Reliability of Local Scale Human Pressure Modeling at the Seafloor of the Baltic Sea

Running title: Human Pressure at the Seafloor of a Shallow Sea

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Abstract

Efforts to understand anthropogenic stress in marine environments have introduced methods of cumulative human pressure modeling in the broad-scale mapping of large sea areas. This paper examines the usability of such modelling in the shallow seafloor and complex shoreline conditions of the Archipelago Sea in the northern Baltic Sea. We employed public spatial data sources to describe the spatial patterns of 24 different human pressures with their normalized values in a 20 m x 20 m pixel size. Public data were also used to classify the seafloor into six different environmental types. The model output was assessed against environmental data from regular seafloor monitoring. Visual examination shows general agreement between the cumulative human pressure model and the health of the benthic fauna, seabed oxygen and, to a degree, also the tributyltin. However, although none of these field parameters show high statistical correlation with the cumulative pressure status, multiple parameters assessed simultaneously could provide a sufficient reference. Local-scale disagreements between the cumulative model and the field parameters particularly occur near the largest harbor in the region where regular dredging is practiced. Model sensitivity to different input variables was further tested by comparing 36 dissimilar variants. The comparisons reveal a general stability across the inclusion, exclusion, or modification of such spatially restricted human pressure data, which only induced local-scale details. High instabilities occurred when the tested input data had a large spatial coverage. As the cumulative human impact model reduces several human pressures into one index, it should be considered as a broad scale descriptor of the likely overall health status of the sea. When implemented with accurate local-scale data it can help coastal and marine spatial planning but it should not be considered as a predictive depiction of any particular environmental characteristic. The cumulative pressure map is particularly powerful in providing unforeseen insights into the distributions of overall anthropogenic influences within the study region, and through these it can also contribute to environmental policies.

1. Introduction

Increasing human activities in marine and coastal areas have induced the need for their sustainable management. Among the key procedures are Integrated Coastal Zone Management (ICZM) and Marine Spatial Planning (MSP), both with an ecosystem-based approach to encompass their embedded environmental interactions (Douvere 2008, Queffelec et al. 2009, Sandström et al. 2015). For example, the EU's coastal zone policy aims to establish a common framework to promote sustainability in European coastal and marine developments (European Commission 2016). Coastal researchers have also found the effectiveness of the framework of the Driving Forces-Pressures-State-Impacts-Response (DPSIR), which helps to develop conceptual understanding about coastal social–

ecological systems (Lewison et al. 2016). As human activities may affect ecosystems with multiple simultaneous impacts, different criteria must be examined and weighed against each other (Teck et al. 2019, Tammi & Kalliola 2014, Knights et al. 2015).

The planning of ecosystem-based management requires that a variety of anthropogenic stress factors are identified and their influences are assessed using well-defined methodologies. Ban & Alder (2008) used GIS with spatial information for 39 marine activities to map potential stressors resulting from human activities in British Columbia. Halpern et al. (2008) presented an ecosystem-specific spatial model to synthesize the anthropogenic drivers of ecological change in world oceans. Their results revealed distinctive geographical patterns in cumulative multiscale human impact with particular complexities in the marginal sea areas. The same fundamentally quantitative methodology was later also adapted to map the drivers of anthropogenic influences in smaller areas, such as the Hawaii coral reefs (Selkoe et al. 2009), the California Current (Halpern et al. 2009), Canada's Pacific waters (Ban et al. 2010), the Baltic Sea (Korpinen et al 2012, Andersen at al. 2015), the Mediterranean and the Black Sea (Micheli et al. 2013) or the Tauranga Harbor of New Zealand (Clark et al. 2016).

Human impact assessments are usually broad scaled general estimates that help to identify and visualize areas with different levels of various kinds of anthropogenic pressures, thus contributing to ICZM and MSP. Due to the multifaceted nature of the theme, transparent methodologies must be used to allow corrections and re-analyses to be made for future needs. For example, the environmental influences of a given human disturbance can be weak and local according to present understanding, but this perception may later change. The cumulative impacts of simultaneous anthropogenic stressors are also open to discussion. Assessment results may also depend on the kinds and qualities of the used input data, as well as any embedded assumptions within the used analytical chains. Some of these difficulties can be minimized through using research-supported estimates and expert panel judgments to help their conversion to spatial mapping. The work should also be employed with as representative spatial data as possible with respect to their thematic content, technical qualities and spatial representativeness (Tolvanen & Kalliola 2008). An ideal dataset would be relevant, recent, spatially precise, and have a consistent spatial coverage over the study area (Murray et al. 2015). A too straightforward data overlay analysis should be avoided without problematizing the extensions of those areas to which the effects of the human stressors are most likely distributed (Ban et al. 2010).

The present paper addresses the possibilities of modeling local-scale cumulative human pressure with these premises. We will focus on the seafloor of a shallow coastal sea with a complex shoreline structure; the hypothesis being that existing, publicly available spatial data can be transferred into a pertinent spatial model of anthropogenic stress on a scale that is relevant for coastal planners, by using the model of Halpern et al. (2008) with two additionally incorporated variables. The depth variable helps to consider the three-dimensional setting of the shallow sea, whilst sea openness (average fetch length) serves as a proxy for water mass and water exchange around the pressure source. The output model will be examined using independent data from seafloor environmental monitoring. We will also test how sensitive the model is to the inclusion or exclusion of selected input data or to other modifications within the applied methodological work chain. The results are discussed from both methodological and practical perspectives.

2. Material and methods

The Baltic Sea is a semi-closed marginal sea in Northern Europe, bordered by nine countries and strongly impacted by humans. The study area is the Archipelago Sea (ca. 40 000 km²) in the northern part of the Baltic Sea where the sea divides into the Gulf of Finland and the Gulf of Bothnia (Figure 1). The city of Turku and its close neighbors is the region´s major center with a total population of ca. 300 000 inhabitants. The sea areas near the mainland are narrow straits between relatively large islands, whilst in the outer parts of the archipelago only scattered small-sized rocky islands occur. The sea depth is generally less than 50 m, however, in some places there are also depths exceeding 100 m. The seafloor substrate presents hard rocks and stones as well as loose till, sand and clays, with their distributions and bathymetric variations determining the patterns of benthic species and communities (Snickars et al. 2014). Human influences within the Archipelago Sea are multiple and co-occurring, comprising of both land and sea based activities. These include fishing and aquaculture, coastal traffic, shore construction, various kinds of leisure time activities, and (treated) sewage water input from towns and industries. In addition, agriculture with its riverine and diffuse runoff is notable in the region. The most noticeable negative developments in the region are related to eutrophication, which has decreased water clarity and thereby caused seafloor darkening and its consequent stress to the benthic communities (Erkkilä & Kalliola 2004, Tolvanen et al. 2013). Moreover, frequent trafficking by large-sized (~200 m long) ferries, cargo ships and boats has had an influence on the nature along the shores and in the open sea (Sandstörm et al. 2005). Regional planning and management in the Archipelago Sea region are currently under focus by ICZM and MSP. In order to support their execution, consistent mapping of anthropogenic pressures is demanded.

Existing spatial data from different sources (the nominal scale of mapping precision varies between 1:20 000 and 1:50 000) were used as surrogates for environmental characteristics. For seafloor depth (bathymetry), we applied raster data that was interpolated in-house (by Dr. Harri Tolvanen) from nautical charts by using the method described by Stock et al. 2010. Data on seafloor substrate was obtained from the Geological Survey of Finland; the data distinguishes between hard and soft seafloor substrates (Stevenson et al. 2011). The distribution of euphotic seafloors, corresponding with benthic macrophyte communities (Luhtala et al. 2016), was computed on the basis of the averaged water clarity data and the bathymetry model. It distinguishes the three classes of permanently, seasonally and never photic seafloors (for method, see Tolvanen et al. 2013). Combined with data from seafloor substrates, the study area consequently distinguishes six kinds of seafloor types. For sea openness, we applied a grid model with 7.5° resolution covering the entire study area (see Ekebom et al. 2003, Murtojärvi et al. 2007). Each cell has an averaged fetch length of 48 compass directions, which were here normalized into the scale from 0 (closed coastal lagoon, see Tolvanen et al. 2004) to 1 (open sea).

The EU's Marine Strategy Framework Directive (European Commission, 2008) contains an indicative list of human pressures and impacts on the environmental status of seas. We applied an existing appraisal to transform them into the conditions of the Baltic Sea with 52 data layers and their weighting scores (HELCOM 2010a,b). However, some of these pressures do not occur in our study area (e.g. bottom trawling, wind farms, nuclear plants, oil rigs), some lack proper indicators (e.g. marine litter) and for a few others we were unable to define reasonable ways to reliably describe their spatial characteristics within the study area (e.g. polluting through accidents and spills, influences from coastal industries, hunting pressure and introduction of non-indigenous species). Our assessment consequently recognizes 24 different human pressures (Table 1). In order to determine the likely influence areas of the different pressures we consulted the best available expert knowledge from the marine protection authority of Finland (Parks & Wildlife Finland). For pressures with crisp borders, a single value (explicit) buffering was used to describe the pressure on its location and surroundings. In other cases, linear distant-decaying spatial models were applied to estimate the pressure's likely reduction until reaching the set maximum distance (Figure 2 and Table 1). In some other cases the pressure's spatial dimension was adjusted by distinct reasoning, for example salinity decreases in the whole water area behind a damn. Finally, all the included human pressure layers were reproduced with 20 m x 20 m pixel sizes and their values were normalized to range from 0 (low pressure) to 1 (high pressure).

Slightly modifying the formula developed by Halpern et al. (2008), we computed the cumulative multiscale human pressure index at the seafloor as follows:

$$\mathrm{I} = \sum_{i=1}^{n} \sum_{j=1}^{m} P_i * E_j * \mu_{i,j} * (D_{i*v}) * (W_{i*v}) \qquad [1]$$

where P_i is the log-transformed and normalized value in the vertical scale of an anthropogenic pressure in the seafloor unit I (0 indicates no impact, 1 is the highest impact), E_j is the presence or absence of a particular kind of seafloor j (1 or 0, respectively), $\mu_{i,j}$ is the weight score for P_i in E_j (range 0–4), D_i is the normalized depth value (from 1 to 0, or from the sea surface until the depth where the pressure is not considered to exist) and W_i is the normalized sea openness value (from 1 to

0, i.e. diminishing value with increasing average fetch). The two latter components in parenthesis are new additions to the formula and they are only used in selected pressures (Table 1) to help in quantifying the pressure at the seafloor. The depth addition was employed to depict those pressures that occur near the surface and have a diminishing stress impact from the sea surface toward the deeper waters (Figure 2). The sea openness factor, in turn, assumes that a given human pressure has a higher impact in places where the open water area is small (average fetch length is low) and, for example, harmful substances have less water mass in which to become diluted. The cumulative multiscale human pressure index obtains its highest values where many anthropogenic pressures co-exist in the same area. The model was computed and visualized with the ArcGIS software; the resulting human pressure map (later: standard model) was visualized using a color palette from red to yellow.

The standard model was assessed against two independent data sets from environmental seabed monitoring in the region. The first data were collected in two cruises (2012 and 2013) of the Finnish Environment Institute’s research vessel m/s Muikku in the vicinity of the city of Turku; the data included 26 sampling stations within our study area (Niemi et al. 2014). This monitoring addressed the seafloor physicochemical conditions (e.g. concentrations of oxygen, phosphorous and harmful chemicals) and the state of the benthic ecosystems (density, species composition, stress indicators), out of which three variables were selected for our comparisons: tributyltin (TBT) concentrations in the topmost sediment layer (0-2 cm) as sample of common harmful chemical of anthropogenic origin (Lilley et al. 2012), near-seafloor (0-1 m) oxygen concentration indicating risk of hypoxia (Conley et al. 2011), and the density of soft bottom zoobenthos (individuals per square meter) as a proxy for the state of the faunal communities. In the comparisons, they all were normalized to the scale from 0 to 1 to allow effective comparisons with the standard model. Normalization was conducted so that values close to 1 indicated the potential for high pressure, and values close to 0 indicated low pressure. High pressure was assumed to occur when high levels of Tributyltin occurred, oxygen levels were low or there was a low number of benthic fauna individuals in the samples. We also calculated correlation coefficients to indicate the relation of individual field parameters to the standard model. The other test data that we used was from a regional benthic fauna inventory comprising 50 stations, most of which were within our study area (Räisänen 2013). We applied the benthic fauna health status classification of that inventory, which recognizes the four classes of: good, moderate, bad, and very bad (figure 10 in Räisänen 2013).

The sensitivity assessment examined how the analytical process responded to the inclusion, exclusion or modification of some individual variables. The standard model was set as the reference, and 35 alternatives were introduced. The alternatives differed in several ways: in the choice of included human pressure variables (24 different models, each time excluding one variable); in the environmental characteristics (4 models; leaving out depth, sea openness (average fetch length), seafloor substrate or all of them); in the weighting scores of selected human pressure variables (3 models; leaving phosphorous, siltation for dredging and siltation for shipping without weighting scores according to seafloor substrate); and by modifying the distance-decay functions for selected human pressures (4 models; two variates for the siltation effects of both dredging and shipping). To allow for comparison, each model was normalized to have pixel values ranging from 0 (no human pressure in this pixel) to 100 (the highest human pressure value detected in this model). The pixel values of each alternative were then compared to those of the normalized standard model through raster subtraction. Zero values indicate no change whereas positive and negative values imply augmented or reduced human pressure estimates, respectively. The dissimilarity level (%) statistics were established by comparing the pixel values of the alternatives with those of the normalized standard model. Site-specific dissimilarities were established through counting the relative proportions of pixels showing minor, intermediate or major differences from zero.

3. Results

The standard model shows a distinctive geographical pattern in the distribution of seafloor cumulative human impact (Figure 3). The largest and most uniform extensions of anthropogenic stress are found near the city of Turku where the main population, industries and harbors are located. Minor occurrences were also scattered elsewhere in the study area, for example, near towns (e.g. Parainen), locally important harbors (medium size industrial or ferry harbors; pleasure craft marinas) or in semi-closed bays with some particular anthropogenic stress (e.g. aquaculture). Intermediate levels of human impact pressure widely abound in the study area. Low human pressure levels can only be found in some peripheral parts of the study area.

Visual overlay analyses revealed fairly good spatial agreement between the standard model and the seafloor characteristics documented by environmental monitoring, but statistical correlations were low (Figure 4A). In the Western and Southwestern parts of the study area, where the human pressure index value is lowest, all of the field parameters also revealed a good environmental status. However, the contrary occurs close to the mainland in areas where the standard model shows high values but the field measured parameters are variable. Both tributyltin (TBT) and seafloor oxygen concentrations also vary considerably in these areas, probably in connection with some local factors. Moreover, the density of the benthic fauna varies considerably in the areas of high human impact. The same observation can be made with the separate dataset showing seafloor health status classification based on the benthic fauna (Figure 4B). In remote areas with low cumulative human impact, the health status is good but near the city of Turku relatively healthy seafloors can also be found even in areas where the cumulative human impact is at its highest.

Sensitivity analyses reveal resilience throughout most of the examined model modifications (Figure 5). Dissimilarities with the standard model were most prominent, in both extent and severity, when comparing the standard model with variants excluding some important environmental input data, in particular bathymetry or seafloor substrate. In anthropogenic variables, the inclusion or exclusion of data from the riverine nutrient load and siltation effect as well as the sites of dredging and trawling activities revealed prominent dissimilarities. The general statistics may, however, hide dissimilarity patterns which may be distinctive when plotted on a map (Figure 6). For example, the exclusion of depth data increases the estimated human pressure in those sea areas which are deeper than is the estimated siltation effect of the big ferry vessels. Omitting seafloor classification, in turn, results in lowered estimates of human pressure throughout the whole study area. Further, the inclusion or exclusion of sea openness data induces only barely discernible changes in a few localities. In addition, the exclusion of many human pressure layers induce only local-scale dissimilarities due to their strong distance-based influence decay. However, their local significance can be considerable. For example, aquaculture sites are often local hotspots but their exclusion from the input data only had an influence on 3% of the study area.

4. Discussion

The results suggest that cumulative human pressure on the seafloor of a shallow coastal sea can be modeled and mapped with reasonable relevance and precision by using publicly available spatial data. Compared with assessments that are based on oceans and sea basins (e.g. Halpern et al 2013, HELCOM 2010b), the main benefits are the increase in spatial accuracy and the possibility of distinguishing specific impacts on the seafloor. These benefits allow further analysis of the resulting model in comparison with field observations. For example, the standard model in this study was reasonably sound in showing the influenced areas in such a way that both met and challenged the expectations of an experienced researcher in the region. The model also highlighted some scattered hotspots of high cumulative human pressure, each of which can help to draw attention to local level details and aid in the detection of potential conflicts, thus contributing to regional planning. As most of the source data used in this study are subject to the European Union’s Inspire directive (Council Directive 2007/2/EC), this notion is likely pertinent to other European shallow seas and more generally wherever similar data sources are accessible.

However, the theoretical basis of the pressure map production deserves attention as it compresses many different kinds of information into a single index. One critique in particular is that the ecological responses to cumulative pressures are hard to predict. This is because individual ecosystem components can respond in diverse ways to the different kinds and levels of human activities. Even the usefulness of the whole scoring-based procedure can be questioned (Andersen et al. 2015). We would, however, agree with Halpern & Fujita (2013) that pressure modeling can provide sound support for planning and management purposes even if the outputs contain uncertainties. The strength of this method lies in the transparent and repeatable work chain.

The risk of subjectivity can be reduced by using structured expert judgment (Teck et al. 2010). In our study, we relied on the weighting scores established by the expert panel of HELCOM (2010b) for the different human pressures occurring in our study area. However this does not mean that the standard model is saved from potential errors. The lists of relevant drivers or data layers for example could change with another expert panel or even with the same panel after a few years. For instance, climate change stressors exhibited great impact on the California Current (Halpern et al. 2009) and on the Papahānaumokuākea Marine National Monument in the Pacific (Selkoe et al. 2009), but we did not consider these stressors because no undisputable data is yet available for the scale of our study. Nevertheless, as climate change scenarios in the northern Baltic Sea now show changes in precipitation, river outflow, salinity, and winter ice conditions (BACC II Author Team 2015), the pressure for their inclusion may rise. The benefit of the transparent modeling approach is its repeatability, and that the contributions of these parameters can later be imbedded and the maps reproduced.

The ground truthing of the outcomes of the model is another problematic challenge since no single metric has been defined for this purpose. An obvious choice is to use ecosystem data for evaluating the accuracy of the cumulative human impact maps. Andersen et al. (2015) addressed cumulative impacts on the Baltic Sea ecosystem condition and reported their regional level relations. Clark et al. (2016) compared cumulative impact maps with the zoobenthos characteristics in the Tauranga Harbor estuary of New Zealand, and found only a weak relationship between these parameters. In our study, both the benthic fauna density (Niemi et al. 2014) and its health status classification (Räisänen 2014) showed overall spatial conformities with the standard model, nonetheless these were not without their controversies. As our results suggest a single parameter inspected on the field describes only a small fraction of all of the pressures that the human pressure modeling strives to display. Therefor strong correlation is not likely to be found between the model and individual ground truthing parameter. ‘Misfits’ are easy to depict from the map overlay for special evaluation. Such examinations may yield a more heuristic understanding and new ideas – or show debatable results that may challenge the theoretical basis or performance of the modeling effort. Additionally, the ground truth data from these areas can be revisited to gain better understanding of ongoing processes. Overall, the visual inspection of the outcome maps is a good way to raise spatial questions for discussion, inspire new discoveries, and stimulate further research.

In this study, we applied two independent physicochemical parameters to compare with the standard model. Although they do not directly specify the human impact they nevertheless represent characteristics with a causal link from human activities to the state of the benthic ecosystems. High organic tin (TBT) contamination in the Archipelago Sea causes, among other things, the turnover of chironomid species and their decreased species diversity (Lilley et al. 2012). In the sampling stations of Niemi et al. (2014), surface sediment TBT concentrations generally agreed with the broad-scale patterns shown in the standard model. The highest TBT concentrations were found near the Port of Naantali, which is to be expected, but in some areas close to the Port of Turku their levels were low – probably indicating the influences of the regular dredging of its seaway, which removes the most affected surface sediments. In the broad picture, seafloor oxygen likewise shows good agreement with the standard model; the lowest oxygen levels found in the eutrophic bays near the mainland where nutrients concentrate through river transportation and as non-point-source loading (Hänninen et al. 2000). This study, however, shows that an all-embracing correlation is probably impossible to find between the standard model and any single field parameter. For future method development, it is to be recommended that researchers should strive to create a set of field parameters that would better reveal the complex characteristics of human pressures at the seas.

Sensitivity analyses of the standard model revealed the importance of the seafloor substrate and sea depth but the contribution of sea openness (exposure) data was marginal in our models. Riverine organic matter and siltation also affected large areas. The tested exclusions of selected human pressure layers or modifications in the pressure distance decay functions mainly induced local alterations. Such small details can nevertheless be important at the sites to which they correspond. Due to the high expectations of user's accuracy in local-scale modeling, the issues of data access and quality must be addressed carefully. The ideal input data would be thematically accurate describing the anthropogenic stress reliably, and available at resolutions corresponding to the actual pressure. However, such data is limited and also the vague understanding of the benthic habitat dynamics can be restrictive. In our study, seafloor area habitats could only be mapped on a robust scale as regards both thematic (different qualities of the seafloor) and spatial terms, and many challenges had to be solved with the pressure data. For example, we had to use a considerable amount of time to collect data about recent dredging sites from the paper archives of the responsible environmental permission authority. This example illustrates an inevitable type of challenge in the modeling of the poorly mapped underwater realm, where the data sources can be vague and scattered. For some pressures, however, lacking direct data could fortunately be circumvented by the means of spatial modeling (see examples in Methodology and Table 1). The mechanistic modeling approach nevertheless allows the results to be analyzed with actualized data from progressed inventories and research. From this perspective, the benefits of algorithm-based cumulative pressure modeling are clear compared with the subjective means of addressing the same theme.

This study confirmed the work hypothesis of using publicly available spatial data to produce a relevant geographical model of anthropogenic stress on a scale that is relevant for coastal planners. However, future human pressure modeling should incorporate not only improved input data but also the inclusion of other variables in the model, such hydro-ecological environmental processes which can be particularly complex in shallow coastal seas (Batista et al. 2014, Murray et al. 2015). Furthermore, methodological development is needed to achieve more explicit modeling constellations, which can involve, for example, the temporal domain that changes with seasonality, inter-annual variations, and accumulated human impacts. Nonetheless, cumulative modeling is also useful in its most simplistic form. Its straightforward visualization enhances communication and gives practical managers and developers the freedom to choose their own way in which to use the information (Judd et al. 2015). It can also inspire scientific discussion on the forming of testable research hypotheses or provide stimulus for better system modeling. In consequence, it fruitfully supports the increasing demand for evidence-based environmental management and policies.

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Table 1. Human pressures and impacts from the Annex III of the Marine Strategy Framework Directive (European Commission, 2008) and their conversion into relevant data layers and the data sources of this study. Data adjustments refer to the transformations made in producing the individual pressure layers. Use of formula additions shows in which pressures either depth or sea openness were considered in computing values for the cumulative multiscale human pressure index.

Pressures and Impacts	**Relevant data layers in our area**	**Data source and remarks**	**Data type**	**Data adjustments**	**Use of formula additions based on**	
					depth	**openness**
Physical loss						
Smothering	Disposal of dredged spoils	Finnish Consulting Group Oy	point	Distant-decaying function up to 2500 m.	no	no
Sealing	Harbors	Finnish Transport Agency, Finnish Environment Institute	point	Buffer of 500 m for large vessel harbors and 100 m buffer for recreational boat harbors.	no	no
	Coastal defence structures	National Land Survey of Finland	line	Buffer of 50 m around the line	no	no
	Bridges and coastal dams	Finnish Environment Institute	line	Buffer of 50 m around the line	no	no
Physical damage						
Changes in siltation	Riverine runoff of organic matter	Varsinais-Suomen ELY	point	Distant-decaying function up to 50 km. All rivers calculated separately and weighted with the measured material content.	yes	yes
	Dredging	Varsinais-Suomen ELY	point	Buffer of 0-1000 m normalized according to dredged mass	yes	yes
	Bathing sites, beaches and beach replenishment	Finnish Environment Institute	point	Beach areas separated as polygon. Distant -decaying buffer of 200 m around the beach.	no	no
	Coastal shipping	Finnish Environment Institute	point (AIS – data)	Distant -decaying buffer of 0-3000 m. Weighted by the size and speed of the ship.	yes	yes
Abrasion	Dredging	Varsinais-Suomen ELY	point	Buffer of 0-1000 m normalized according to dredged mass	no	no
Selective extraction	Dredging		point	Buffer of 0-1000 m normalized according to dredged mass	no	no
Other physical disturbance						
Underwater noise	Coastal shipping	Finnish Environment Institute	point (AIS – data)	Distant-decaying function from weighted (speed & size) sources to cover the whole study area.	yes	no
	Recreational boating and sports	Finnish Transport Agency	vector	Distant-decaying function of 1000 m from recreational boat harbors and 500 m from boat lanes and jetties.	yes	no
Marine litter	None	-	-	No indicators*		
Interference with hydrological processes						
Significant changes in thermal regime	None	-	-	No indicators*	no	no
Significant changes in salinity regime	Bridges and coastal dams	Finnish Environment Institute	point	Water bodies separated by dams or bridges selected	no	no
	Coastal wastewater treatment plants	Finnish Environment Institute	point	Distant-decaying function of 100 m	yes	yes
Contamination by hazardous substances						
Introduction of synthetic compounds	Harbors	Finnish Transport Agency, Finnish Environment Institute	point	Distant-decaying function of 2500 m for large vessel harbors and 500 m decaying function for recreational boat harbors.	yes	yes

Introduction of non-synthetic substances and compounds	None	-	-	No indicators*	-	-
Introduction of radionuclides	None	-	-	No indicators*	-	-
Systematic and/or intentional release of substances						
Introduction of other substances	None	-	-	No indicators*	-	-
Nutrient and organic matter enrichment						
Inputs of fertilizers	Aquaculture	Finnish Environment Institute (supplemented by HELCOM)	point	Distant-decaying function up to 1000 m	yes	yes
	Waterborne discharges of nitrogen	Varsinais-Suomen ELY & Hilska (2010)	Point & polygon	Distant-decaying function up to 50 km. All rivers calculated separately and weighted with the measured material content. Readily available areal data from smaller watersheds normalised and combined to final output.	yes	yes
	Waterborne discharges of phosphorus	Varsinais-Suomen ELY & Hilska (2010)	point & polygon	Distant-decaying function up to 50 km. All rivers calculated separately and weighted with the measured material content. Readily available areal data from smaller watersheds normalised and combined to final output.	yes	yes
Inputs of organic matter	Aquaculture	Finnish Environment Institute (supplemented by HELCOM)	point	Distant-decaying function up to 1000 m	yes	yes
	Riverine runoff of organic matter	Varsinais-Suomen ELY	point	Distant-decaying function up to 50 km. All rivers calculated separately and weighted with the measured material content.	yes	yes
Biological disturbance						
Introduction of microbial pathogens	Aquaculture	Finnish Environment Institute	point	Distant-decaying function up to 1000 m	yes	yes
	Coastal wastewater treatment plants	Finnish Environment Institute	point	Distant-decaying function of 100 m	yes	yes
Introduction of non-indigenous species and translocations	None	None		No indicators*	-	-
Selective extraction of species	Commercial surface and mid-water fishery	Lounaispaikka map service		Distant-decaying function of 1000 m from known mid-water trawling lines. 100 m distant-decaying function from known fish-trap sites.	no	no

*No indicators were available in the study area or the spatial accuracy of data was not sufficient to show differences in the area.

FIGURES

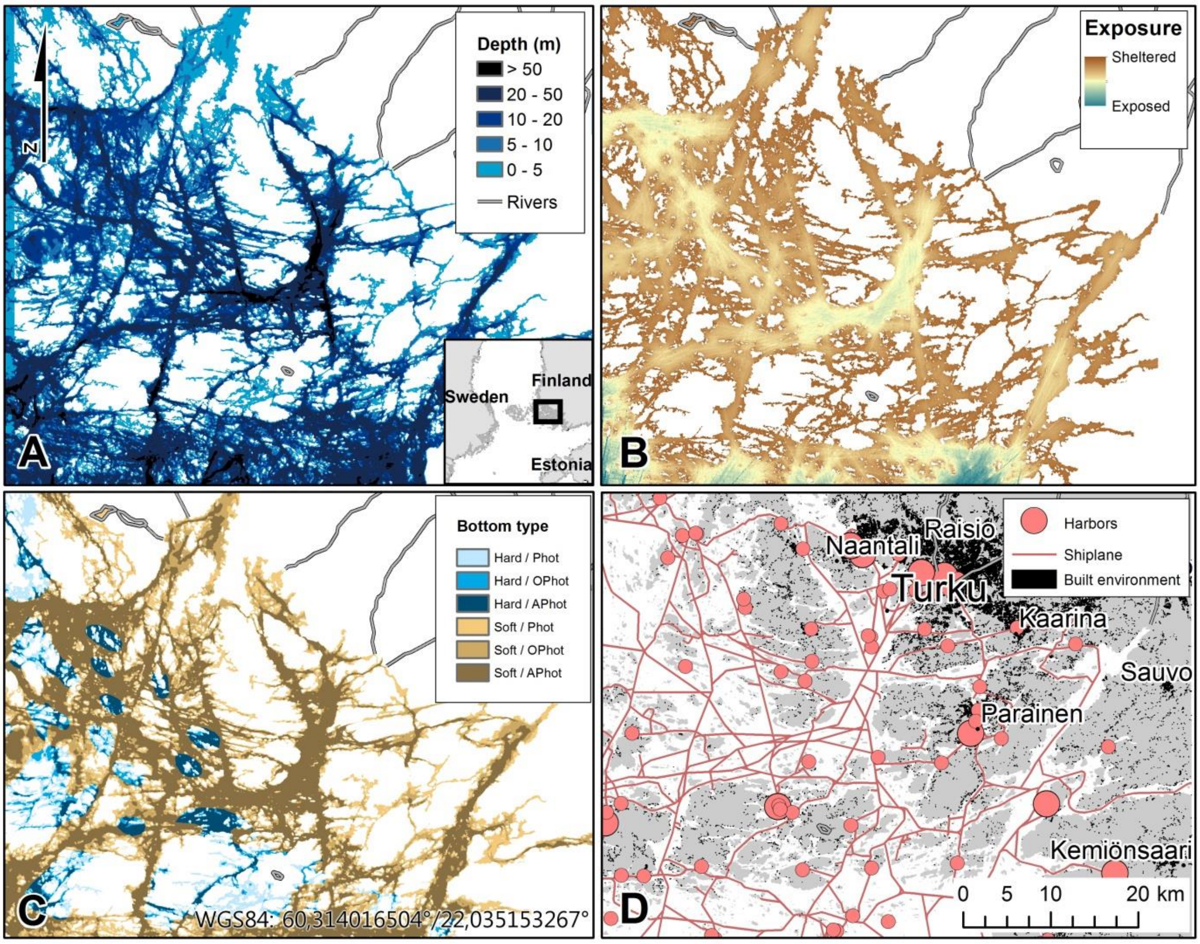


Figure 1. Research area location (inset) with its geographic characteristics. A. Bathymetry. B. Sea openness (average fetch length). C. Seafloor substrate and illumination. D. Built environment and marine transportation.

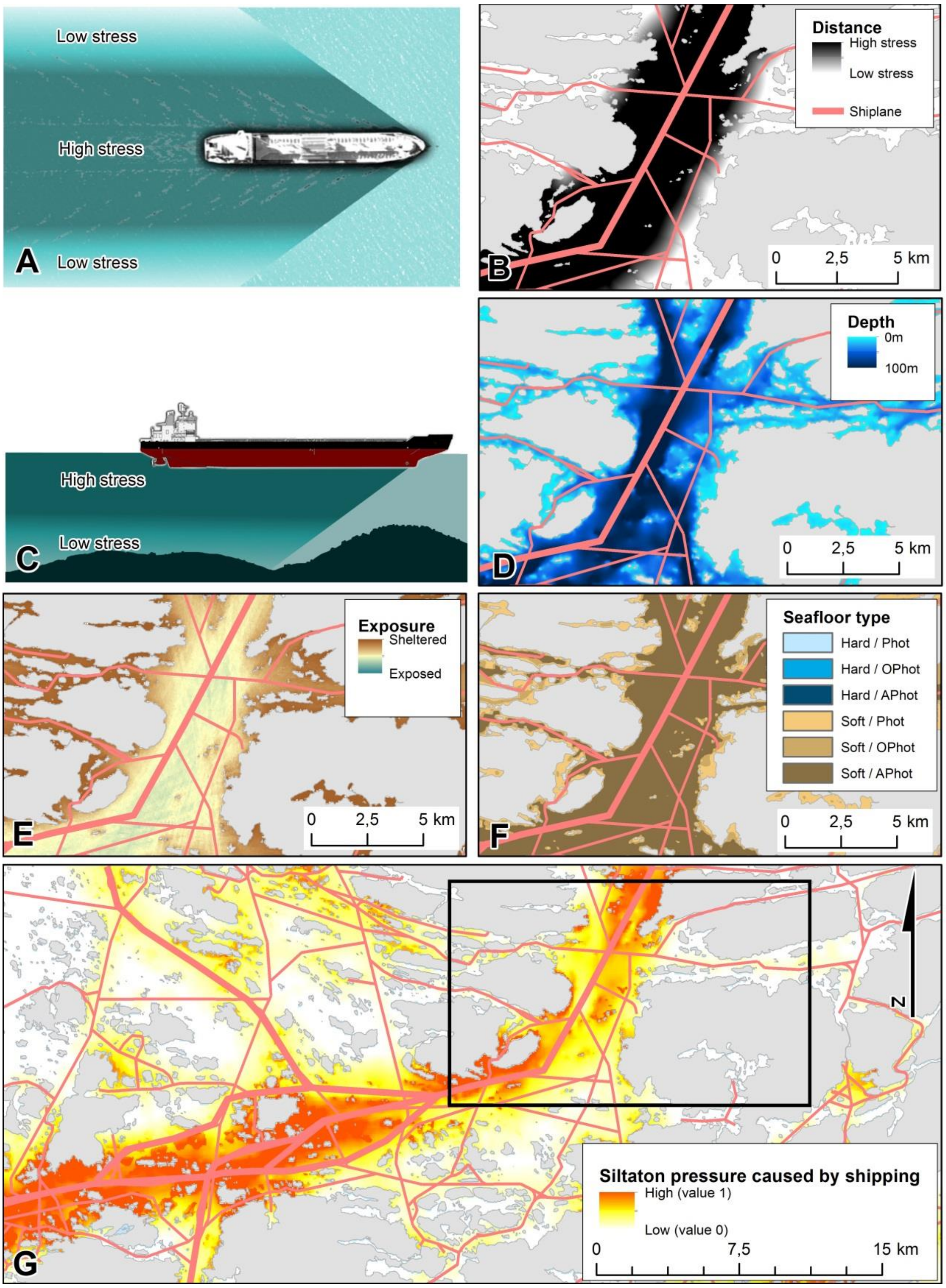


Figure 2. Pressure layer modelling using siltation caused by marine transportation as example. A. Physical disturbance stress in the horizontal dimension. B. Modeled horizontal physical disturbance. C. Physical disturbance in the vertical dimension. D. Depth (vertical distance decay). E. Sea exposure model. F. Seafloor substrate and illumination. G. Cumulative model of siltation pressure. Thick line shows the seaway used by frequent ferry boat shipping whilst other seaways are mainly used in boating (the model is based on AIS – data on actual ship traffic in August 2010).

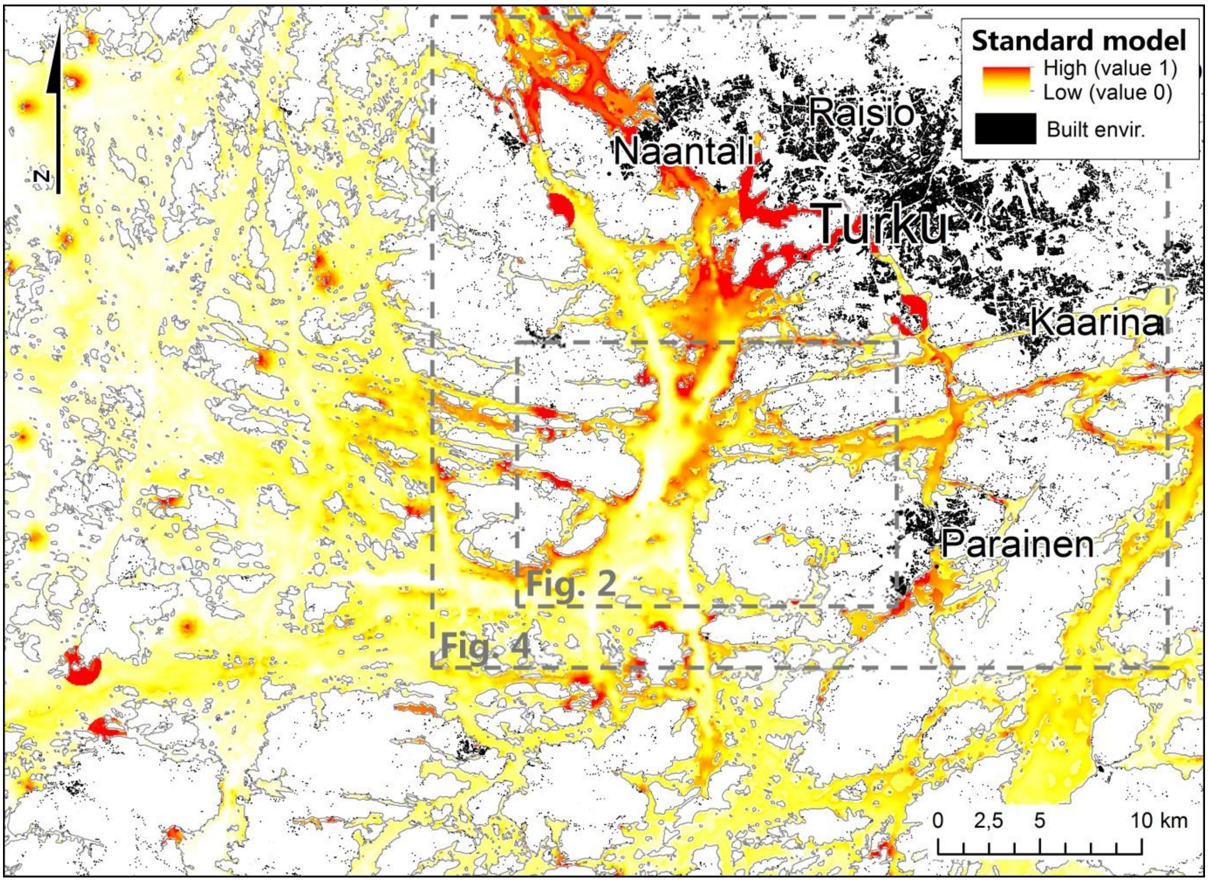
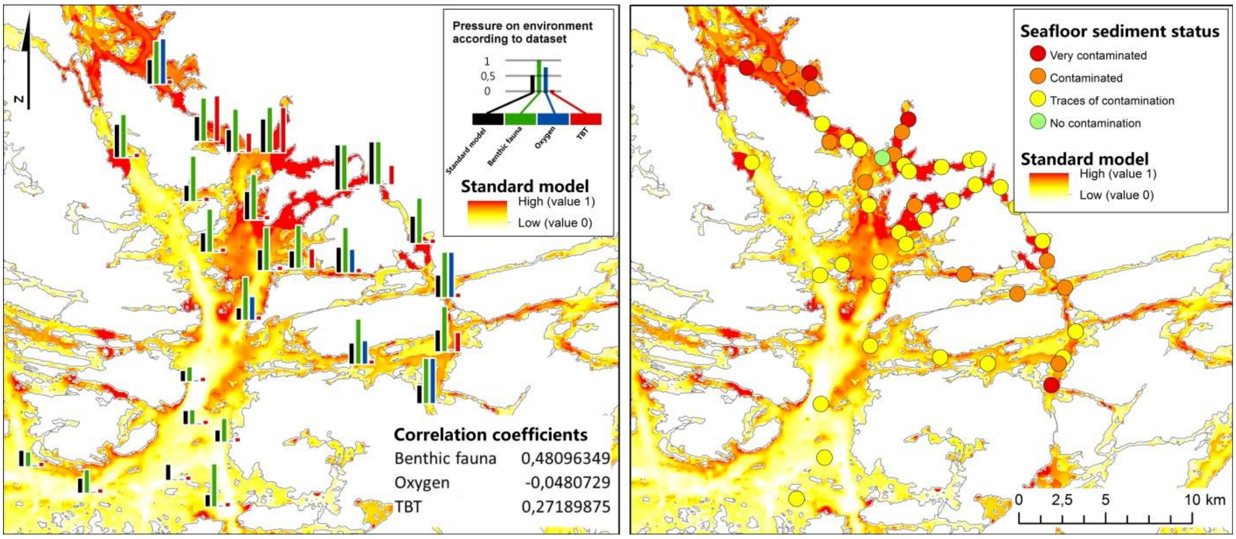


Figure 3. Standard cumulative human pressure model in the study area. Dashed squares indicate areas covered in Figure 2 and 4.



Correlation coefficients

Benthic fauna	0,48096349
Oxygen	-0,0480729
TBT	0,27189875

Figure 4. Standard model with independent data from seafloor monitoring. A. Normalized data of three field parameters at the seafloor in 26 sampling stations (data from from Niemi et al. 2014). B. Benthic fauna health status classification at the sampling stations of Räisänen (2013). Correlation coefficients are computed against the standard model.

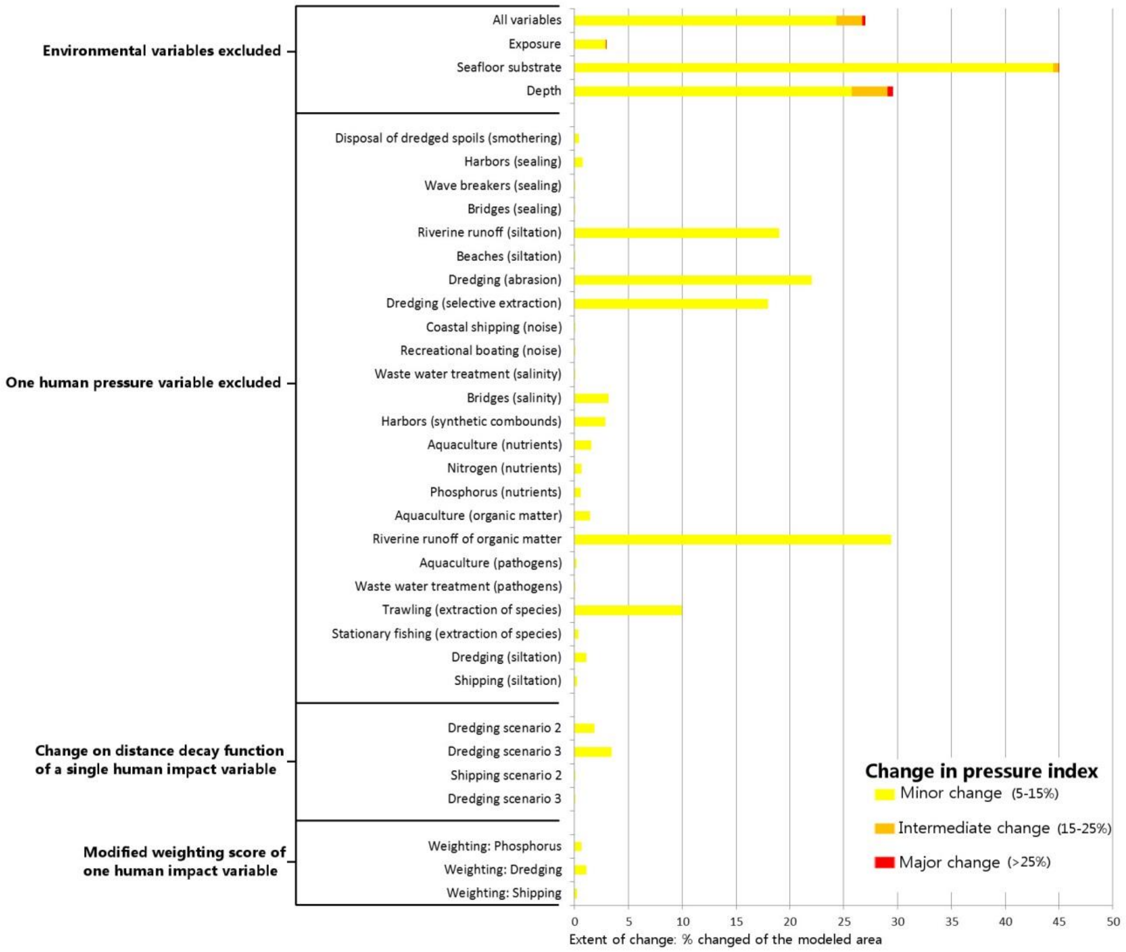


Figure 5. Sensitivity of the cumulative human pressure analysis for 35 adjustments in the input data. Horizontal axis refers to proportion of changed surface area and colours to the change in pressure index, both in relation to the standard model.

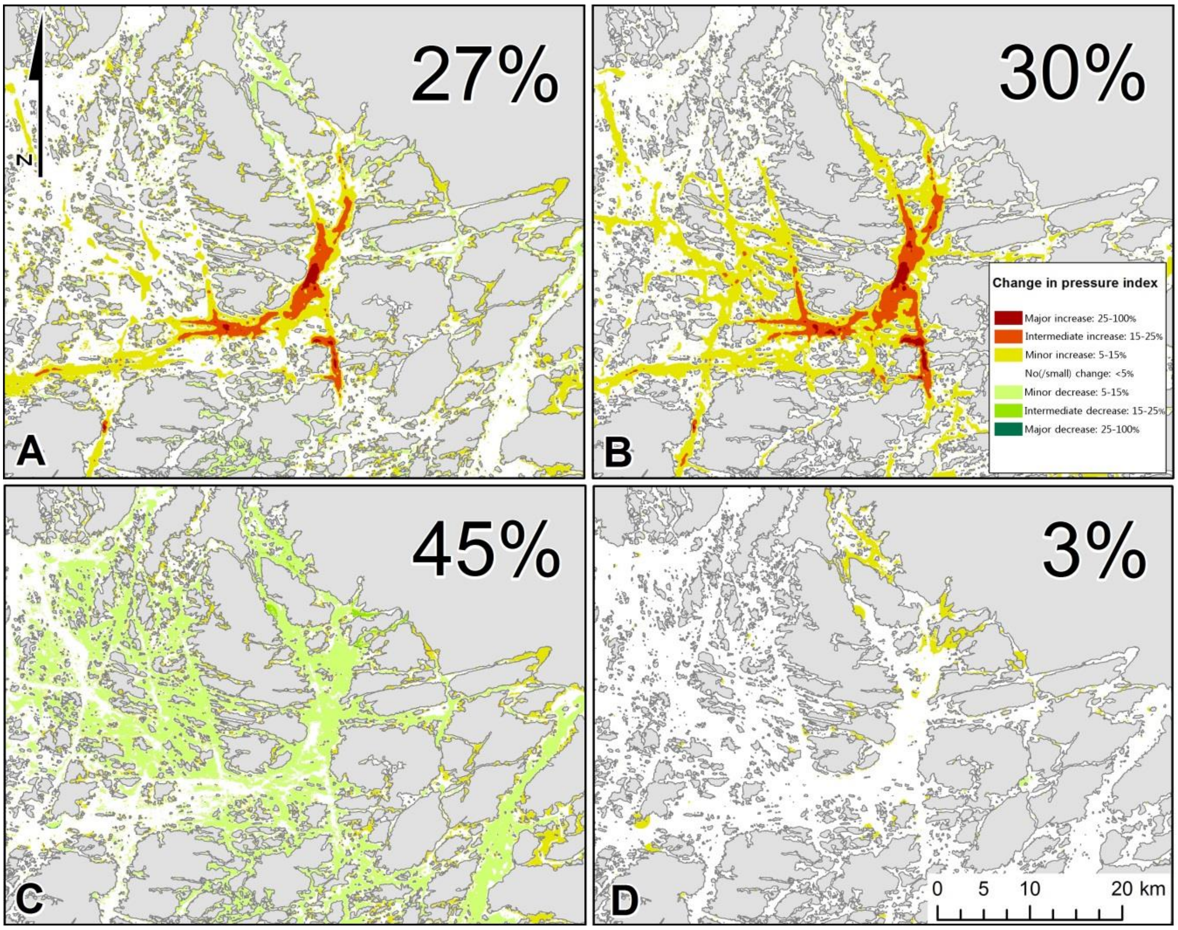


Figure 6. Geographical differences in the sensitivity of the cumulative human pressure assessment for changes in the input data. A. All environmental input data excluded. B. Exclusion of depth data. C. Exclusion of seafloor substrate data. D. Exclusion of individual human pressure (synthetic compounds from harbors). Percentage in the upper right corner refers to proportion of changed surface area and colours to the change in pressure index, both in relation to the standard model.