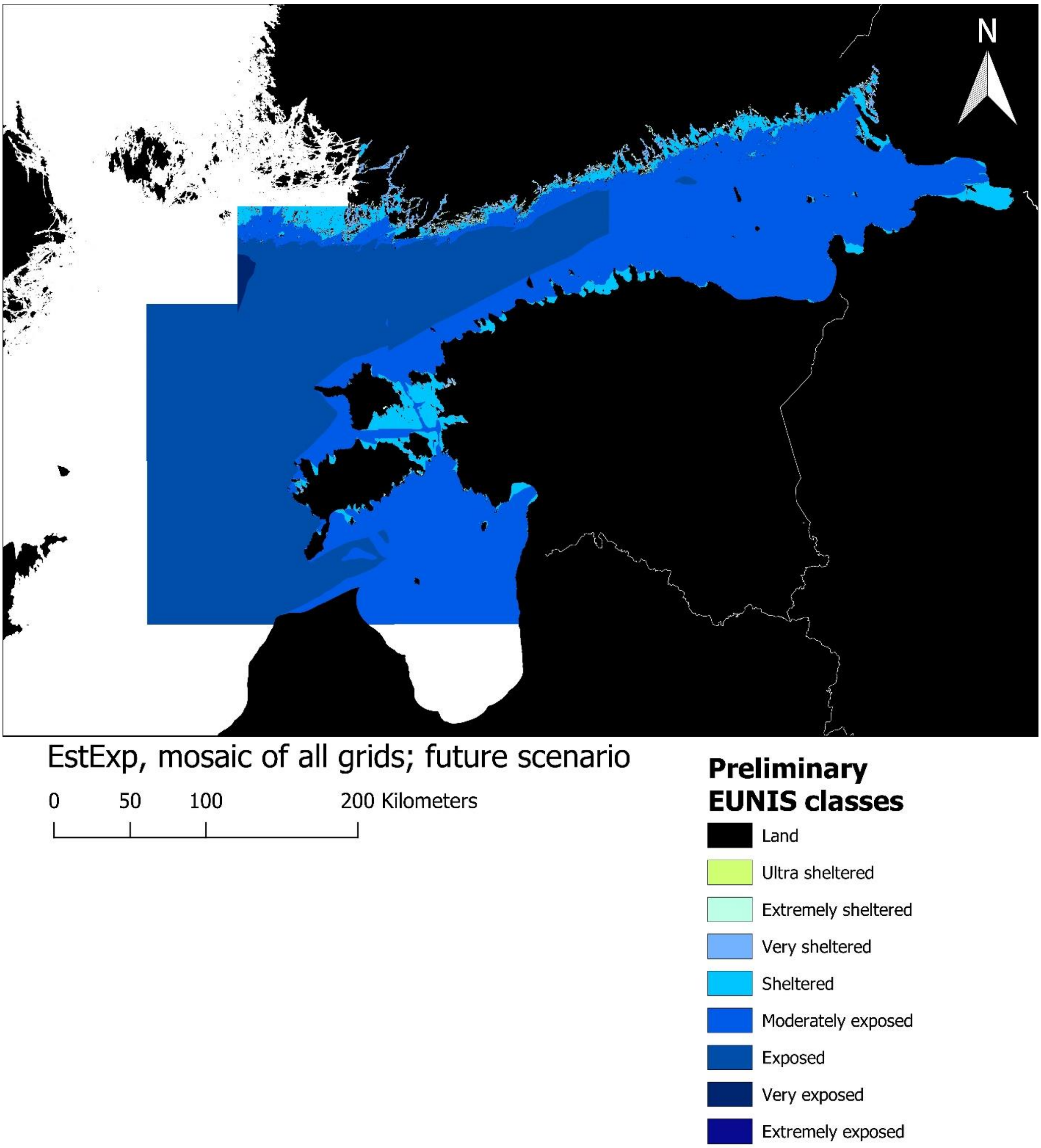

Figure 6. *An overview of the Gulf of Finland showing a mosaic of the calculated nine wave exposure grids for the 'future' scenario. The colors indicate preliminary EUNIS classes according to the legend.*

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Estonia-Russia Cross Border Cooperation Programme 2014-2020 aims to foster cross-border cooperation across the borders between the Republic of Estonia and the Russian Federation to promote socio-economic development in the regions on both sides of the common borders. The Programme web-site is www.estoniarussia.eu.

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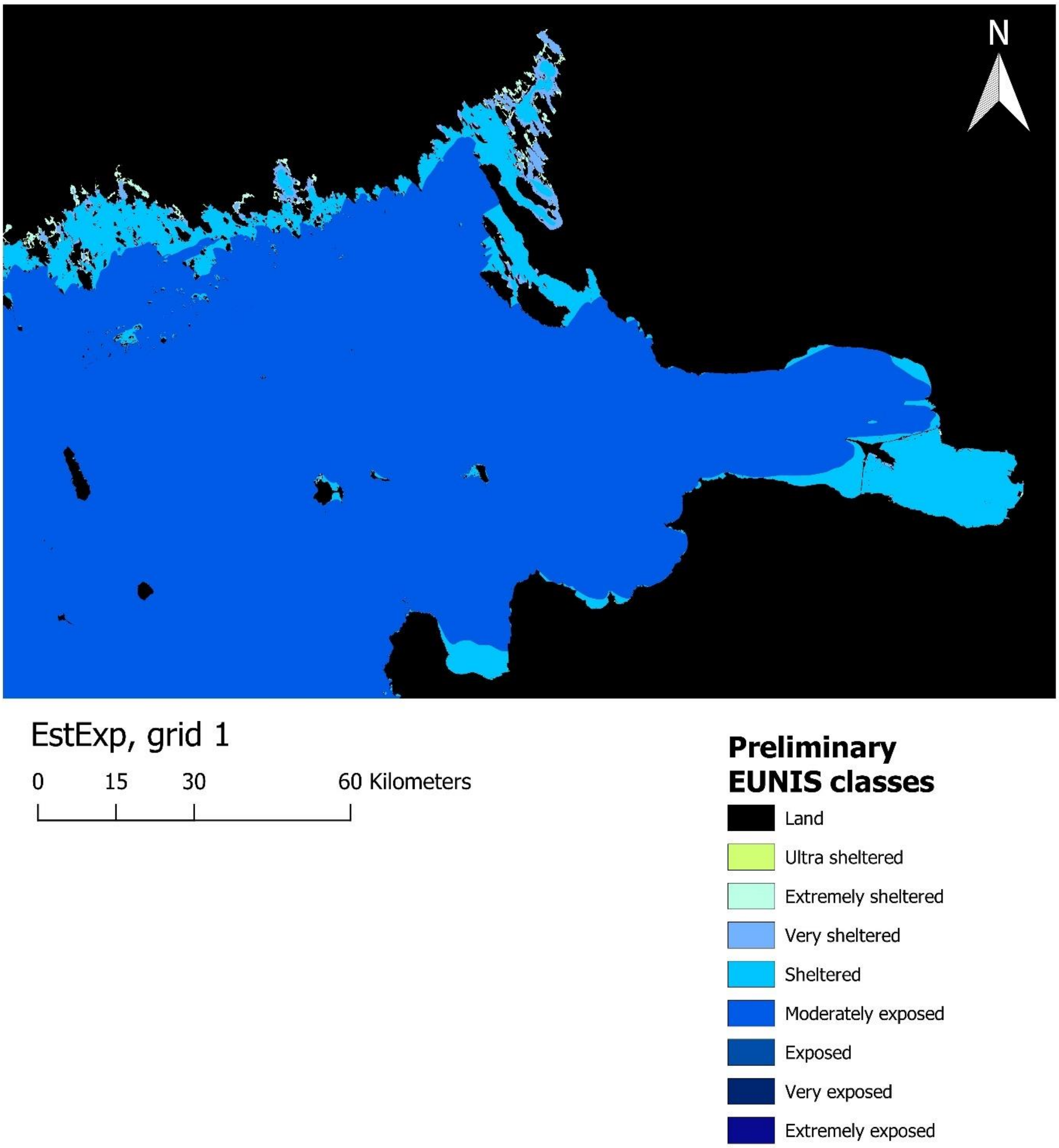
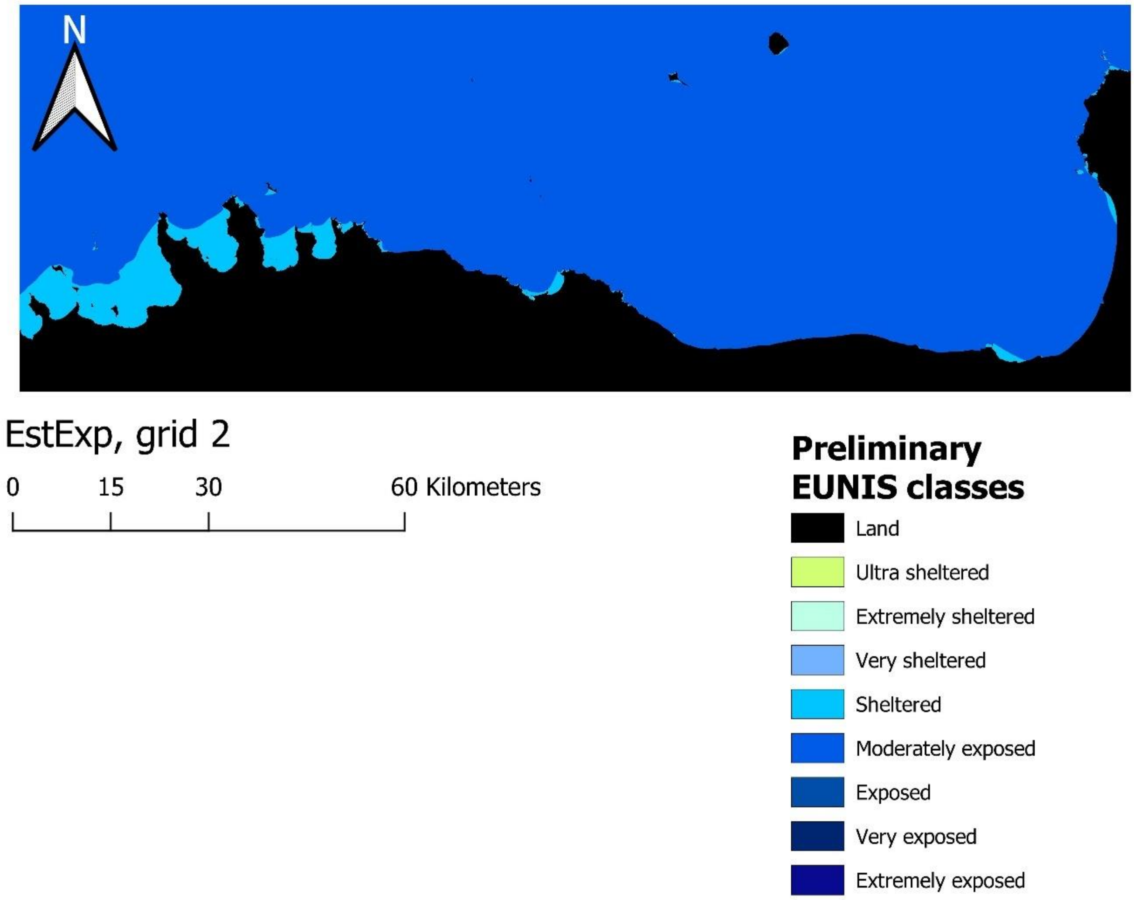
Göran Sundblad, Swedish Board of Fisheries, Institute of Coastal Research/Öregrund (goran.sundblad@fiskeriverket.se).

APPENDIX: WAVE EXPOSURE GRIDS 1-9 (CURRENT SCENARIO)


N
EstExp, grid 1
0
15
30
60 Kilometers
Preliminary EUNIS classes
Land
Ultra sheltered
Extremely sheltered
Very sheltered
Sheltered
Moderately exposed
Exposed
Very exposed
Extremely exposed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15
30
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Preliminary
EUNIS classes
Land
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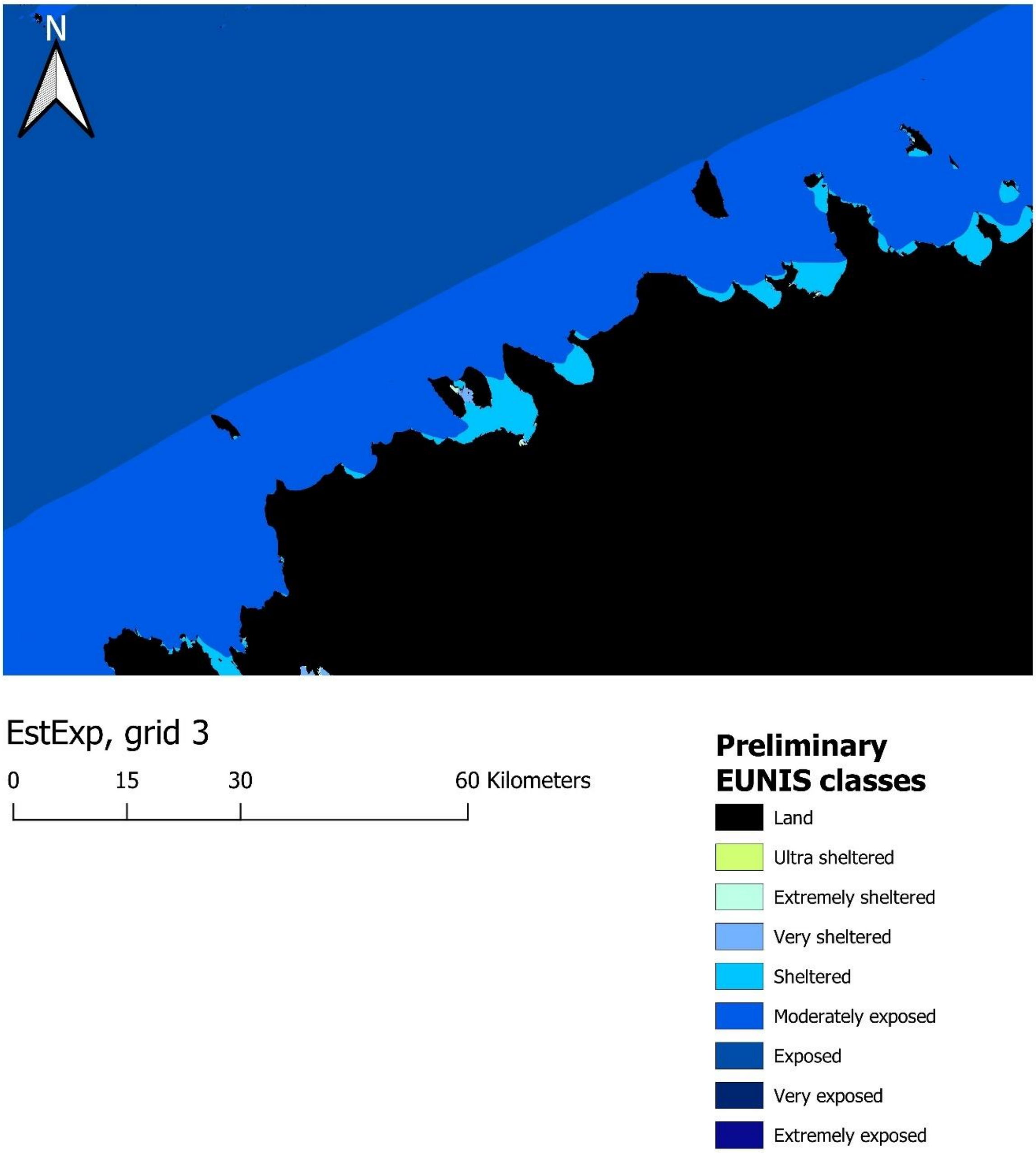
Exposed
Very exposed
Extremely exposed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15
30
60 Kilometers
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Very sheltered
Sheltered
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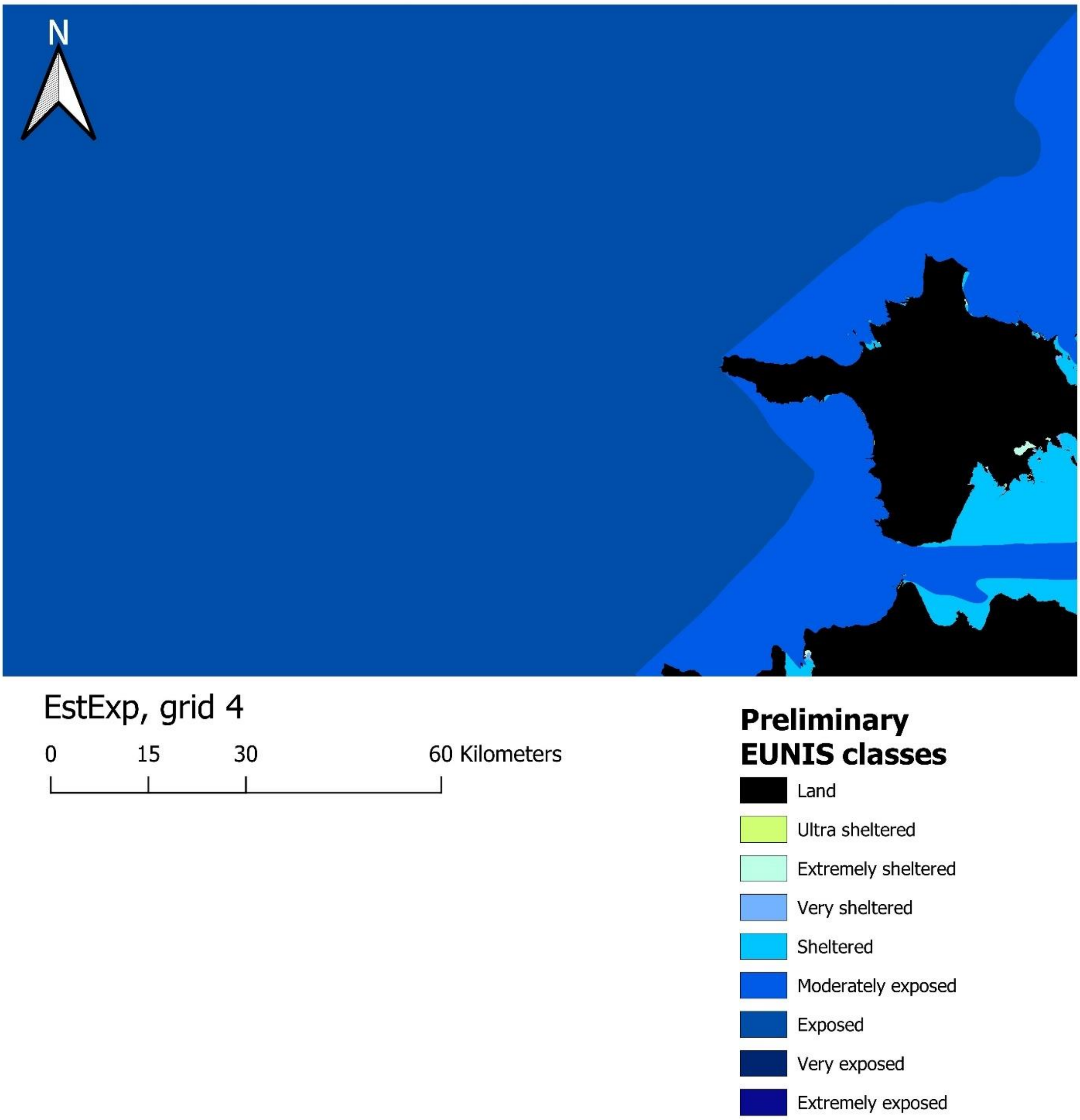
Exposed
Very exposed
Extremely exposed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EstExp, grid 4
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Preliminary EUNIS classes
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Very sheltered
Sheltered
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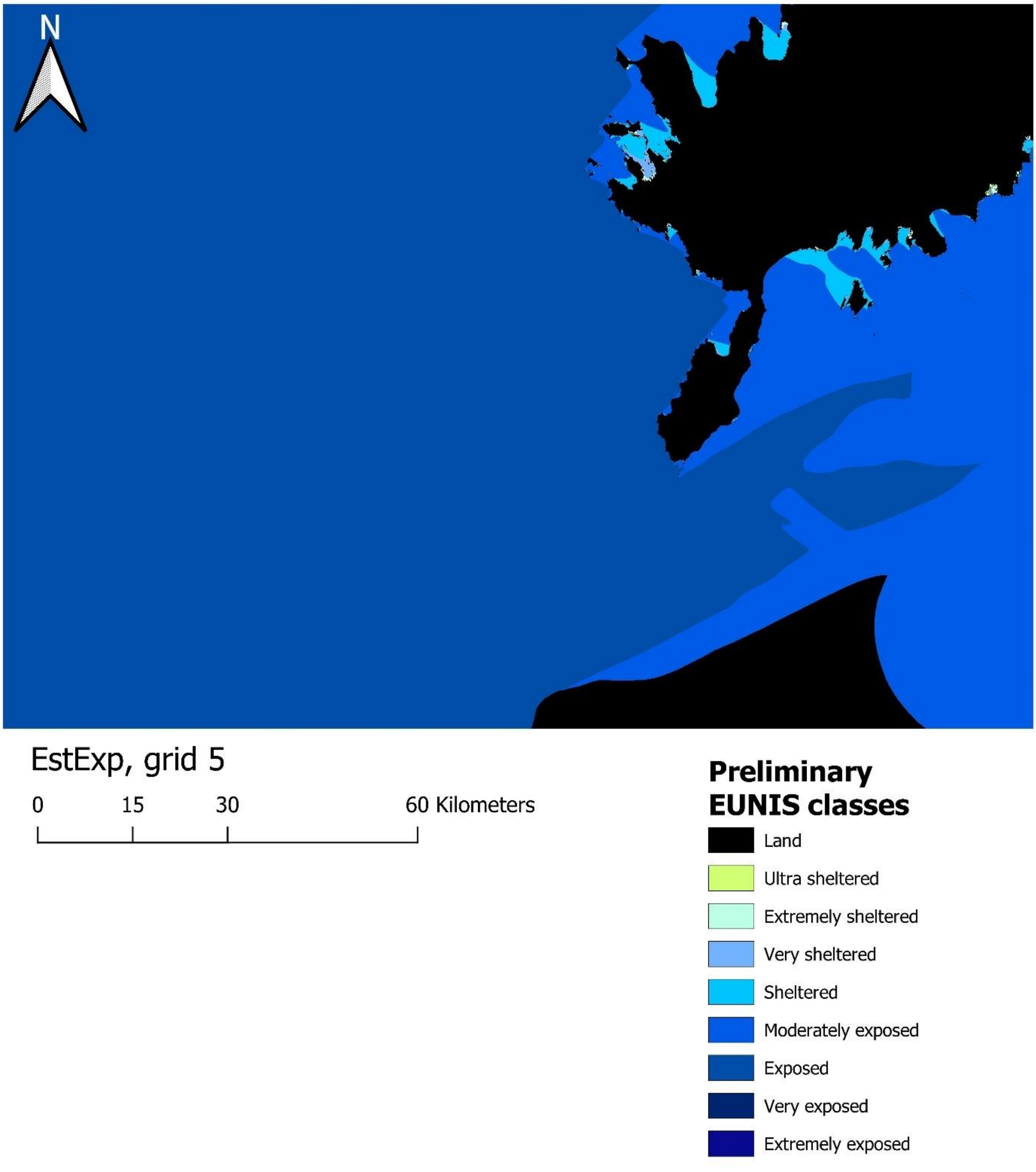
Exposed
Very exposed
Extremely exposed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30
60 Kilometers
Preliminary EUNIS classes
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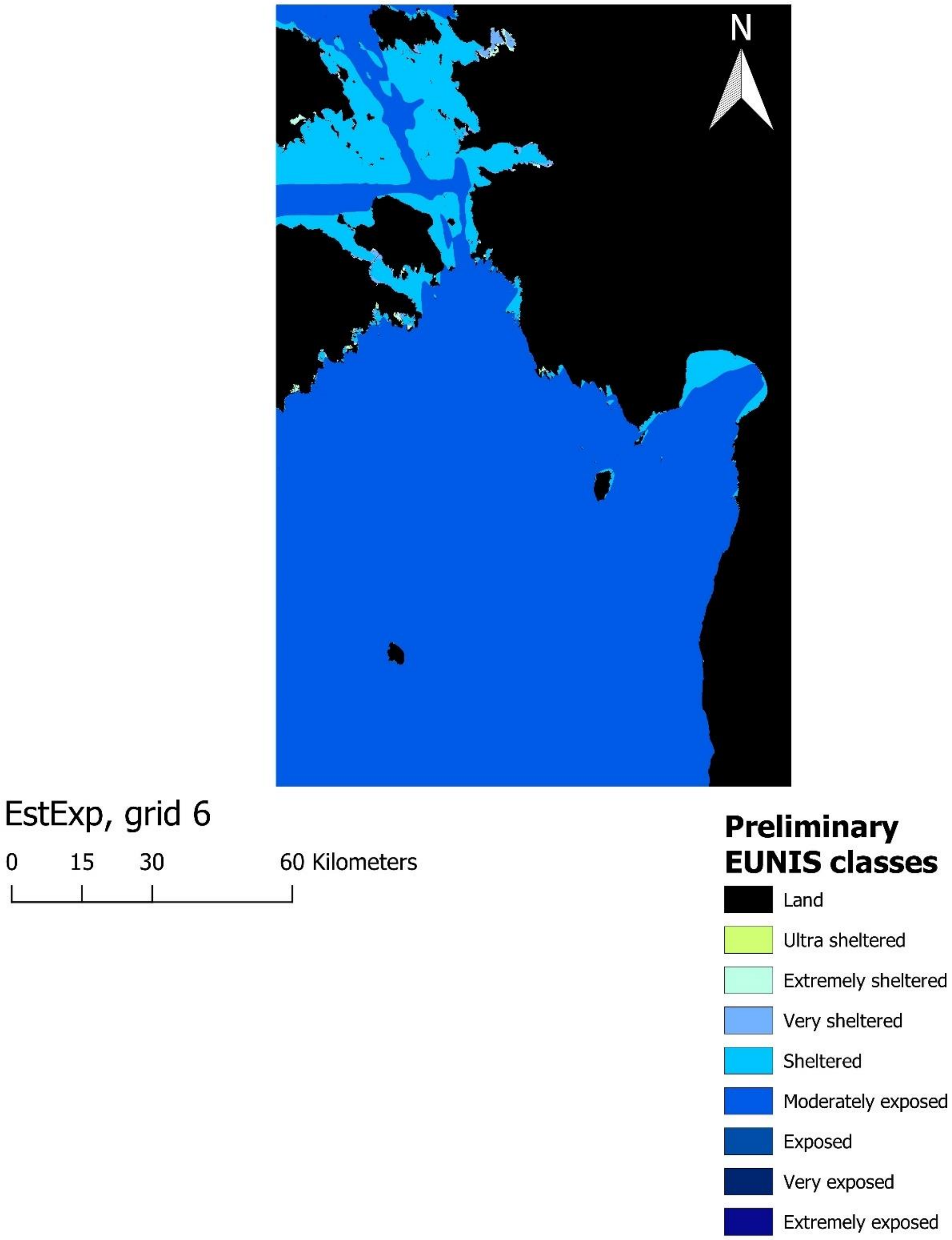
Exposed
Very exposed
Extremely exposed


N
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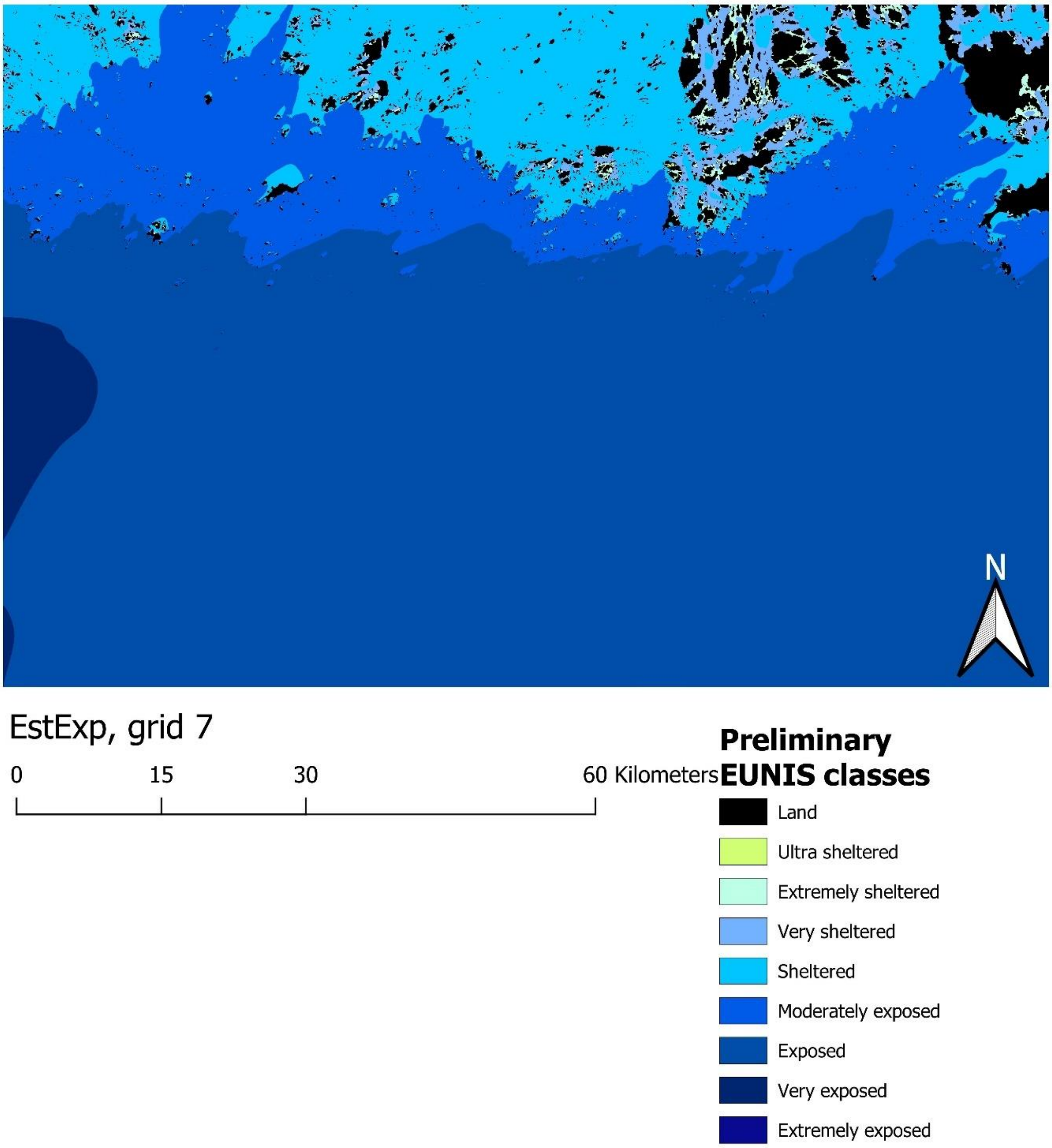
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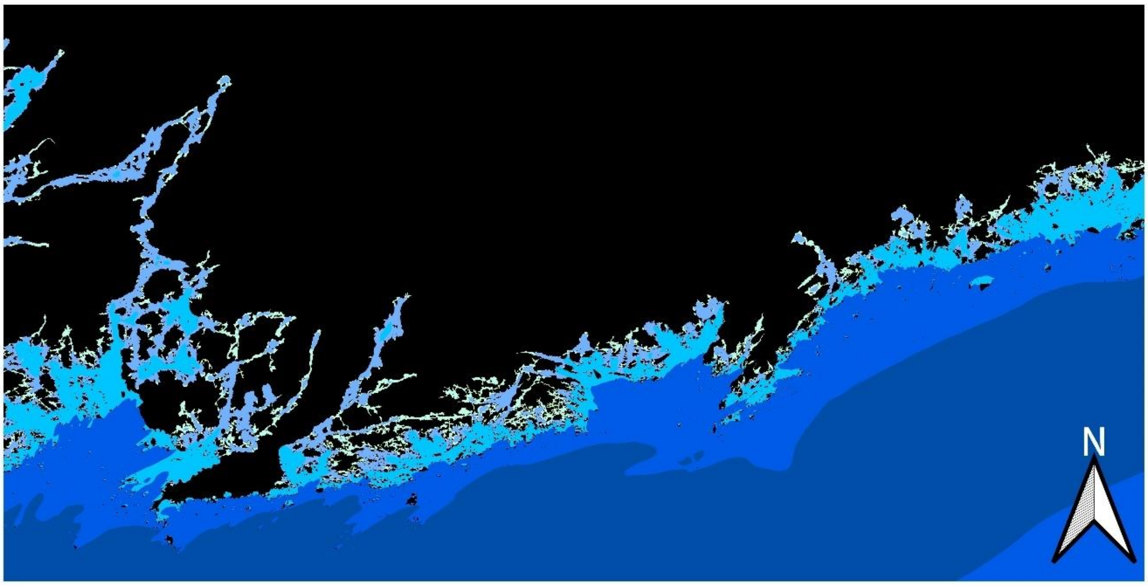
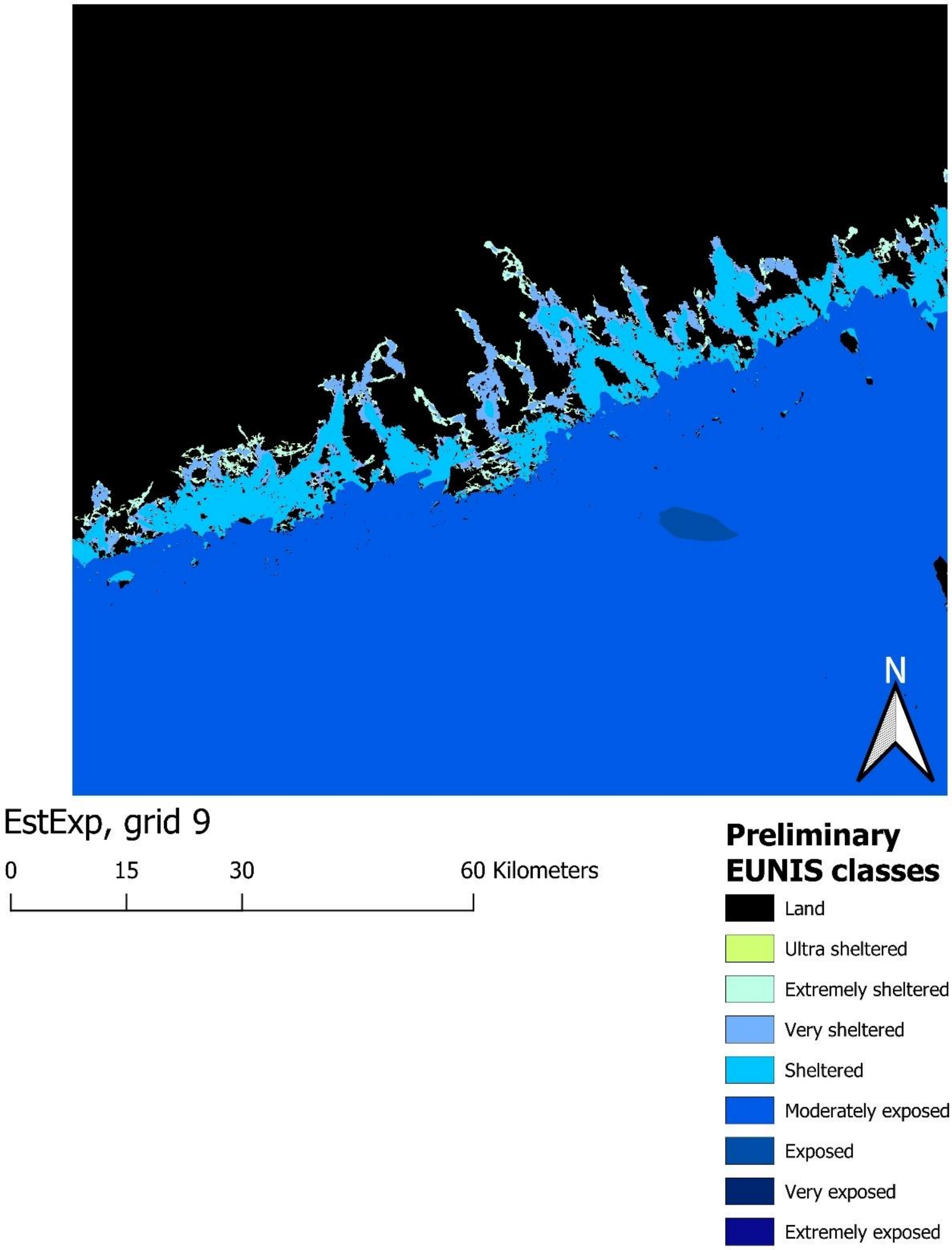
Extremely exposed



EstExp, grid 8

Preliminary EUNIS classes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15
30
60 Kilometers
Preliminary EUNIS classes
Land
Ultra sheltered
Extremely sheltered
Very sheltered
Sheltered
Moderately exposed
Exposed
Very exposed
Extremely exposed

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