Environmental Advances 2 (2020) 100026

Contents lists available at ScienceDirect

Environmental Advances

journal homepage: www.elsevier.com/locate/envadv

Online tool to integrate evidence-based knowledge into cumulative effects assessments: Linking human pressures to multiple nature assets

J. Kotta*, M. Fetissov, R. Szava-Kovats, R. Aps, G. Martin

Estonian Marine Institute, University of Tartu, Mäealuse 14, Tallinn 12618, Estonia

ARTICLE INFO

Keywords:
Decision support tools
Maritime spatial planning
PlanWise4Blue
Cumulative effects assessment (CEA)
Baltic sea

ABSTRACT

Intensification and diversification of human-induced pressures in marine ecosystems have raised concerns over several sustainability-diminishing consequences, such as hypoxia and overexploitation of resources. We present the PlanWise4Blue tool (PW4B), which assesses the cumulative effects of multiple pressures on nature assets. In order to express the sensitivity of different nature assets to a plethora of pressure combinations, a meta-analysis based on published literature and available datasets was performed to calculate a set of standardized effect sizes. These calculations relied mostly on experimental or observational evidence; expert knowledge was used to estimate the impact coefficients only in the absence of impact data. Spatial modelling techniques (machine learning) were used to model the probability of occurrence and abundances of different nature assets in lattice grids with a cell size of 1 km^2. Users can use the portal to estimate impacted areas and changes to natural assets caused by any combination of anthropogenic pressure. The PW4B tool can be used to predict individual and synergistic effects — both current and future — of a wide range of human activities and can be used regardless of scientific background. The tool was tested in the Baltic Sea region in coordination with the process of the Estonian Maritime Spatial Planning. This test evaluated the combined effects of human activity such as fisheries, aquaculture, wind energy, mining and maritime transport sectors on nature assets such as selected seaweed, invertebrate, fish habitats as well as bird and mammal species. The analyses showed that current Estonian maritime spatial planning will result in a moderate loss of some nature assets and a significant gain of benthic suspension feeders, although predicted losses in wind park areas can be mitigated if novel aquaculture activities such as mussel or macroalgal farming are established This test demonstrates how the PW4B tool can be used by planners to minimize adverse environmental effects, to suggest effective mitigation strategy, and to attain sustainable planning solutions.

1. Introduction

Coastal areas are among our most ecologically and socioeconomically important ecosystems, but are also focal points for human activity and resultant impact (e.g. Dailianis et al., 2018; Gerovasileiou et al., 2019). Marine organisms in coastal ecosystems are under threat from a broad range of multiple interacting human stressors often resulting in species loss and habitat degradation. Such intensifying and diversifying human pressures jeopardize the sustainability of these ecosystems and services they provide globally.

Successful management, restoration and conservation of intensively used coastal ecosystems demands knowledge of the response of key species and habitats to the increasing pressure of the combined effects of multiple stressors. Earlier research has focused mainly on the impacts of individual pressures in isolation (e.g. Todgham and Stillman, 2013) and therefore the relative contribution of different human stressors and their interactive effects on ecosystem structure, function and services remain poorly understood. Over the last decade, however, a large body of literature has evolved that specifically targets interactive effects of multiple pressures on a large variety of ecosystem assets and their services (e.g. Przeslawski et al., 2015; Gunderson et al., 2016a).

Cumulative effects can be defined as impacts on the environment that result from pressures of several human activities acting together, such as shipping, fisheries, and wind parks, as caused by past, present or any possible foreseeable future actions (Judd et al., 2015). A central concept for most cumulative effects assessments (CEA) is that human activities can trigger different types of pressures, and that these pressures affect differentially different parts of the ecosystem (Knights et al., 2013). CEA reduce complexity and allow for a transparent assessment of uncertainty, streamline the uptake of scientific outcomes into a science-policy interface, and thereby bridge the gap between science and decision-making in ecosystem-based management (Stelzenmüller et al., 2018).

* Corresponding author.
E-mail addresses: jonne@sea.ee (J. Kotta), mihhail.fetissov@ut.ee (M. Fetissov), robszav@sea.ee (R. Szava-Kovats), robert.aps@ut.ee (R. Aps), georg.martin@ut.ee (G. Martin).

https://doi.org/10.1016/j.envadv.2020.100026
Received 10 October 2020; Received in revised form 30 November 2020; Accepted 5 December 2020

Despite this plethora of information, the existing tools for spatially-explicit CEA are still limited to a simplified pressure-response system (mostly single pressure on single or multiple nature assets) (e.g. Krueger and Schouten-de Groot, 2011; Hav, 2019; HELCOM, 2018a). This limitation renders the guidance of ecosystem-based allocation of human activities at sea highly biased, thereby undermining any assurance that societal environmental and socio-economic sustainability objectives will be achieved.

To date, we still lack effective communication between science and policy as there exists no suitable models with which to disseminate the complex relationships between pressure, nature assets and ecosystem services to important stakeholders responsible for management of nature assets. Improving management strategy demands a realistic and easy-to-use link from scientific knowledge to maritime policy and management of human activities affecting marine environment (Stelzenmüller et al., 2018).

In this paper we introduce a methodology with which to perform CEA on ecosystem elements that combines existing scientific evidence with expert judgement which is then communicated through a dynamic online tool to environmental managers. The PlanWise4Blue (PW4B) tool presented here is a free-to-use resource, available online for use by marine managers and/or policy makers without scientific backgrounds and based on the best available scientific data. Most importantly, the PW4B tool is capable of quantifying both single and synergistic effects of most important human activities on a broad range of nature assets. PW4B was used in the process of Estonian MSP to inform managers of the environmental sustainability of planning solutions. In the planning process the cumulative environmental effects of the combined effects of human activity (fisheries, aquaculture, wind energy, mining and maritime transport sectors) were assessed on nature assets (selected seaweed, invertebrate, fish habitats as well as bird and mammal species) to suggest effective mitigation strategies, and to attain sustainable planning solutions.

2. Material and methods

2.1. Description of study area

Coastal waters of Estonia belong to north-eastern part of the Baltic Sea. The Baltic Sea is a semi-enclosed brackish waterbody which lacks tidal cycle and therefore, an intertidal habitat. The low salinity allows only a few marine species to extend their distribution to the north-eastern part of the sea with freshwater species restricted to even more diluted bays and estuaries (Kautsky and Kautsky, 2000). Low species richness and the presence of organisms near their physiological tolerance renders vulnerable the whole ecosystem of the Baltic Sea (Bonsdorff and Blomqvist, 1993; Westerbom, 2006).

The coastal waters of Estonia are characterized by different environmental gradients (e.g. salinity, wave exposure) and complex topography, including extensive shallows. Salinity can be above 7 in the Baltic Proper, while river inflows reduce salinity to nearly zero in the inner parts of some bays. Areas highly exposed to waves are characterized predominantly by the presence of hard substrate, such as limestone cliffs or granite boulders. Moderately exposed areas typically contain sediments of sand, gravel, and pebbles. Bottom sediments in most sheltered bays along the coastline consist predominantly of fine sand and silt. Although the summer temperature of surface water in some bays can occasionally reach 28°C, summer temperatures are usually < 20°C and ice cover in winter may remain for over three months. There exists a gradient in trophic conditions from highly eutrophicated waters in sheltered bays to moderately eutrophied open sea (Kotta et al., 2008).

2.2. Nature values

The Marine Strategy Framework Directive (MSFD) (EU, 2008), the Habitats Directive (HD) (EU, 1992) and the Birds Directive (EU, 2009) are the key EU policy documents providing guidance on the protection of marine ecosystems for the MSP process. The Habitats Directive lists and protects habitats considered valuable by the European Community, and in conjunction with the Birds Directive ensures the conservation of a wide range of rare, threatened or endemic animal, bird and plant species. MSFD lists a coherent network for the protection of marine areas as an important tool to enable the sustainable use of marine ecosystem services and to prevent a decline in environmental status. Based on these directives, the PW4B encompasses species and habitats spanning from underwater habitats to birds and mammals relevant to the Estonian marine areas (Table 1, Fig. A1–6).

Essential Fish Habitat (EFH) is a concept that defines waters and substrate required by fish for spawning, breeding, feeding, or growth to maturity (NOAA, 1998). In this concept waters comprise respective aquatic areas and their associated physical, chemical, and biological properties, whereas substrate pertains to sediment, hard bottom, structures underlying the waters, and associated biological elements that support a sustainable fishery and the contribution of managed species to a healthy ecosystem. Safeguarding sustainable management of different fish stocks depends greatly on maintaining spawning grounds as a part of EFH sea area. In order to emphasize the importance of the fisheries sector and of spawning grounds to the reproductive capacity of fish stocks, the PW4B tool contains the spawning grounds of key fishes as a part of their EFH (Fig. A3).

The most evident information gap is a lack of spatial data on nature assets (species and habitats) and ecosystem processes at a resolution suitable to support Maritime Spatial Planning (MSP) (EU, 2014). A direct visual observation of every part of the sea for this purpose is unrealistic, so this study relies on existing modelled spatially-explicit layers of different nature assets.

Except for the resting, moulting and breeding areas of seals, which obtained from the Estonian Nature Information System (EELIS, 2020), spatial modelling techniques were used to predict spatial patterns of all other nature assets. All benthic map layers were obtained from Aps et al., (2018). This study used boosted regression tree (BRT) models, an ensemble machine learning method that combines the strength of regression trees and boosting (Elith et al., 2008). BRT modelling does not use any predefined data model, rather an algorithm to analyse the relationship between biotic and environmental variables and then makes predictions based on the established environment-biota relationships. Each benthic model described > 80% of the variability in the data suggesting a good fit of the empirical data to the distribution model.

The “The quality of fish spawning grounds” Project provided a map layer of herring, pikeperch and whitefish spawning grounds in the Estonian coastal sea (TÜ Eesti Mereinstituut, 2015). This project used another machine learning technique, the MaxEnt modelling (Elith et al., 2006), to model the probability of the presence of fish spawning grounds in the Estonian coastal area. The MaxEnt technique is a presence-only species distribution model. Specifically, the MaxEnt model minimises the relative entropy between two probability densities (one estimated from current presence data of spawning grounds observed during the field campaigns and the other from all locations that lacked fish spawning) defined in covariate space. Like the BRT models, the MaxEnt model was used to establish relationships between key environmental variables (characteristics of bottom substrate, macroalgal species coverages, seasonal averages of temperature, salinity, water currents, water chlorophyll a) and the probability of the presence of suitable spawning area of the studied fishes. MaxEnt modelling using these environmental predictors accounted for most of the variability in the quality of fish spawning grounds (AUC > 0.9). This suggests that the models exhibit extremely low uncertainty and that the selected variables account largely for the observed patterns of fish spawning grounds (Fielding and Bell 1997).

Spatial data on birds were based on aerial mapping and modelling by Luigujõe and Auniņš (2016), Eesti Ornitoloogiaühing (2019) and integrated information on the density of benthos feeders, fish feeders, gulls,

Table 1
Overview of ecosystem component layers included in the PW4B tool. The layers were based on data collected from multiple sources, more details below.

Environmental layer ID	Environmental layer	Source
1	Bird - Benthos feeders	Eesti Ornitoloogiaühing, 2019
2	Bird - Fish feeders	Eesti Ornitoloogiaühing, 2019
3	Bird - Migration routes	Eesti Ornitoloogiaühing, 2019
4	Bird - Wintering areas	Eesti Ornitoloogiaühing, 2019
5	Bird - Herbivores	Eesti Ornitoloogiaühing, 2019
6	Fish - Herring spawning areas	TÜ Eesti Mereinstituut, 2015
7	Fish - Pikeperch spawning areas	TÜ Eesti Mereinstituut, 2015
8	Fish - Whitefish spawning areas	TÜ Eesti Mereinstituut, 2015
9	Habitat - Charophytes	Aps et al., 2018
10	Habitat - Fucus	Aps et al., 2018
11	Habitat - Furcellaria	Aps et al., 2018
12	Habitat - Higher plants	Aps et al., 2018
13	Habitat - Richness of flora and fauna	Aps et al., 2018
14	Habitat - Suspension feeders	Aps et al., 2018
15	Habitat - Zostera	Aps et al., 2018
16	Seals - All species	EELIS, 2020
17	HD - Sandbanks	Aps et al., 2018
18	HD - Mudflats and sandflats	Aps et al., 2018
19	HD - Reefs	Aps et al., 2018

Table 2
Summary of bird feeding groups included in the study from the models of Luigujõe and Auniņš (2016) and Eesti Ornitoloogiaühing (2019).

Herbivores	Fish feeders	Benthos feeders
Cygnus olor	*Gavia stellata*	*Aythya ferina*
Cygnus columbianus	*Gavia arctica*	*Aythya fuligula*
Cygnus cygnus	*Podiceps auritus*	*Aythya marila*
Anser anser	*Podiceps griseigena*	*Bucephala clangula*
Tadorna tadorna	*Podiceps cristatus*	*Clangula hyemalis*
Anas platyrhynchos	*Phalacrocorax carbo*	*Somateria mollissima*
Spatula querquedula	*Mergellus albellus*	*Polystrica stelleri*
Anas crecca	*Mergus merganser*	*Melanitta nigra*
Anas acuta	*Mergus serrator*	*Melanitta fusca*
Mareca penelope	*Alca torda*	
Mareca strepera	*Cepphus grylle*	
Spatula clypeata		
Fulica atra		

and swans in Estonia (Table 2). Here, BRT was used to predict the probability of occurrence of bird habitats as well as the number birds per km^2. Owing to bird mobility and the moderate number of bird observations, the models predicted only 42–86% of the observed bird variability. For most benthos feeding birds, however, the predictive performance was greater (70–86%).

2.3. Human uses

The Estonian MSP focuses extensively on new marine uses, i.e., those with current or foreseeable interest for development such as aquaculture and energy production. To develop these fields of activities, the plan defines both guidelines and requirements, and with respect to wind energy, also the spatial aspects of development. Other human uses were shipping, commercial fishing, dredging and extraction of minerals (Table 3, Fig. A7–9).

All these human activities exert different pressures on the biota and one human activity often involves multiple pressures. Pressures from human activities can be broadly divided into four groups: inputs of substances, inputs of energy, physical pressures and biological pressures. For a comprehensive list of human pressures and their association with different human activities in the Baltic Sea region, see HELCOM (2018b). Although human activities impact marine life through these pressures, planners do not manage these pressures *per se*, rather planners designate sea areas for different human uses. This is why the PW4B tool environment allows users to upload maps of different human uses (rather than maps of pressures), which are then used to establish cumulative impacts based on established human use – pressure associations (for further details see below).

Table 3
Overview of human activities included in the PW4B tool. The map layers of human activities were obtained from the portal of the Estonian maritime spatial plan (http://mereala.hendrikson.ee/en.html, accessed Sept 1 2020).

Human activity ID	Human activity
1	Dredging
2	Wind park development
3	Shipping
4	Commercial fishing
5	Harbour development and maintenance
6	Extraction of minerals (mining)
7	Military activities
8	Wastewater discharge
9	Coastal protection
10	Fish farming
11	Mussel and algal cultivation
12	Marine plant harvesting
13	Tourism and leisure activities
14	Laying underwater cables

2.4. Approach to CEA in the Estonian MSP

The Estonian MSP addressed cumulative effects in two ways. First, the draft included some generic descriptions of the individual and synergistic effects of various human activity on different nature assets with no specific spatial analyses. Second, whenever spatial information on human activity was available, the PW4B tool was used to predict the individual and synergistic effects of all these human activities, either those currently present or those planned for future implementation.

The Estonian MSP recognizes both offshore wind energy production and herring fishery as important economic drivers in the marine region. Environmental effects related to the establishment of marine wind parks have not yet been described in suitable detail (e.g. Dannheim et al., 2019); nevertheless, there exists increasing evidence linking the construction of wind parks with environmental change that can be considered when assessing cumulative impacts on the marine environment. For example, the construction of offshore wind farms is expected to damage the reproduction potential of fish stocks and should be undertaken so as not to physically disturb fish spawning grounds or create temporal disturbance during critical spawning periods. In addition, sediment dispersal in important recruitment habitats for fish and during times of reproduction should be avoided and other adverse effects such as electromagnetic fields should be minimized (Bergström et al., 2012). On the other hand, once construction is completed, offshore wind parks provide hard, stable, and elevated substrates favourable for reef forming biota as spawning habitats for many fishes, thereby enhancing spawning (Šaškov et al., 2014). Yet internationally-regulated open sea pelagic trawl fishing itself imposes a direct adverse impact on the efficiency of herring stock recruitment, an impact that also requires assessment (Lundin, 2011). In trawl fisheries the survival of young herring selected from the trawl cod-end is low and the trawl fishery actually removes a considerably larger amount of age 0 to 1 herring from the stock than indicated by landing statistics (Suuronen et al., 1996a, 1996b).

Adding to these pressures, maritime transport is estimated to grow both globally and in the Baltic Sea (e.g. HELCOM, 2018a). Larger port areas on land and deeper fairways would probably be needed, but opportunities for port expansion are confounded by their proximity to conservation areas and adverse effects posed on different nature assets. Thus, shipping itself and maritime efforts to sustain shipping (e.g. dredging, dumping, mining) are expected to exert considerable pressure on marine habitats (including herring spawning grounds), birds and seals.

Finally, the planning also incorporated novel sectors of aquaculture in the Baltic Sea area (i.e. mussel and macroalgal farming). These types of aquaculture are considered to be the most promising compensatory measures to mitigate increased eutrophication in the Baltic Sea. Both algae and mussels store nutrients, which are removed from the marine environment upon harvesting. These activities can greatly enhance local water quality, which in turn improves the condition of benthic habitats and favours associated fish, bird and mammal populations (Lindahl et al., 2005; Gren et al., 2009). In other words, it is vital that the evaluation of human impact on nature assets also focus on possible benefits, because it provides the needed insight on possible remediation measures.

2.5. The calculation of CEA in PW4B

Accurate CEA assessments require solid ecological understanding of cause-effect relationships between pressures and biota and sound estimates of associated uncertainties. Because the total effect is not the sum of single effects but interactions overwhelmingly prevail in nature, it is essential that the synergistic effects of different pressures on nature assets are also quantified and integrated into the assessment. The existing assessments for the Baltic Sea region and for other European waters, however, are not yet able to incorporate this complexity and express impact as the sum of the individual effects of different pressures on different nature assets. Moreover, these assessments are based largely on expert judgement and not original data (e.g. HELCOM, 2018b).

Our procedure involves 1) meta-analysis of published or raw data that indicated separate and/or synergistic impacts (either from experimental manipulations or ecosystem changes observed before and after impact) and 2) linking the impact data (effect-size estimates) and existing spatial prediction of different nature assets into a cumulative impact assessment framework (e.g. Liversage et al., 2019). Some of these pressures are largely manageable and some are not (e.g. non-indigenous species) and in order to assess the existing unmanageable pressures, the developed assessment scheme considers the cumulative impacts of manageable pressures with respect to unmanageable pressures.

The PW4B tool integrates maps of different pressures and nature assets using pressure – nature asset specific impact coefficients by incorporating impact coefficients derived from literature-based and data-driven meta-analysis. When impact evidence is lacking, expert knowledge is used to estimate the impact coefficients. Although impact coefficients of some combinations of pressures still rely on expert judgement rather than empirical data, the PW4B tool will in future use more objective input as new data become available. The calculation of impact coefficients and their corresponding uncertainty depends on the type of data or summary statistics available (see Appendix B for details). Standard errors for model predictions are calculated by bootstrap (100 replications) using the "dpd" R package (Greenwell, 2017).

The spatial resolution of the cumulative impact model of the PW4B tool is 1 km^2, and the temporal timescale is 1 year. PW4B runs a CEA assessment by first analysing the spatial distribution of different human activities in the Estonian MSP. In this analysis all Estonian sea areas are classified based on the unique combinations of human activity found in each area (Fig. 1). The nature-value and pressure-specific coefficient of cumulative effect in each region of interest is then multiplied by the respective value of the nature asset (e.g. the density of wintering birds) to ascertain the expected changes of this nature asset (Fig. 2). The established methodological framework for CEA is updated dynamically by incorporating both the map layers of nature assets as well as the matrix of the separate and interactive effects of human use on nature assets. The CEA methodology allows different stakeholders to examine different spatial allocation scenarios and assess the expected extent of environmental impacts of each scenario.

2.6. Description of PW4B software

The PW4B tool is based on the ASP.NET MVC with PostgreSQL database engine, JavaScript, ESRI ArcGIS API for JavaScript, ESRI ArcGIS Server and ArcInfo, HTML5, CSS technology enabling its use on any device (phone, tablet, and computer) with Windows, iOS or Android operating systems. Single Page Application (SPA) approach was used in development, which enables users to interact dynamically with all controls, data and elements on one page, without the need to reload the page after each action. PL/pgSQL Procedural Language was used to create conditional and impact matrix tables and to fill them with data. The Python programming language was used in the analysis, the obtaining of different human pressure combinations, and calculations of cumulative effects of various pressure-types on nature assets.

The PW4B tool as a complex system consists of Server and Client/User Interface sides. The GIS data are prepared, analysed and stored in the geodatabase with ArcGIS Desktop and Python scripts. ArcGIS Server is used to share GIS data as Web Map Services (WMS) as well as the Geoprocessing tool Services. Auxiliary tables such as conditional and impact matrix tables used in preparation and calculation phases, information on WMS layers, model parameters and user interface tables are stored in PostgreSQL database and processed using PL/pgSQL procedural language. WMSs are visualized on the Client side with ESRI ArcGIS API for Javascript. User interface implemented on the client side supports setting models parameters, execution of Geoprocessing services, which are the main engine for the models, and viewing the results (Fig. 3).

The PW4B is a user-friendly geoportal tool (Fig. 4) that combines novel spatial modelling products of environmental background (e.g. maps of benthic habitats) with spatial data related to marine resources use with an emphasis on fishery, shipping and energy. The PW4B tool is based on ecosystem indicators (e.g. the number of wintering birds) that can quantify the intensity of ecosystem services (in contrast to many earlier assessments based solely on the presence/absence of ecosystem services).

3. Results

The cumulative effect of the studied human pressures varied largely among different nature assets. The bladderwrack habitats were affected in a few nearcoastal sites. The areal loss of this habitat in these sites was mostly < 1% per grid cell, which represents 1% loss of all available bladderwrack habitat in the Estonian coastal sea (Fig. 5). The impact on habitats of suspension feeders extended to both nearcoastal and offshore areas. Importantly, the effects were mostly negative in nearcoastal areas (the maximum loss per grid cell was estimated at 7 %) and positive in offshore areas (a maximum gain per grid cell at 10%) resulting in a

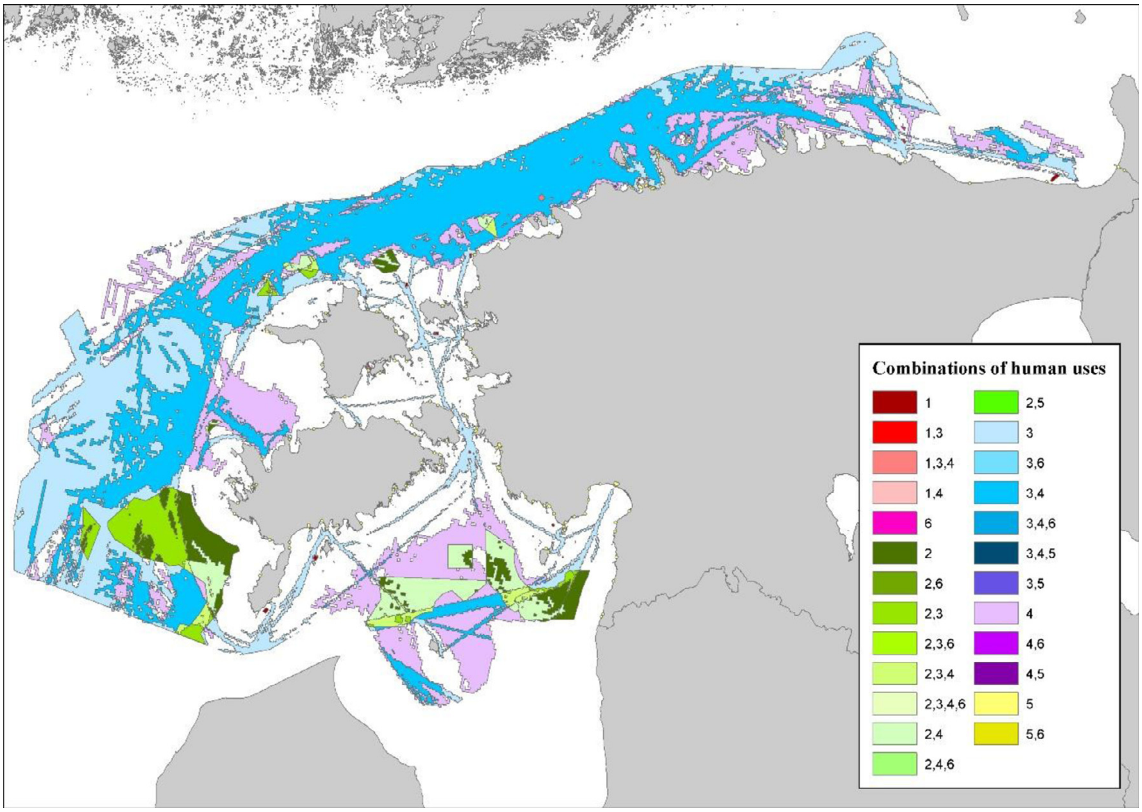

Fig. 1. Different combinations of human activities in the Estonian MSP. The code of pressures are as follows: 1 – dredging, 2 – areas suitable for wind energy development, 3 – shipping, 4 – open-sea pelagic trawl fishing, 5 – harbours, 6 – areas dedicated for mining.

total increase in the area of this habitat by 170% (Fig. 6). Like the bladderwrack habitat, the cumulative impacts of human activity on herring spawning grounds were limited to nearcoastal areas and the extent of the impacts within the impacted grid cells was low, between 1 and 5%, corresponding to a loss of total spawning habitat of 0.7% (Fig. 7). Benthic feeding birds were affected mostly in larger waterbodies within the West-Estonian Archipelago Sea as well as in offshore areas; the feeding grounds were reduced by 1–5% per grid cell, corresponding to a 5% overall loss of these feeding grounds (Fig. 8). The cumulative effects on wintering birds were more widespread, an estimated loss of 5–25 birds in the impacted areas (Fig. 9). However, a scenario incorporating development of novel aquaculture, such as mussel or macroalgal farming in wind park areas (the current Estonian MSP encourage such activities), predicted significantly reduced losses of the numbers of wintering birds (Fig. 10). The resting areas of seals were reduced in a few coastal areas, representing a 0.3% loss of total resting areas (Fig. 11).

The analyses showed that in general the greatest negative impact is caused by current marine traffic but there was large variability in how different nature assets responded to different combinations of human activities. For example, fishing exerted the strongest pressure on seals, accounting for nearly 95% of the estimated impact (note that impact include both individual and interactive effects; thus this percentage indirectly involve impacts of other pressures acting in the same area as fishing). On the other hand, the impact of shipping was only 13% of total effects. The impacts on bladderwrack habitats (mostly in ports) was nearly 96% of total effects. Herring spawning grounds were affected mostly by the combined impacts of harbour construction (34%), shipping (47%), dredging (44%) and extraction of minerals (21%). Suspension feeders were negatively affected by harbour construction/maintenance (1%) and dredging (4%) but the construction of wind parks would double the extent of suspension feeding populations in offshore habitats (100%).

4. Discussion

4.1. PW4B CEA analyses

Human activity occurs almost everywhere in the Estonian sea but is more intense in offshore areas due to shipping, commercial fishing and the future wind farm development. The cumulative effects of these human uses varied greatly for different nature assets. The current Estonian maritime spatial planning was predicted to result in a moderate loss of these nature assets primarily in nearcoastal areas e.g. bladderwrack habitats, herring spawning grounds, resting areas of seals. This moderate loss is due to a lack of spatial overlap between human pressures and nature assets under the current MSP scenario. Most human pressure is situated in offshore areas, whereas the above nature assets are typically located in shallow coastal waters. Nevertheless, the cumulative human impact on nearcoastal nature assets is greater than the current MSP assessment as many key pressures (e.g. land-based nutrient input, fish farms, introduction of non-indigenous species) are not yet included as map layers in the current MSP but can potentially be assessed in the PW4B tool.

Substrate heterogeneity is an important structuring factor for benthic seaweed communities in the study region (Kautsky et al., 1999; Martin & Torn 2004; Kotta et al., 2008) and any human activity (e.g. harbour construction/maintenance) that modifies a mosaic of substrate at small (100 m) spatial scales most likely reduces the spatial extent of habitat forming seaweeds. Moreover, harbours and shipping are often a source of elevated nutrient loading. Overly high nutrient loads will likely cause a decline in the biomass of habitat forming species in the bladderwrack habitats (Hällfors et al., 1984). This decline is likely not a direct consequence of nutrients on perennial seaweed species, rather the indirect result of a worsening of light conditions caused by an increase of opportunis-

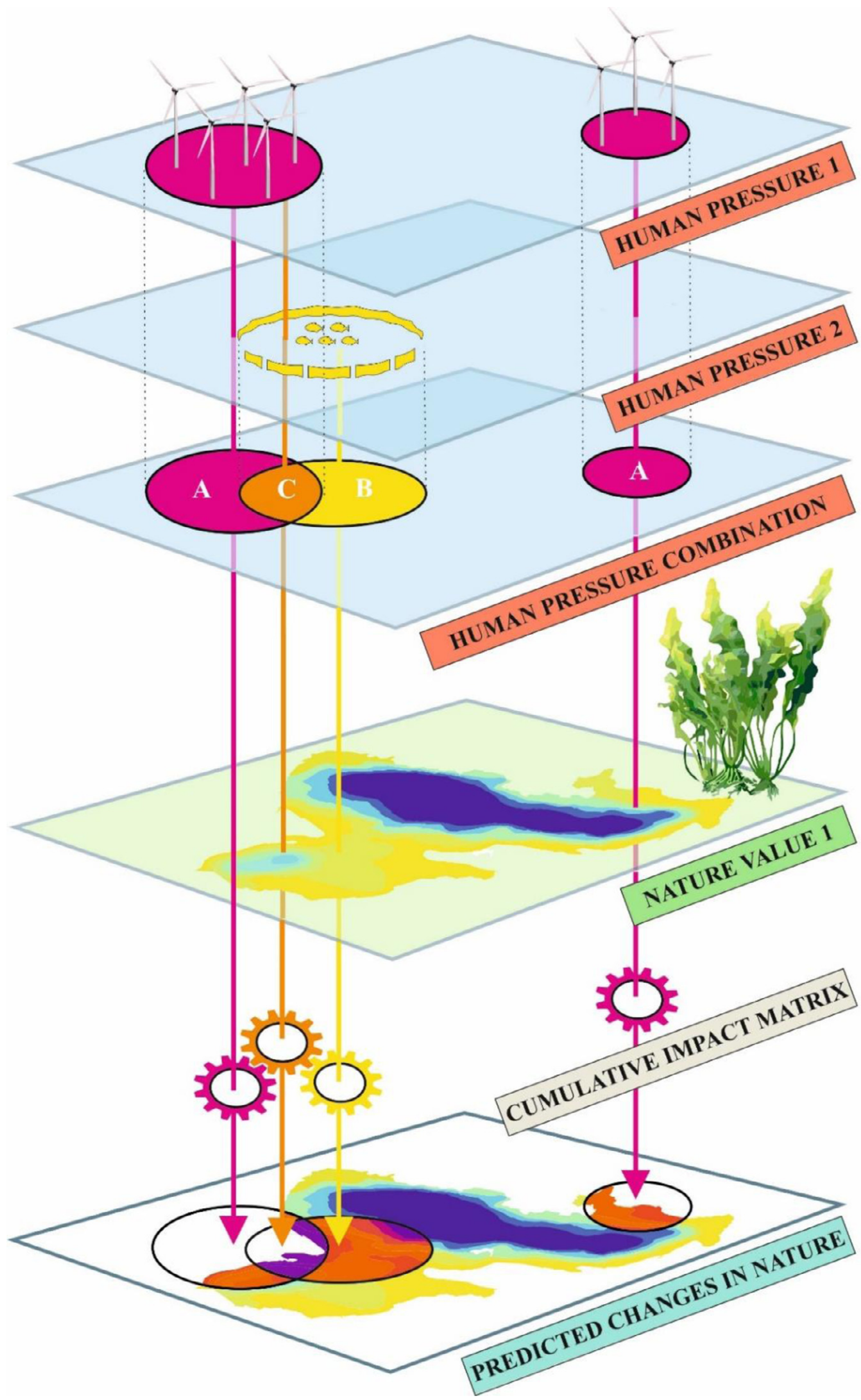

Fig. 2. A schematic representation of the cumulative impact assessment of the PW4B portal. The portal first classifies the region of interest based on the unique combinations of human activity found in each area. In this example, separate and interactive effects of the two pressures (human pressure 1 = wind park, human pressure 2 = aquaculture development) are applied on a single nature asset (nature value 1 = seaweed habitat). Cumulative impact matrix represents impact coefficients derived from literature-based and data-driven meta-analysis. The nature-value and pressure-specific coefficient of cumulative effect in each region of interest is then multiplied by the respective value of the nature asset to ascertain the expected changes of this nature asset. The resulting map represents the predicted cumulative effects of the studied human pressure on this nature asset.

tic filamentous algae on perennial seaweeds (e.g. Wallentinus, 1984; Pedersen, 1995; Morand and Briand, 1996; Torn et al., 2006).

The greatest negative impact on herring spawning grounds is due to shipping, with commercial open sea pelagic trawl fishing responsible for significant and unaccounted herring mortality in the 0 and 1 age groups (Suuronen et al., 1996a, 1996b). In addition, human activities that negatively affect perennial seaweeds, such as harbour construction, dredging and extraction of minerals, are expected to disintegrate herring spawning grounds. Specifically, herring spawning occurs in early May during migration to the coast (Lundin, 2011). Herring spawn in shallow waters along the entire Baltic Sea coast except for its most freshwater embayments. Spawning grounds are often located in areas with moderate to good water exchange and with high primary productivity. Herring spawn mostly on hard bottoms covered with brown and red algal species, such as *Furcellaria lumbricalis, Pylaiella littoralis* and *Fucus vesiculosus*, which likely reflects the prevalence of these algae in the Baltic Sea rather than a preference towards specific algal species (Aneer, 1989). However, spawning on firm algae that have extensive 3D structure (e.g. *F. lumbricalis*) can be advantageous, as such substrates can accommodate more eggs and ensure their proper aeration during early developmental stages (Messieh and Rosenthal, 1989). In general, the quality of spawning grounds exhibits low natural interannual variability. However, actual use of the spawning grounds and the efficiency of herring year-class production usually vary depending on seasonality in water temperature, pelagic primary and secondary production, and likely also on the intensity of human activity in the area. After spawning, herring migrate from

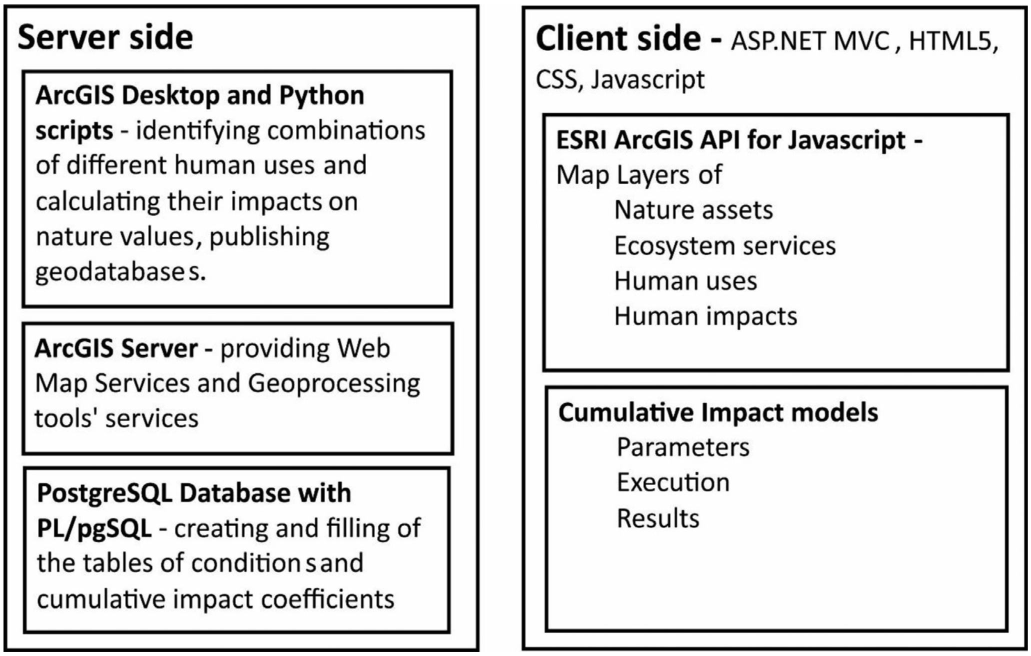

Fig. 3. Basic configuration of PW4B tool and based technology used in development.

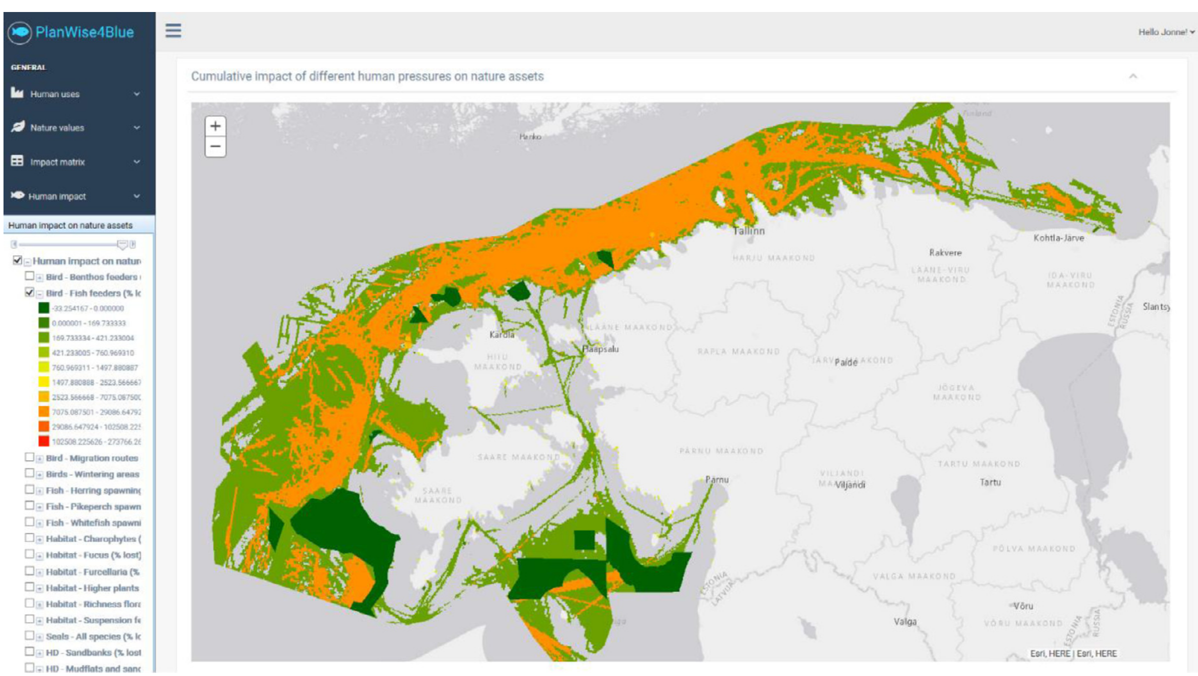

Fig. 4. User interface of the PlanWise4Blue tool.

the coast back to deeper waters where they remain for the rest of the year (Rajasilta et al., 1993).

Fishing and shipping were identified as the two most important human activities affecting the integrity of seal resting areas in Estonian waters. As seal number increased in the Baltic Sea region, fishermen started to report elevated bycatch of seals in different fishing gear including trawls (Lunneryd et al., 2003). Despite the increased by-catch of seals, the increase in seal population has continued; possibly the bycatch consists mostly of young seals that would suffer high natural mortality (Vanhatalo et al., 2014). Nevertheless, reduction of seal by-catch demands deployment of more environmentally friendly gears. Vessels can also have severe impact on seals (Jones et al., 2017). Shipping traffic is a major component of underwater low-frequency noise and is likely audible to seals over long ranges. Seals are unable to communicate above a particular noise threshold (Bagočius, 2014), and may even cause auditory damage (Southall et al., 2007); in the long run seals start avoiding important habitats (Morton and Symonds, 2002). Currently, the PW4B tool is limited to the resting areas of seals and this explains why the predicted cumulative effects of human activities on seals was low. To quantify realistic impacts of the exposure of shipping traffic on marine

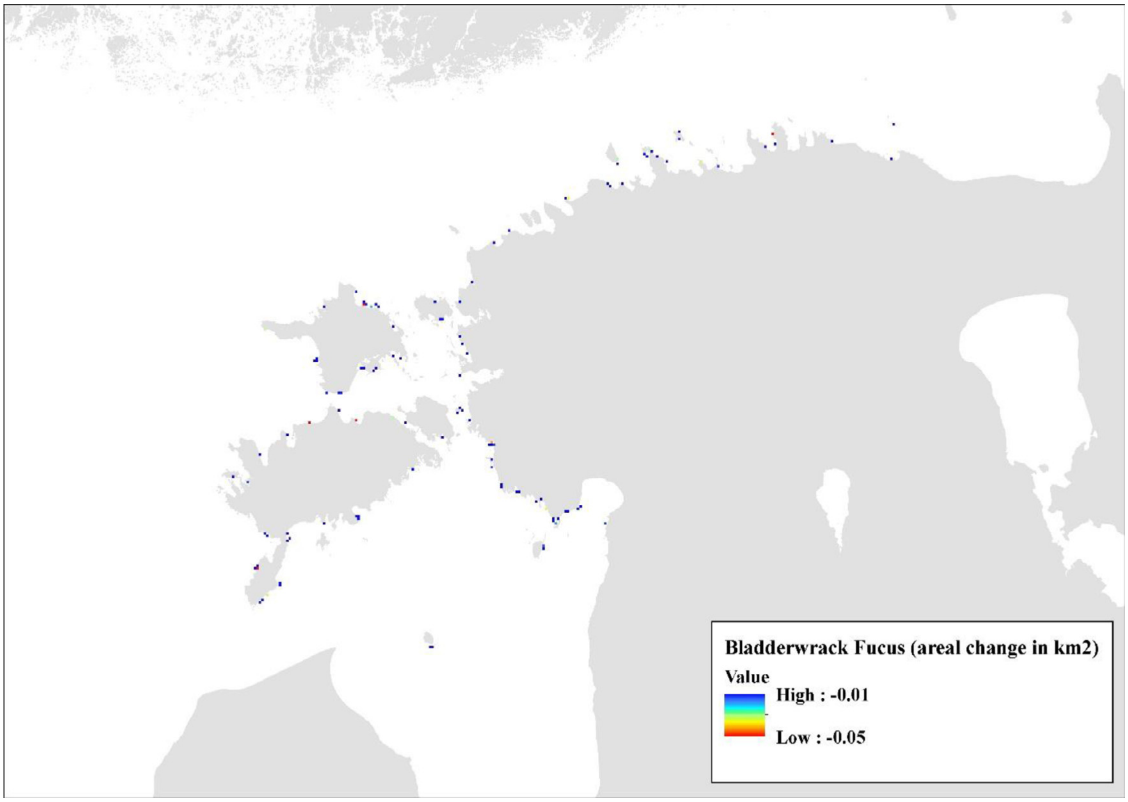

Fig. 5. Areal change of bladderwrack habitats in the current Estonian MSP scenario (habitat change in km^2 in a 1 km^2 cell).

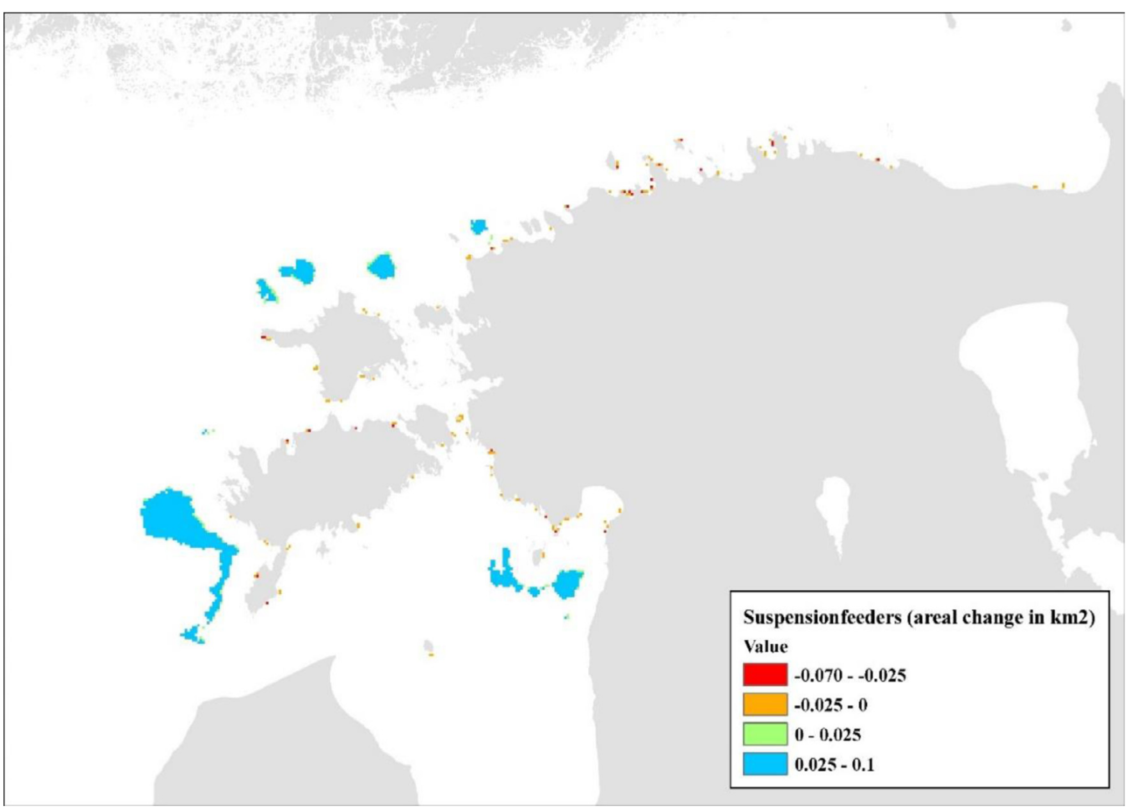

Fig. 6. Areal change of suspension feeding habitats in the current Estonian MSP scenario (change in km^2 in a 1 km^2 cell).

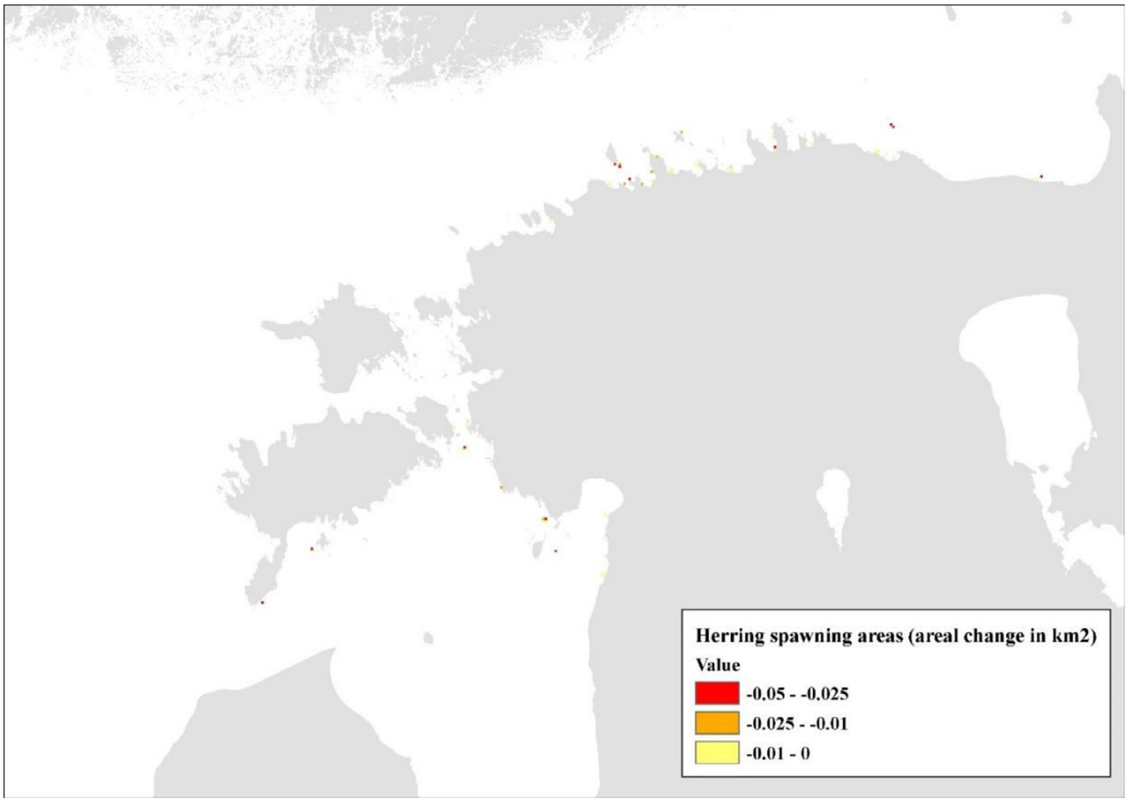

Fig. 7. Areal change of herring spawning grounds in the current Estonian MSP scenario (change in km^2 in a 1 km^2 cell).

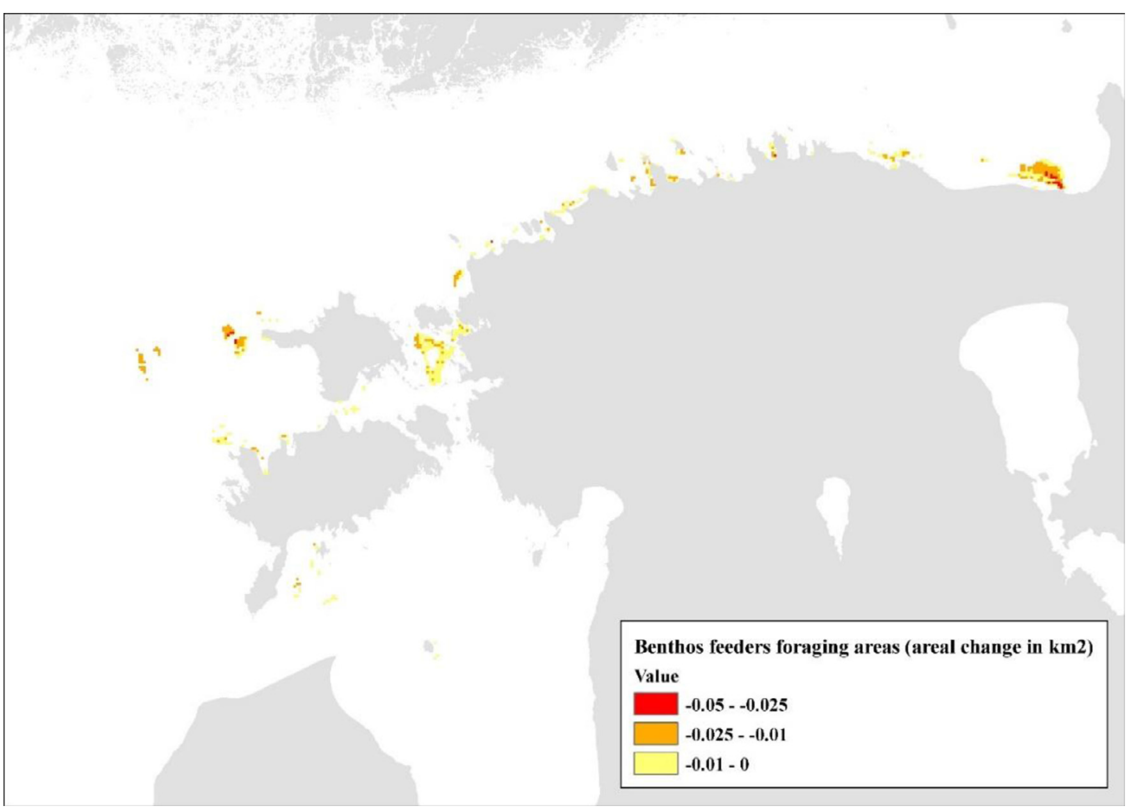

Fig. 8. Areal change of benthic feeding bird habitats in the current Estonian MSP scenario (change in km^2 in a 1 km^2 cell).

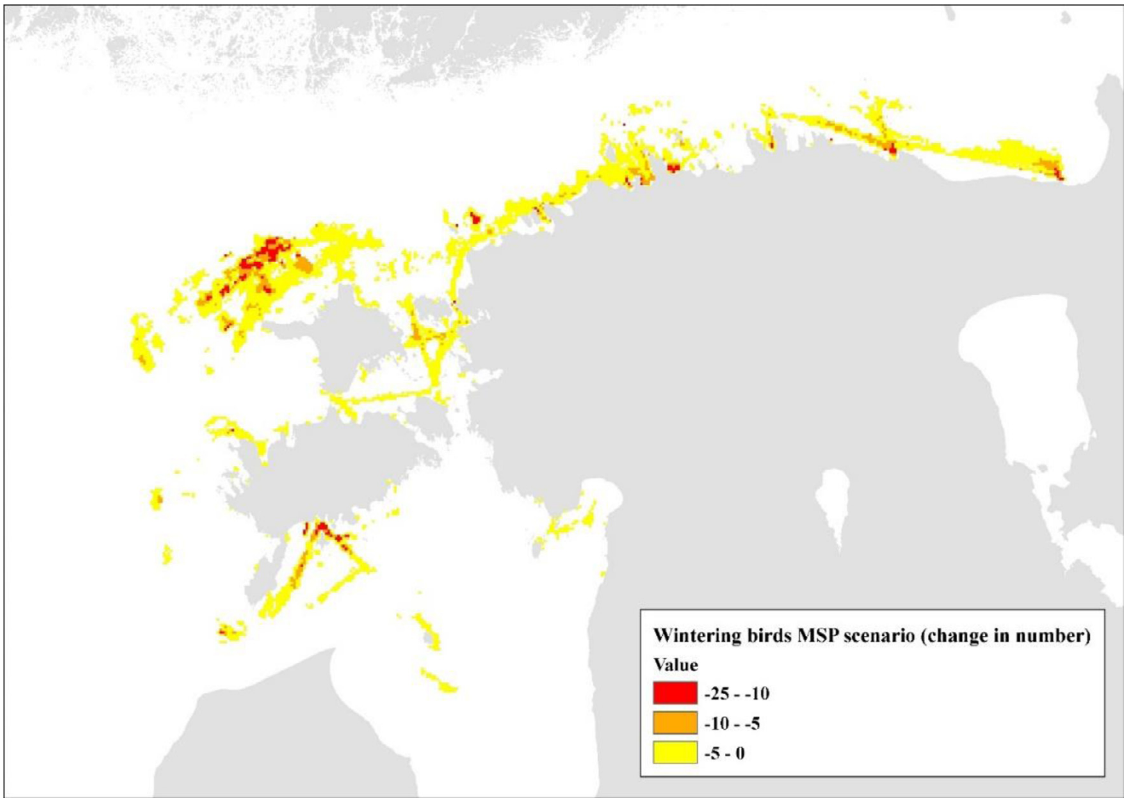

Fig. 9. Change in the density of wintering birds in the current Estonian MSP scenario (change in numbers in a 1 km^2 cell).

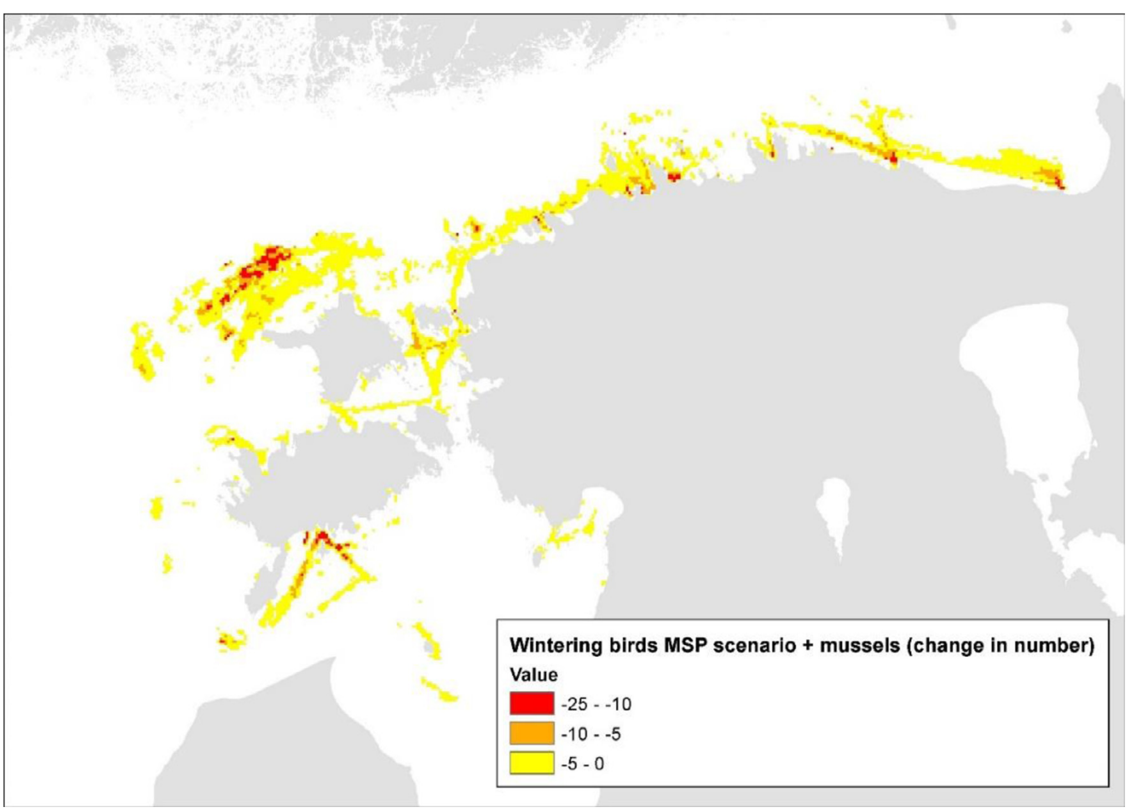

Fig. 10. Change in the density of wintering birds in the current Estonian MSP scenario including novel aquaculture (algal and mussel farming) in the wind park areas (change in numbers in a 1 km^2 cell).

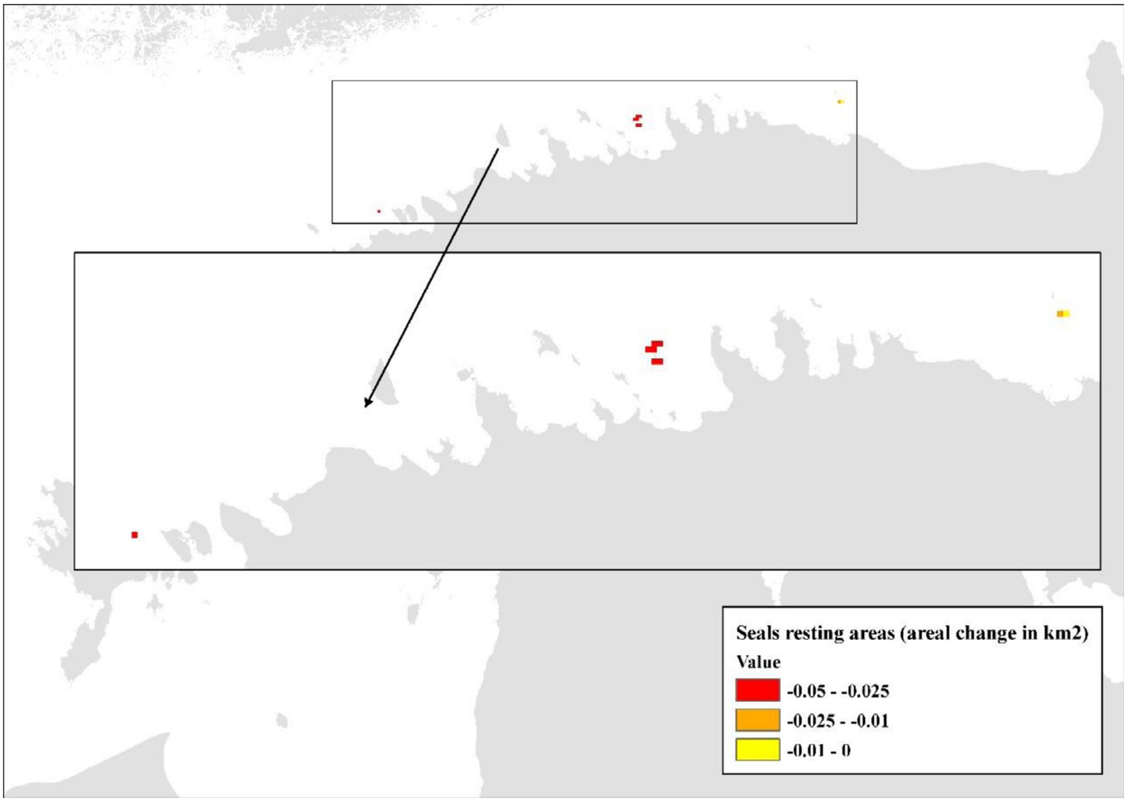

Fig. 11. Areal change of the resting habitats of seals in the current Estonian MSP scenario (change in km^2 in a 1 km^2 cell).

mammals requires density maps of seals based on the existing movement data of seals fitted with UHF global positioning satellite telemetry tags which are overlain with maps of predicted ship noise.

Offshore human activities had an overall negative effect on birds but positive effects on the habitats of suspension feeders. The effect on birds was due to shipping and partly on fishing. The greatest risk of shipping to waterbirds are oil spills and marine accidents. Despite increasing shipping traffic, the number of recorded oil spills has decreased; nevertheless, the concentrations of total petroleum hydrocarbons in the water column (an indicator of oil spills) has not decreased (Skov et al., 2011). Currently, over 10% of the Baltic Sea birds has oil residues on their feathers, which can be explained only by unreported oil spills (Larsson and Tydén, 2005, 2009). In addition, incidental bird mortality in fishing gear is observed in all countries around the Baltic Sea. Unfortunately, no comprehensive surveys on the bird by-catch exist at the pan-Baltic scale, therefore, the actual numbers of caught birds are unknown and the current assessment is certainly an underestimate. The construction of wind energy parks would result in a loss of benthic feeding birds of only 0.04% but a loss of bird wintering area by 10%. The greatest impacts on wintering waterbirds are expected during the operation phase when suitable bird habitats are unavailable for long periods (Bergström et al., 2014). Nevertheless, existing evidence also indicates that water birds quickly adapt to wind parks and the long-term effect of wind energy development is not as severe as short term monitoring assessments suggest (Skov et al., 2011).

A moderate effect of wind park development to benthic feeding birds relates to the creation of hard bottom habitats at a depth range that are otherwise absent in offshore regions, thereby providing support for totally different fauna and flora (Wilhelmsson and Langhamer, 2014). Artificial hard substrate, when properly mimicking natural substratum, is an ideal habitat for suspension feeding mussels. The key benthic suspension feeding mussel in the Baltic Sea region is *Mytilus edulis/trossulus*, whose habitat is dependent largely on the availability of hard substrate. Within its habitat (hard bottom areas) higher abundances generally coincide high food availability (Kotta et al., 2015). Food supply is a crucial factor for benthic suspension feeders with sedentary lifestyle, as mussels are able to deplete near-bottom water layer quickly (Fréchette et al., 1989) and starve even with abundant phytoplankton if there is insufficient water movement. In general, offshore areas are characterised by high wave energy, which replenishes the food supply (Kotta et al., 2015). A high density of suspension feeders in turn are expected to attract benthic feeding bird populations and counteracts mortality due to wind park development.

Moreover, when novel aquaculture activities such as mussel or macroalgal farming are established in wind park areas, as suggested in the current draft of the Estonian MSP, predicted losses of wintering bird areas are significantly reduced. Algal and mussel farming offers a means by which to remove nutrients, thereby inhibiting eutrophication in the Baltic Sea and to improve the quality of many nature assets including wintering birds (Petersen et al., 2014). Currently hundreds of tons of mussels are harvested in the Baltic Sea, but there is potential for much more. The production potential of mussels is currently limited by outdated legislation and an underdeveloped market for farmed mussels. Moreover, most farms have been established in sheltered waters where a lack of space has been presented to argue against large-scale mussel farming. However, technical development would enable establishment in offshore areas, especially in conjunction with wind parks. Eutrophication is considered the greatest threat to the integrity of the Baltic Sea ecosystem and is caused primarily by excessive amounts of legacy nutrients stored in the sediment and water (Conley et al., 2009). Due to the interactive effects of nutrient loading and other human pressures on different nature assets, high eutrophication levels set limits on the sustainable intensity of other human activities. Therefore, in addition to the spatial planning of traditional sectors, MSP solutions should analyse the impacts of compensatory measures in order to reduce adverse effects of eutrophication in the Baltic Sea.

4.2. Comparison of the PW4B tool with the HELCOM cumulative impact assessment

The HELCOM's Baltic Sea Impact Index (BSII) is the best known approach to assess the potential cumulative effects of different human activities on nature assets in the Baltic Sea region. The index gives information on areas where the greatest impacts from human activities likely occur (HELCOM, 2018b). Here, we used map layers of human use and nature assets in order to compare the PW4B approach with the BSII assessment.

The BSII and PW4B assessments in conjunction with the Estonian Maritime Spatial Planning showed similar spatial extent of impacts. The largest exception was the western archipelago region in which the BSII tool predicted smaller areal impacts than the PW4B tool (Fig. A10). Currently, birds in the BSII tool are limited to wintering areas omitting other seasons and aspects. The West Estonian Archipelago region is an important bird region throughout the year and is subject to year-round pressure by shipping and commercial fishing.

When comparing impact magnitude, however, the BSII predicted a much less detailed impact than the PW4B tool. Moreover, the regions of the severest impacts did not completely overlap. There are multiple reasons that account for these different outcomes.

First, the HELCOM algorithm examines each human activity individually (e.g. commercial fishing and dredging) without addressing the combined effects of different activities. However, the Baltic Sea that the sea area is affected by several human activities simultaneously; realistic effect estimates require assessment of the interactions of different pressures. For example, industrial fishing may have a moderate environmental impact. However, if large-scale dredging is also carried out in the same area, the combined effect is significantly greater than the sum of their individual effects. Dredging changes the nature of the seabed and the disturbs biota (oxygen is depleted in the bottom water layer and sediments and benthos may be destroyed).

Second, the HELCOM methodology assesses the effects of individual human activities on an ordinal scale (e.g. small, medium, large) and the data layers of natural values are on a nominal scale (natural value is present or absent). However, a realistic assessment of the magnitude of the impact of human activities depends on the abundance of a natural value at a given spatial point. However, in order for the natural environment to be able to offer us various benefits in the long run, it is important that the level of natural values does not fall below a critical level. For example, the presence / absence of different benthic habitats in Estonian marine areas is defined by the threshold biomasses of the characteristic habitat-determining species. If we want to know to what extent human activities reduce or increase the area of such valuable habitats, the calculation algorithms for the effects of human activities must be based on realistic estimates of the density of natural values and / or biomass. The PW4B algorithm is based on continuous layers of nature assets data (e.g. bird population density) and impact coefficients obtained from scientific literature or databases, which determines the relative increase or decrease in nature asset for a given combination of human activities. This aspect accounts for the HELCOM BSII tool's inability to distinguish between the extent of human activity in low and densely populated bird colonies. The maximum effects of the PW4B tool were found where the population densities of natural values were the greatest.

Third, the HELCOM approach does not consider the positive impact that human activities can have on the environment. This consideration aspect is vital if we want to assess the suitability of compensatory measures against the background of existing human impacts, e.g. the use of algae and / or shellfish farming to mitigate the negative environmental impact of fish farming. HELCOM's BSII tool predicted the loss of suspension feeders in wind farm areas, while the PW4B tool also predicted that wind turbines would provide a stable substrate thereby allowing extensive development of reef communities in areas where they are not found naturally.

In order to mitigate these shortcomings, we have developed an innovative methodology in which the assessment of cumulative effects is based on the causal links between different pressures and natural values based on quantitative knowledge published in the scientific literature and / or calculated from databases. Consequently, our methodology allows compilation in the calculation algorithms of most of the regional observations and experimental studies that demonstrate the separate and combined effects of different pressure factors on different natural values. Moreover, this approach allows the databases to be updated, i.e. the calculation algorithm can be readily supplemented with new knowledge on pressures and their effects on natural values.

4.3. Current lack of knowledge and possibilities to alleviate these limitations

The effectiveness of CEA to provide useful information centres on the availability of scientific knowledge and data on different nature assets and specific pressure effects. However, many aspects lack both knowledge and data. Some lack of data and knowledge is due to poor mapping of marine habitats, e.g. coastal habitats are often better mapped than offshore habitats. Similarly, impacts of more traditional human pressures (e.g. nutrient loading) are better known than more recent activities (e.g. wind park development) (Dannheim et al., 2019). Importantly, our understanding of different interactive effects of human activities on different nature assets is likewise limited (e.g. Andersson, 2011; Wake, 2019). Experimenting with multi-stressors is a relatively new area of research and a great need exists for robust experimental work that is comparable and reproducible and that can generate ecologically meaningful results. That said, the current unknowns may involve even more complex impact chains. For example, the distance that inshore fishing vessels can travel from their home ports is limited by the speed, size and capacity of their vessels, while the cumulative effects of these factors on fisheries are often poorly understood by those outside the industry (Johnson and Rodmell, 2009). Moreover, the effects likely depend on the developmental stage of nature assets, which is rarely considered in CEA (Popper et al., 2014). Nevertheless, all these limitations can be easily alleviated if the frame of CEA assessment can readily accept new knowledge and data as they become available. Moreover, the matrix of the CEA can be used to inform managers of the current gaps in knowledge in order to address these limitations more effectively.

Uncertainty in the CEA takes two principal forms: first, the uncertainty of the nature asset assessment, and second, the uncertainty of the effect coefficient, i.e., that arising from the literature-based meta-analysis. Likewise, measures of uncertainty serve two functions. The first function is straightforward, to provide planners and stakeholders with a quantifiable measure of confidence in any proposed strategy. The second function helps the developers of the PW4B tool to spot particular interactive relationships that demand further research in order to reduce uncertainty to more acceptable levels.

4.4. PW4B portal features

The nature and human activity layers are linked by an impact matrix that defines pressure-specific impacts (individual and synergistic effects) on different nature assets. The matrix is based on the best available scientific impact data linked through a meta-analytical frame (i.e. storing pressure and nature asset specific standardized effect sizes). Many other similar applications are limited to expert judgement on impacts. Moreover, the matrix quantifies both individual and synergistic effects of different human-induced pressures on ecosystem services. Many other applications succumb to complexity and disregard all interactive/synergistic effects despite of the known existence of multiple interactions in ecosystems (e.g. Helcom, 2018b; Menegon et al., 2018).

The PW4B tool continues to rely on expert judgement on those pressure combinations currently lacking concrete data, but only until new information becomes available (e.g. Gunderson et al., 2016b), after which the impact matrix is readily updated. The tool is dynamic and users can upload novel information on nature assets and impact knowledge that automatically generates novel algorithms to quantify cumulative effects.

These features enable PW4B to identify rapidly spatial conflicts between different human activities as well as to assess the CEA of different planning scenarios on nature assets. This tool has been developed to assist with maritime spatial planning but is also applicable in other fields. Importantly, when combining environmental impact of different human activities with the economic benefits of various management scenarios, the PW4B tool enables development of sustainable solutions to maximize the economic benefit gained from the use of marine resources with minimum damage to the environment.

4.5. Benefits, shortcomings and future developments of the PW4B model

4.5.1. Benefits and uses of the model

The PW4B model provides several benefits for its users. First, it is open source and therefore publicly accessible. Second, it incorporates key economic sectors with a variety of nature assets and their ecosystem services with which to quantify CEA assessments. The values of ecosystem services reflect provisioning, regulating and maintenance services. Third, the tool is versatile: users can choose input data on pressures and nature assets – both actual and theoretical. The tool has the potential for implementation regions beyond Estonia.

4.5.2. Shortcomings and limitations of the model

The PW4B model is currently a work-in-progress and requires further testing. Some combinations of pressures still require more data in order to decrease uncertainty in model output. In addition, the 1 km^2 spatial resolution may be too large for some aspects of coastal management. The model is likewise limited to Estonian sea space and may suffer edge effects from neighbouring countries and does not account for interactions (e.g. cascading food web effects) among different nature assets.

4.5.3. Potential for model development

The model is a useful tool for planning and prioritizing the use of coastal areas, drafting development plans and contributing to political decision making. However, the current model can be enhanced to produce more accurate predictions and the associated added value. It is judicious to make enhancements to validate concrete development plans.

4.5.4. To enhance the model

The most important improvement to the tool is regular updating of the model data, i.e. input data layers and information concerning impacts, and refinement to the model algorithms. This will result in enhanced predictive capacity and a reduction in uncertainty in particular regions, as well as the ability to measure model sensitivity and to stream-line modelling and calculation processes. By incorporating data from beyond Estonian sea space, the model can remove edge effects and perhaps eventually encompass the entire Baltic Sea.

Conclusions

The extent of impacts in the PW4B tool is a function of the availability of nature assets in the region of interest, the types of human pressures acting in the region as well as values of the impact coefficients of the relevant nature-value-pressure combinations. In this study the tool was used to analyse how different human activity would interactively affect different nature assets with respect to the Estonian MSP. Although we demonstrated use of the PW4B tool on selected pressures and nature assets, other pressure types (not represented as map layers in the Estonian MSP) and nature assets are available in the assessment tool. Although many interactive linkages are still resolved based on expert judgement, the exponential growth of knowledge will allow future updates of the tool reflecting continual improvement of the knowledge-base, resulting in more accurate forecasts. This impact assessment tool dynamically combines the distribution of nature assets and evidence-based cumulative effects of different human pressures on these assets. As such, the PW4B tool allows knowledge from empirical marine science to be applied effectively in decision-making, bridge the divide between science and management and support sustainable development. Importantly, users with or without science training can make use of the PW4B tool. Impact estimates are based on the best available knowledge from manipulative and correlative experiments and thus form a link between science and management. From a concrete perspective, the tool in the hands of non-scientist users such as government planners, NGOs and entrepreneurs can plan their respective activities in order to minimize adverse environmental effects, to advise effective mitigation strategy and ultimately to attain sustainable planning solutions. Simplifying both the public and private sector's ability to engage in sound environmental management will help to ensure a healthier environment for the general public.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The study was financed by the Estonia-Russia Cross Border Cooperation Programme project "Adrienne", the European Regional Development Fund within National Programme for Addressing Socio-Economic Challenges through R&D (RITA1/02-60) project "Innovative approaches to monitoring and assessing marine environment and nature values in Estonian sea area".

Author contributions

Conceived the study and wrote the paper: MF, JK, RA, RSK, GM. Analysed data: MF, JK. Designing and developing the PW4B tool: MF, JK. Obtained funding: JK, GM. All authors discussed the results and edited the manuscript.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envadv.2020.100026.

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