



A GIS-based tool for an integrated assessment of spatial planning trade-offs with aquaculture



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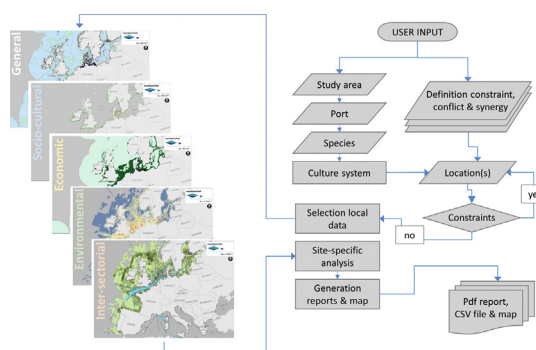
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HIGHLIGHTS

- The selection of aquaculture sites in a multi-use context requires integrative tools.
- The new AquaSpace tool allows for a spatially explicit and integrated assessment.
- Assessment indicators cover economic, environmental and social effects.
- Tool outputs can facilitate marine spatial planning and trade-off discussions.
- The GIS AddIn is freely available and builds on open datasets at European scale.

GRAPHICAL ABSTRACT



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ABSTRACT

The increasing demand for protein from aquaculture will trigger a global expansion of the sector in coastal and offshore waters. While contributing to food security, potential conflicts with other traditional activities such as fisheries or tourism are inevitable, thus calling for decision-support tools to assess aquaculture planning scenarios in a multi-use context. Here we introduce the AquaSpace tool, one of the first Geographic Information System (GIS)-based planning tools empowering an integrated assessment and mapping of 30 indicators reflecting economic, environmental, inter-sectorial and socio-cultural risks and opportunities for proposed aquaculture systems in a marine environment. A bottom-up process consulting more than 350 stakeholders from 10 countries across southern and northern Europe enabled the direct consideration of stakeholder needs when developing the GIS AddIn. The AquaSpace tool is an open source product and builds in the prospective use of open source datasets at a European scale, hence aiming to improve reproducibility and collaboration in aquaculture science and research. Tool outputs comprise detailed reports and graphics allowing key stakeholders such as planners or licensing authorities to evaluate and communicate alternative planning scenarios and to take more informed decisions. With the help of the German North Sea case study we demonstrate here the tool application at multiple spatial scales with different aquaculture systems and under a range of space-related development constraints. The computation of these aquaculture planning scenarios and the assessment of their trade-offs showed that it is entirely possible to identify aquaculture sites, that correspondent to multifarious potential challenges, for instance by a low conflict potential, a low risk of disease spread, a comparable high economic profit and a low

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impact on touristic attractions. We believe that a transparent visualisation of risks and opportunities of aquaculture planning scenarios helps an effective Marine Spatial Planning (MSP) process, supports the licensing process and simplifies investments.

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Software availability

Name of software: AquaSpace tool - a GIS Addin
 Developers: Antje Gimpel, Sandra Töpsch, Vanessa Stelzenmüller
 Email: antje.gimpel@thuenen.de
 Year first available: 2017
 Operating System: Microsoft Windows 7, Windows 8/8.1 (32 or 64 bit) or Windows 10
 Processor/CPU: 2.7 GHz Intel Core i5 processor or equivalent (4 cores) (hardware below/above will increase/decrease tool run times)
 System RAM: 4 GB total minimum, 16 GB recommended
 Windows Feature .NET Framework: .NET 4.6 Framework
 ESRI ArcGIS license required: ArcGIS Desktop Basic, Standard or Advanced with Spatial Analyst Extension
 Python Environment: Standard Python library 32bit of ArcGIS installation 10.3 and higher
 Program size: 1.7 MB; GDB 400 MB
 Availability: <https://gdi.thuenen.de/geoserver/sf/www/aqspce.html>
 Cost: nil

1. Introduction

Worldwide the demand for protein from aquaculture is increasing, triggering an inevitable expansion of the sector in coastal and offshore waters. (Maritime) aquaculture production may contribute to food security and relieve some of the pressures on wild stocks (FAO, 2014). In Asia, Norway or Canada aquaculture has already become an important human activity in coastal waters in terms of spatial expansion and economic viability (EEA, 2017). These developments take place at a much slower rate in European member states. As a result, European aquaculture as a future management objective addressing sustainable use is currently a matter of debate (EC, 2017). Further steps towards the Europe 2020 strategy should involve efforts to create a stable environment attractive to investors (Remotti and Damvakerak, 2015). As a management tool, Marine Spatial Planning (or Maritime Spatial Planning; MSP) can allocate space for upcoming activities such as aquaculture at sites with both favourable operational characteristics as well as lower potential for conflict with other sectors (Christie et al., 2014; Guerry et al., 2012; Stelzenmüller et al., 2017). MSP aims to integrate ecological, social, and economic interests, interactions among human activities, regardless of whether cross-border or inter-sectorial nature, whether conflict or synergy (Ehler and Douvère, 2009; Foley et al., 2010; Halpern et al., 2008). Since MSP is a public process, the implementation of strategic plans integrates greater accountability and transparency of decision-making by including a wide range of stakeholders from all sectors (Ehler and Douvère, 2009; Gilliland and Laffoley, 2008; Stelzenmüller et al., 2013; Wever et al., 2015). The MSP process is characterized as dynamic and evolving, integrating multiple feedback loops and permanent revisions (Ehler and Douvère, 2009). It can therefore increase the effectiveness of investments. MSP was identified by the European Commission as the cross-cutting policy tool that contributes to “sustainable growth of maritime economies, the sustainable development of marine areas and the sustainable use of marine resources” while “applying an ecosystem-based approach as referred to in Article 1 (3) of Directive 2008/56/EC with the aim of (...) achievement of good environmental status” (EC, 2014b). In Art. 51 of EU regulation no 508/2014 “the identification and mapping of the most suitable areas for developing aquaculture” is fostered. The regulation establishes the

European Maritime and Fisheries Fund (EMFF) in support of MSP, promoting a balanced and inclusive territorial development of fisheries and aquaculture areas (EC, 2014a).

The development of aquaculture should follow an Ecosystem Approach to Aquaculture (EAA) which comprises six steps (FAO and World Bank, 2015). Scoping (i) includes the establishing of the relevant geographical scales or ecosystem boundaries and the relevant stakeholders and institutions within each. The Identification of issues and opportunities (ii) integrates the selection of criteria thresholds to address the issues including considerations of risks (risk assessment and risk mapping). Subsequently, the maximum production is determined during carrying capacity estimation (iii), whereas the allocation of area/user access (iv) and/or management rights (consultation with stakeholders and setting operational and management objectives) are conducted according to this agreed production. Based on the results, the final management plans are developed (v). Their implementation and compliance is monitored (vi) and evaluated regularly, leading to planning and implementation adjustments – within the scope of the initially assessed opportunities and risks.

As yet, integrating such frameworks in MSP processes constitutes a challenge for European countries. In support of EAA, spatially explicit methods and tools are needed to assess both the environmental opportunities and risks of spatial planning options within important European ecosystem types. Some practical solutions are already available to support MSP. The number of spatially explicit tools highlights the usefulness of Geographic Information System (GIS)-based tools for MSP (Pınarbaşı et al., 2017; Stelzenmüller et al., 2017; Stelzenmüller et al., 2013). Nevertheless, specific tool functions are needed to support the planning and management of sustainable aquaculture development. Each step of the EAA framework can benefit from tool functions addressing the key issues which constrain or strengthen the growth of aquaculture.

In the course of the EU project AquaSpace the current and future obstacles for the expansion of aquaculture has been elaborated in nine case studies at regional levels with a total of 305 experts and stakeholders from the fields of nature conservation, governance, industry, science and administration. The outcomes (issues mentioned) of those regional stakeholder workshops have been pooled and ranked by the number of times case study outcomes included the same issue (Gimpel et al., 2016). The results showed that the majority of constraints were related to the EAA step of opportunity and risk assessment with a focus on economic and market concerns (Fig. 1). Further it became clear that unfavourable production conditions or a negative image of both aquaculture production and aquaculture products push back potential farmers and investors. Environmental threats such as high potential of pollution e.g. through faecal contamination were issued as being of nearly equal importance. This was followed by policy and management issues mostly related to low accountability in aquaculture and other sector issues (e.g. insufficient marine spatial management) (Gimpel et al., 2016).

In detail, the study revealed a need for integrated planning tools allowing i) the explicit consideration of economic and market issues; ii) a spatially explicit assessment of cumulative risk and an analysis of conflicts and synergies between sectors; iii) a comprehensive assessment of environmental effects at different spatial scales; and iv) to be easily handled by end-users such as industry and policy-makers. Hence, a clear gap was identified regarding an integrative decision support tool, which facilitates a systematic process for calculating and

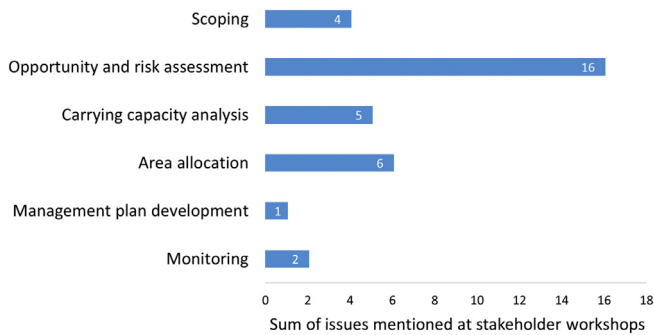


Fig. 1. Ranked issues from local stakeholder workshops (at AquaSpace case study level), classified by the Ecosystem Approach to Aquaculture (EAA) framework steps. Workshop participants included 305 experts and stakeholders from the fields of nature conservation, governance, industry, science and administration. Outcomes have been generalized and ranked (number of case studies mentioning the same issue). Adopted from Gimpel et al. (2016).

comparing opportunities and risks of a proposed aquaculture site in a multi-use (i.e. the mutual use of an area by different users) context (Gimpel et al., 2016). Such a tool should allow to determine if it is a sound investment, to see how it compares with alternate projects and to allow for a spatial representation of all opportunities and risks, including environmental ones (CA.GOV, 2017).

A gap analysis of tools and methods supporting EAA, conducted by Gimpel et al. (2016), showed that the majority of tools reviewed were developed to solve environmental issues such as BLUEFARM-2 (Brigolin et al., 2015; Brigolin et al., 2017), supporting the assessment of environmental interactions or MERAMOD (Cromey et al., 2012), focussing on benthic effects for finfish aquaculture. This was followed by tools and methods to address policy-management issues, for instance Seascape (Miller and Morrice, 2002), focussing on visual impact and other sector issues, e.g. MaRS (Davies et al., 2012), providing maps of opportunity and constraint for various types of aquaculture. Tools considering economic and market issues were rare, i.e. the FARM model (Ferreira et al., 2012), supporting e.g. an economic optimisation of culture practices. Albeit, no practical tools were found which can be applied to consider all of those categories assessed. However, a few tools could address some of those simultaneously. For example GIS-based tools such as SISAQUA (Gangnery et al., 2015) addressed up to three categories (other sector, environmental and policy and management issues), hence pointing the way ahead to identify optimal locations, based on multiple defined constraints and targets. A recent study done by Depellegrin et al. (2017) presented e.g. a set of multi-objective spatial tools for sea planning and environmental management, where, next to nutrient dispersion (nitrogen and phosphorus), ecosystem service capacities or cumulative impact, conflict potentials have been assessed.

The here presented GIS AddIn 'AquaSpace tool', comprising data and functions that enable the user (i.e. key stakeholders from the field of industry, marine planners, licensing authorities) to conduct an integrated and spatially explicit indicator assessment for different aquaculture planning scenarios in European waters, should close this gap. Its socio-economic dimension will increase the acceptance of these new developments by local communities and society-at-large (Ramos et al., 2014; Stelzenmüller et al., 2017). Environmental assessments will contribute to the implementation of the Integrated Maritime Strategy and its environmental pillar, the EU Marine Strategy Framework Directive (Gimpel et al., 2013; Gimpel et al., 2016; Stelzenmüller et al., 2014). Integrating indicators supporting the assessment of inter-sectorial effects enables authorities to account for the principles of good MSP practice as required by the EU Maritime Spatial Planning Directive. Further, the GIS AddIn is freely available and builds on open datasets at European scale, improving reproducibility and collaboration in aquaculture science and research (Stewart Lowndes et al., 2017). Ultimately, this

integrated assessment approach could support the licensing process and facilitate investments. Here the technical concept and implemented components are described together with a practical demonstration of the full functionality using the German Bight of the North Sea as an example.

2. The AquaSpace tool

The AquaSpace tool (Gimpel et al., 2017) was developed based on a combination of the GIS model builder and python scripts under Arc GIS 10.3. It runs with Arc GIS 10.3 and newer versions and is composed of the mxd (ArcGIS format) project, a Geodatabase (GDB) providing the data required to run the tool, and the tool bar. It allows a spatial representation of opportunities and risks of a proposed aquaculture site in marine areas exposed to multiple human activities and their respective pressures. The tool depends on a pre-assessed suitability of ecological conditions for the specific aquaculture species ("suitability maps", further described in Appendix A) and inter-sectorial, environmental, economic and socio-cultural data and information in order to assess for each candidates' aquaculture site its potential economic viability, legal constraints, conflict or synergy (i.e. co-location) potential with other sectors, and relative environmental impacts under different aquaculture planning scenarios (Fig. 2). In terms of scenario evaluation, location-specific indicator values are selected in order to transfer spatially explicit information directly to the report. In application of AquaSpace tool functions, a range of input data are processed further, aiming to receive additional real time site information such as e.g. an overall cumulative impact score. Here, the impact exerted by/on the tested aquaculture system is added. Information about the AquaSpace tool indicators can be found in Appendix A and Appendix B.

Reflecting the need for spatially explicit assessment approaches to be easy to access, the AquaSpace tool is equipped with an end-user driven interface and an interactive menu (Appendix C). The Arc GIS mxd file visualises the spatial extent of the tool in terms of a background map (esri bg map) and ensures the correct paths' and symbolisation of all datasets required to run the tool. The AquaSpace tool builds on open data with European scale (Appendix B) to accelerate tool performance and to promote tool exchange and its general applicability. Further, tool settings can be changed individually and datasets can be replaced (Gimpel et al., 2017). Running the tool requires a fair knowledge of GIS and detailed (spatial) information on sectorial requirements and economic considerations.

As described in Fig. 3, each tool section (e.g. user input) addresses one specific process step. The user defines the study area (e.g. country), the port from which aquaculture business should be transacted, the culture species and corresponding culture system, the constraints (e.g. exclusion zones or other management regulations), and the conflict matrix indicating conflicts or synergies with other human uses. The selection of the study area limits the spatial extent of the data processed and thus speeds up the tool performance. The port is used as a baseline for economic, distance-based calculations. From an initial set of aquaculture species most common in European waters (Fig. 2), the species and a related culture system with the respective spatial dimension must be selected. Further specifications (e.g. related to investment costs, average fuel costs, market price, the cage size in m³, the stocking density per m³, and the amount of production in kg/tons) can be made to allow for an Economic Impact Assessment (EIA). The background layer of the report map can be changed individually and selected from a range of indicators, which are visualised in terms of their current status (e.g. current state of cumulative pressure). Finally, the planning sites that should be evaluated have to be defined. Here, the user is directed to act in a sustainable way, being aware of the ecological footprint of a specific aquaculture or its interaction with other human activities as the user input point is buffered by a species-specific environmental footprint. Assuming a precautionary approach, the environmental footprint of shellfish is determined to be 50m (Chamberlain et al., 2001) and for

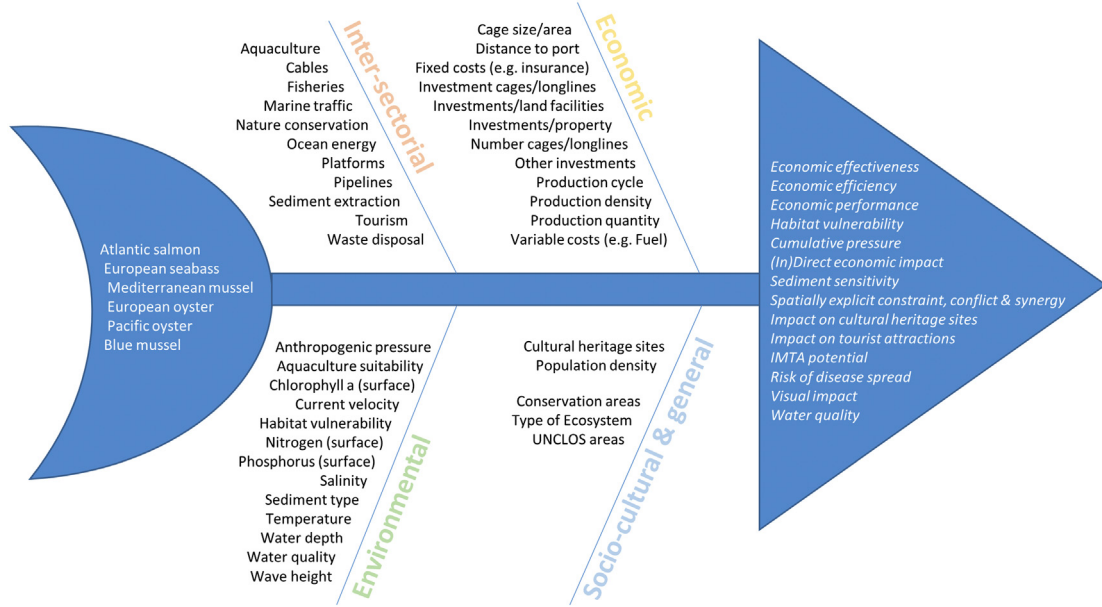


Fig. 2. A brief insight in the AquaSpace tool, (from left to right) giving an overview about i) all species considered, ii) data and information AquaSpace tool assessments are built on and iii) (additional) site-specific information received by applying the AquaSpace tool functions (Economic performance = Revenue, Added Value (AV); Economic effectiveness = Return on Fixed Tangible Assets, Opportunity costs; Economic efficiency = Net Present Value; Economic impact = (In)Direct impact on the AV and production; IMTA = Integrated Multi-Trophic Aquaculture, UNCLOS = United Nations Convention of the Law Of the Sea).

finfish aquaculture 800m (Hall-Spencer et al., 2006; Holmer et al., 2008; Marbà et al., 2006; Sanz-Lázaro et al., 2011).

Tool output is the AquaSpace tool Assessment Report, provided in pdf-format, which summarises general planning site information (e.g.

species assessed, water depth, water quality) and all inter-sectorial (e.g. spatial conflict potential, disease spread), environmental (e.g. degree of exposure, cumulative pressures, distance to waste disposal sites), economic (economic performance, effectiveness and efficiency)

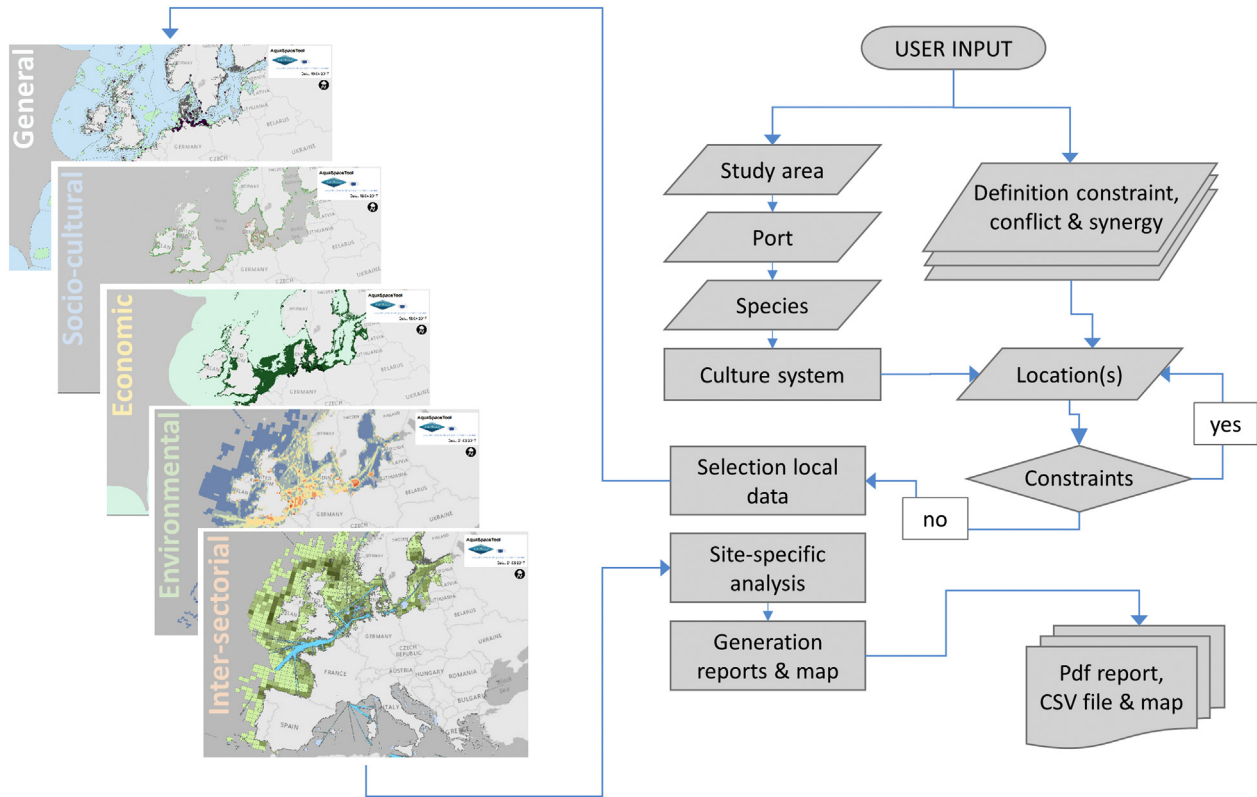


Fig. 3. AquaSpace tool conceptual overview. The users input defines the study area (e.g. country), the port from which aquaculture business should be transacted, the culture species and accordingly, the culture system, the compilation of constraining, conflicting or synergistic human uses and the aquaculture locations to be tested. Next to general input data (e.g. management area or culture system to be assessed), inter-sectorial, environmental, economic and socio-cultural data are processed.

and socio-cultural indicator values. As there is no limitation of the quantity of scenarios one can assess, the tool emits a csv file, facilitating the comparison of multiple indicator values. In order to investigate (spatial planning) trade-offs among those scenarios, templates are provided enabling a comparison of indicator performances with values normalised by using a z-transformation (Rowell, 2008). Further, outputs contain maps and graphics, enabling the user to proactively communicate opportunities and risks, since a transparent information policy builds stakeholders support, which is critical to the successful establishment of aquaculture and ongoing operations.

3. The North Sea case study

The German part of the North Sea (Appendix C) consists out of the German EEZ (ca. 28,500 km²) and the German coastal waters (ca. 11500 km²). In Germany, MSP was stimulated by the effect of newly developed maps displaying numerous proposals for large-scale offshore wind energy farms (UNESCO, 2014). The German maritime spatial plans for the EEZs of the North and Baltic Sea are regulatory plans and were implemented in 2009 (BSH, 2009b). The plans constitute sectorial priority areas where the particular uses have priority as well as areas where certain uses are prohibited. The main human activities regulated are shipping, oil and gas exploitation, cables and pipelines, renewable energy development, and aggregate extraction (BSH, 2009a; Buck et al., 2004). The allocation of fishing activities is currently not included (Fock, 2011; Stelzenmüller et al., 2011). Issues mentioned at regional AquaSpace stakeholder workshops include for instance untapped scientific resources (e.g. advance German offshore technologies, reduce chemical usage), complex licensing procedures, unfavourable image of aquaculture products, high spatial conflict potentials, high risk potentials (e.g. disease risk), and open questions related to interactions of culture species (Integrated Multi Trophic Aquaculture (IMTA), Aquaponic etc.) (Gimpel et al., 2016). As to date marine aquaculture is merely taking place nearshore, no sectorial priority areas exist in the EEZ. In contrast, within the coastal waters of the Wadden Sea National Park, which falls under the jurisdiction of the federal state of Schleswig-Holstein, existing license areas of 3300 ha have been designated for bottom cultures of blue mussel with a production of round about 5000 t/y. The national aquaculture strategy foresees an increase of the current blue mussel production from 5000 t to 40,000 t within the existing license areas (BVAQ, 2014). Further, potential co-locations of offshore windfarms and IMTA systems are discussed (Gimpel et al., 2015). To date offshore wind development applications cover in total approximately 13% of the EEZ. The enormous spatial expansion of this sector increases conflict potential with other sectors such as fisheries targeting flat fish, for instance plaice (*Pleuronectes platessa*) or sole (*Solea solea*). To mitigate this increasing conflict potential, the development of suggestions for potential synergies between different sectors such as a co-location of offshore wind farms and aquaculture is of current interest (Stelzenmüller et al., 2016).

4. AquaSpace tool application

In order to showcase the AquaSpace tool functionality (Fig. 3), the case study area was defined to be the German part of the North Sea. Accounting for their native occurrence in the German North Sea, their resistance to hydrodynamic conditions in offshore environments (Gimpel et al., 2015) as well as their economic potential for the EU market (Ebeling, 2016), European seabass (*Dicentrarchus labrax*) and blue mussel (*Mytilus edulis*) were selected for altogether 30 aquaculture expansion scenarios within the case study area.

4.1. Scenario set up

To mitigate increasing conflict potential (Gimpel et al., 2015; Stelzenmüller et al., 2016), scenarios 1-15 were concerned with co-

locating wind farms with seabass cultures with free standing cages offshore (Fig. 4 top). The port from which location the aquaculture site should be managed and supplied was defined to be Helgoland, as the port is located on an Island and therefore in the immediate vicinity to offshore areas. Using prior studies as a baseline (Ebeling, 2016), the most efficient stocking density for European seabass was defined to be 0.025 kg per m³ for a single free standing cage and a cage size of 8960 m³. Further a production cycle of two years was assumed, projected onto 36 cages resulted in an annual production of 4000 t. Here, the assumed production quantity should not exceed 4000 t/y, the maximum volume based on current market conditions for this species (Ebeling, 2016). As demonstrated in Appendix D.1, system-related specifications (e.g. related to investment costs, average fuel costs or market price), were incorporated within an economic input table in order to allow for a spatially explicit EIA (Appendix A).

Testing the national aquaculture strategy for blue mussel in the German North Sea (BVAQ, 2014), scenarios 16–30 were concerned with an increased production with longlines (Buck et al., 2010; Ebeling, 2016) nearshore (Fig. 4). For all scenarios Hörnum (Sylt) was identified as the port from which the aquaculture site should be managed and supplied as it constitutes the main place of transshipment of blue mussel. For each longline system with blue mussel a stocking density of 0.01 t per meter and a total culture line length of 1675 m was defined (Buck et al., 2010). Assuming a production cycle of two years, projected onto 4776 longlines, a total annual production of 40,000 t was defined. The total annual production reflects the development targets on increasing the production from 5000 t to 40,000 t/y and comply with the maximum volume based on the designated and licensed areas available (BMELV, 2014). Again, system-specific data were incorporated within an economic input table in order to allow for a spatially explicit EIA (Appendix A, Appendix D.2).

4.2. Case study-specific input

An interaction matrix (Table 1; further information given in Appendix A) has been completed in order to define spatial constraints (score 6), conflicts (scores 2–5) and opportunities (i.e. spatial synergy potential due to co-location; score 1) before testing both scenarios for aquaculture in a wider MSP context. While waste disposal sites constitute for instance a constraint for both, the finfish and shellfish scenarios, one has to differentiate between spatial interactions with MPAs. Such a co-location won't be realistic with finfish, but with filter feeders as blue mussel cultures are already part of the Wadden Sea National Park.

Table 1 presents the filled interaction matrices for both cases, which are transferred consequently in terms of a visualisation of spatial constraints, conflict and synergy potentials (Fig. 4) to the AquaSpace mxd (Appendix C).

In general, the risk of disease spread (based on a minimum distance between aquaculture sites; Appendix A) is greater for finfish than for shellfish species. As there are currently no finfish aquacultures in place yet, some dummy finfish cultures were interspersed throughout the German EEZ of the North Sea in order to demonstrate both tool functions, the risk of disease spread and the IMTA function.

Building on previous results, provided binary suitability maps were replaced with highly resolved and continuous suitability maps for seabass and blue mussel, further described in Gimpel et al. (2015). In the course of the economic specifications, an Annual Equivalent Rate (AER) of a potential investment of 0.09 was assumed (IMF, 2017) to complete the qualitative assessment of economic effectiveness and efficiency. The region-specific input parameters required for the direct quantitative economic assessment were calculated as followed: 0.26 for an induced direct impact on production, 0.45 for an induced indirect impact on production, 1.45 for the total impact, 0.16 for an induced direct impact on added value, and 0.27 for an induced indirect impact on added value. Specifications made on investment on equipment (per cage/trestle/longline), other investments (excl. Equipment, land

facilities and properties), investment on land facilities, investment on properties, market value culture species per ton, average no. of days at sea/culture site, average fuel costs Euro/km, annual expenditure on wages/salaries, intermediate costs variable (e.g. juveniles/seeds/food), other costs (variable), annual rate on capital resources (%), intermediate costs fixed (e.g. insurance/maintenance and repair ship), and other costs (fixed) were based on Ebeling (2016) for all scenarios and can be extracted from Appendix D.1 and Appendix D.2.

4.3. Scenario locations

In application of the AquaSpace tool interaction matrix and subsequently transferred GIS-mapping (Fig. 4), altogether 30 locations were identified for scenario evaluation. Scenarios 1–15 (European seabass) have been chosen as prescribed by the tool due to their low potential for management-related constraints, their high synergy potential, the local aquaculture suitability and the distance to the port chosen.

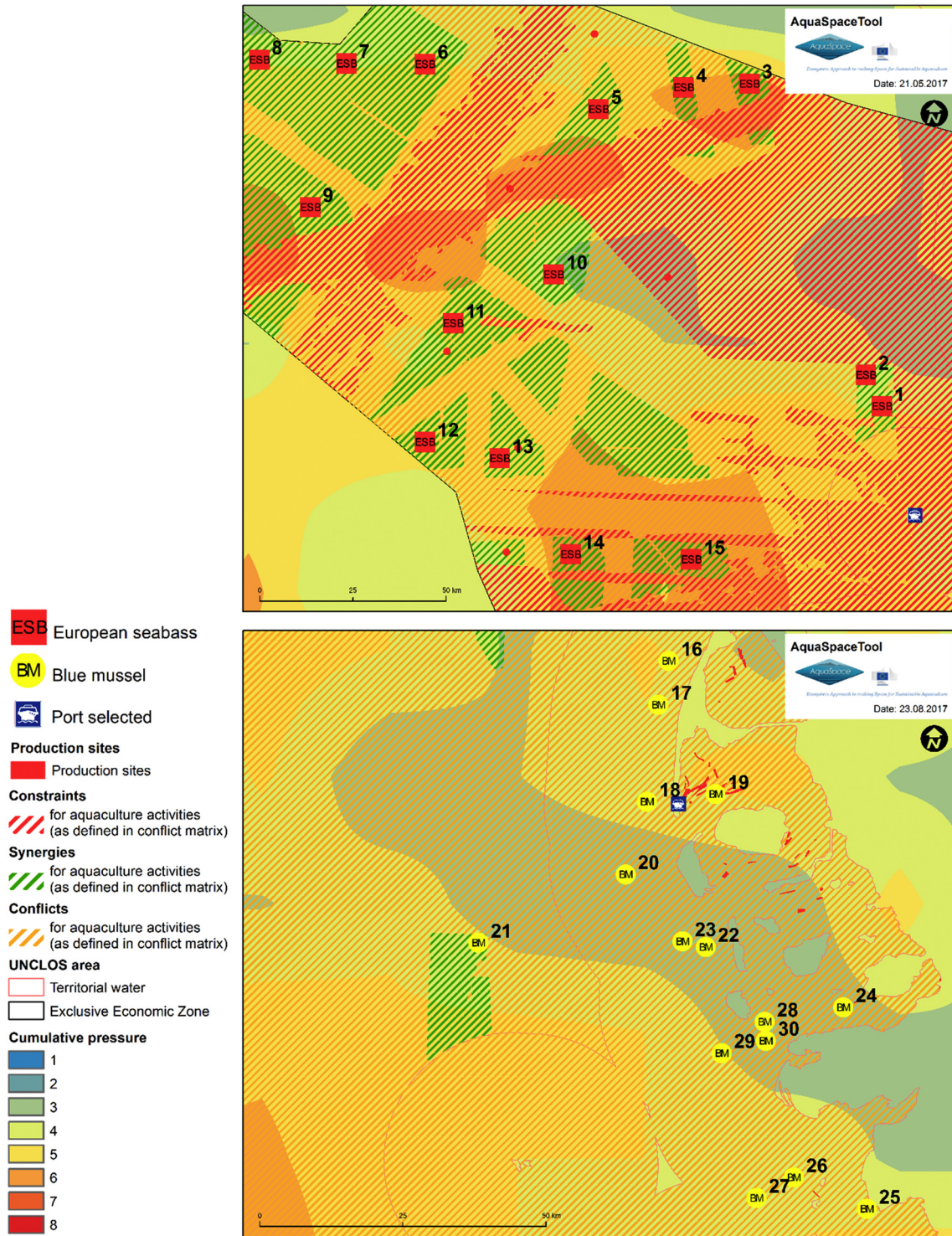


Fig. 4. AquaSpace tool output map (pdf format) for European seabass (top) and blue mussel. Shown are the locations of the scenarios 1–30, the case-specific port selected (seabass = Helgoland; blue mussel = Hörnum/Sylt), areas of constraint, synergy and conflict, management boundaries, areas of aquaculture production (please note, that finfish culture sites are just proxies to showcase tool functionality) and a cumulative pressure layer, an indicator selected manually as background for the AquaSpace tool map output.

Table 1
Interaction matrix based on user input to define constraints, conflicts and opportunities (i. e. synergies), further explained in Appendix A.

	European seabass aquaculture	Blue mussel aquaculture
Cables	5	5
Fisheries	2	2
Fisheries (q3)	5	5
Marine Protected Areas (MPAs)	6	2
Marine traffic	6	5
Ocean energy	1	1
Pipelines	5	5
Platforms	6	5
Sediment extraction	5	5
Tourism	3	2
Waste disposal	6	6

Potential blue mussel aquaculture sites (scenarios 16–30) were identified as prescribed by the tool with regard to the aquaculture suitability, the proximity to sites where blue mussel aquaculture already exists and due to their low potential for management-related constraints. The background layer of the report map chosen was the cumulative pressure layer.

4.4. Case study results

Appendices E.1 and E.2 present a shortened AquaSpace tool Assessment Report exemplifying the first blue mussel scenario (scenario 16; Appendix E.1) and a comparative summary of assessed sites (compared are scenarios 16, 19, 24, 25 and 26; Appendix E.2). The AquaSpace tool mapping output (Fig. 4) visualises the area of interest for European seabass (scenarios 1–15, top) and blue mussel (scenarios 16–30), the locations of the port selected (seabass = Helgoland; blue mussel = Hörnum/Sylt), areas of constraint, synergy and conflict (transferred from Table 1), management boundaries, areas of aquaculture production and a cumulative pressure layer, an indicator selected manually as background for the AquaSpace tool map output. Results have been further exploited in terms of i) distance to port-related comparisons of selected AquaSpace tool indicators (Fig. 5) and ii) an assessment of spatially explicit trade-offs between the inter-sectorial, environmental, economic and socio-cultural indicator values and the aquaculture planning scenarios (Fig. 6). The latter is enabled by using a z-transformation,

a standardisation based on the mean value and the standard deviation of all scenarios to be compared (Rowell, 2008).

The seabass aquaculture scenarios showed a general high sensitivity of the environmental indicators with increasing distance to the port of Helgoland (Fig. 5 left). For instance, while NH3 decreased from 2.08 to 0.18 mol/L with increasing distance (km), the PO4 values increased from 0.1 to 0.18 mol/L. In contrast, sediment sensitivity or water quality remained relatively stable with increasing distance from the port, whereas values of water depth (m) and wave height (m) were highly variable. Economic indicators followed the same patterns. The indicators RoFTA, profit and opportunity costs showed a linear decrease with increasing distance to the port (RoFTA from 0.13 to 0.128, the opportunity costs from 0.054 to 0.052). Considering the effect on the profit, the results varied around 95432.97 € (Fig. 5). Socio-cultural effects could only be recorded for the indicator tourism that decreased the farther away the site selected was from the coastline. Inter-sectorial effects were only detected for the conflict potential indicator, here values increased with an increasing distance to the port. According to results of aquaculture scenarios with blue mussel (Fig. 5, right), the distance to the selected port (Hörnum, Sylt) did not seem to be the most important factor. Environmental effects were observed to fluctuate between tested scenarios instead to increase or decrease constantly. NO3 decreased from 2.56 to 4.65 mol/L, while PO4 decreased from 0.1 to 0.09 mol/L. The sediment sensitivity and water quality remained also stable across all scenarios. The indicator wave height exposure decreased with the distance to the port selected and the increasing water depth. Accordingly, the economic indicator values decreased with distance to the port. Considering the effect on the profit, the results varied around 23359.32€ (Fig. 5). However, socio-cultural effects could not have been identified although all planning sites were distributed near to the coastline and the islands, close to several bathing sites. In contrast, while conflict potential increased with distance to the port selected, synergy potential was only given once.

In Fig. 6a the trade-offs between all indicators calculated for each seabass aquaculture planning site (scenarios 1–15) are shown. Assessing inter-sectorial effects, the IMTA potential remained low (0) at all sites. In contrast, the risk of disease spread (please note, that finfish culture sites are just proxies to showcase tool functionality) reached its peak value for scenario 13, followed by a comparable high value for scenario 11. Comparing all scenarios, 2 and 3, and 12–15 showed decreased conflict potential. Surprisingly, the spatial synergy potential showed a negative value at site 1, which highlights the fact, that at this site no co-location is possible. It has to be noted, that the

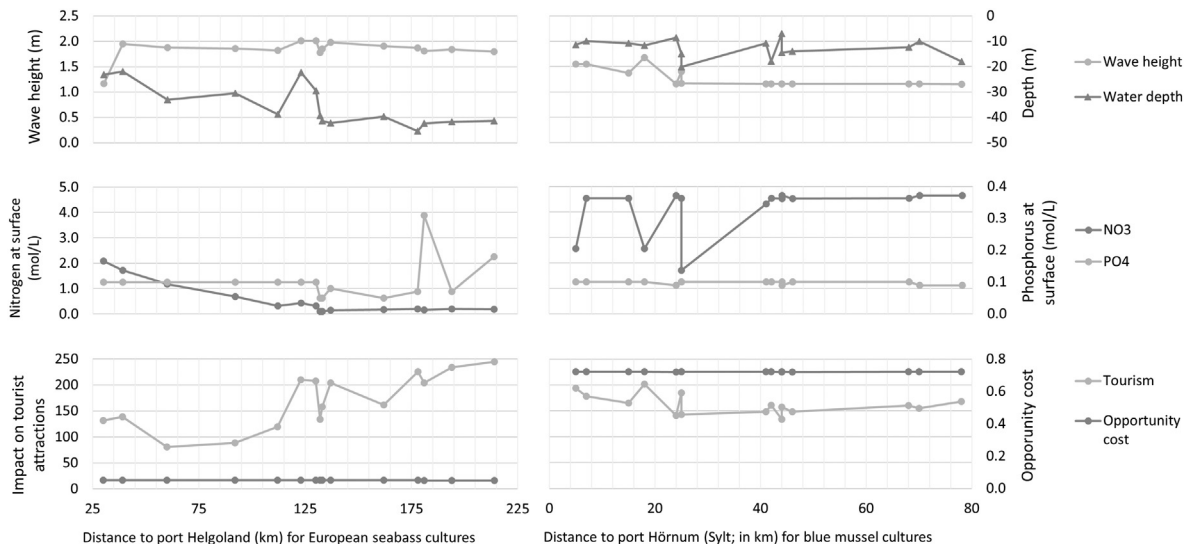


Fig. 5. Comparison of selected AquaSpace tool indicators against distance from port (given in km). Data are plotted for European seabass (left) and blue mussel (right).

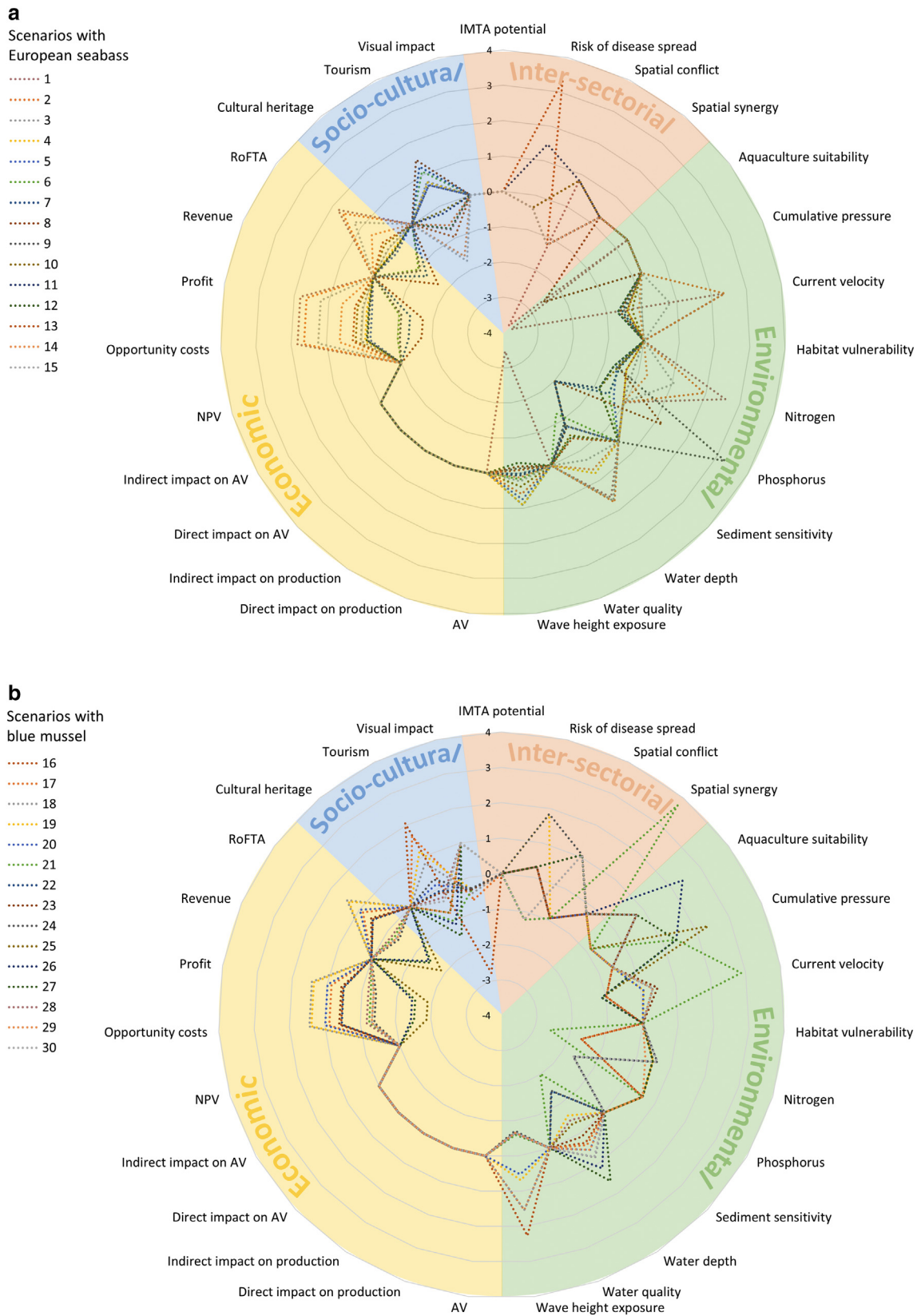


Fig. 6. : Spatially explicit performance of inter-sectorial, environmental, economic and socio-cultural indicators (categories highlighted in red, green, yellow and blue; prescribed order) for 15 different aquaculture planning scenarios with European seabass (a) and blue mussel (b). Shown are potential trade-offs in between the AquaSpace tool indicators by comparing data normalised in application of a z-transformation. Indicators required merely to assess the growth performance of a species (i.e. chlorophyll a concentration at surface, temperature and salinity) are not included (AV = Added Value, IMTA = Integrated Multi-Trophic Aquaculture, NPV = Net Present Value, RoFTA = Return on Fixed Tangible Assets).

AquaSpace tool allows velocity assessments at large scales, but with a high-quality resolution. Nevertheless, the negative synergy potential value at site 1 for seabass highlights the importance of an appropriate user-specific handling of the GIS AddIn and a site selection which needs to be highly precise (i.e. use of the zoom function). Looking at the environmental effects, the habitat vulnerability and water quality indicator values remained stable across all scenarios tested. While phosphorus showed peak values for scenario 9, nitrogen reached lowest values for scenarios 11 and 12. Compared with the rest of the scenarios tested, wave height exposure and the cumulative pressure was lowest for scenario 1, the current velocity values highest for scenarios 1 and 2. Both, the aquaculture suitability and the sediment sensitivity remained mostly stable, but decreased for scenarios 7 and 8. Sediment vulnerability showed again a comparable low value for scenario 11. The water depth reaches its maximum in scenario 6 and its minimum in scenario 3. The economic indicators Added Value (AV), induced (in) direct impact on production and AV, Net Present Value (NPV) and revenue remained stable over all 15 scenarios. In contrast, the opportunity costs, the profit and the Return on Fixed Tangible Assets (RoFTA) showed peak values for scenario 1 and the lowest for scenario 8. Finally, comparing the planning sites from a socio-cultural perspective, site specific contrasts were obvious for the distance related indicator tourism, which showed its lowest value for scenario 15 and its highest value for scenario 8.

Comparing the potential trade-offs across scenarios calculated for blue mussel (scenario 16–30; Fig. 6b) showed that inter-sectorial effects were related to the conflict potential showing peak values for scenarios 24–30 and low values for scenarios 16–23. While the risk of disease spread should not be considered for shellfish, the IMTA potential and the synergy potential remained low (0). Nevertheless, the latter showed one increased value for scenario 21. Looking at the environmental effects, the sediment sensitivity, the habitat vulnerability, and water quality remained stable across all scenarios tested. Nitrogen values were lowest for scenario 16, while phosphorus showed peak values for scenarios 24, 26, 28 and 30. Scenario 26 was found to have the highest suitability for the blue mussel longline culture system and showed a high value of cumulative pressure, which even increased for scenario 25. In contrast to site 16–20, the wave height specific exposure remained low for scenarios 21–30. The current velocity indicator revealed highest values in scenario 21. The economic indicators AV, induced (in) direct impact on production and AV, NPV and revenue showed similar values across all 15 scenarios. The opportunity costs, the profit and the RoFTA showed peak values for scenario 18 and lowest values for scenario 25. The socio-cultural evaluation showed that scenario 16 would be favourable, based on the distance related indicator tourism and the visual impact, which was found to be lowest (Fig. 6b).

5. Discussion

The case study results demonstrate the outputs the user is able to produce in application of the AquaSpace tool, although achieved results do not fully satisfy real-world requirements for decision making due to limited data availability. The tool outputs (i.e. AquaSpace tool Assessment Report) comprise detailed reports and graphical outputs (synthesised through the Fig. 6a and 6b) and can facilitate trade-off discussions hence allowing key stakeholders (e.g. industry, marine planners, and licensing authorities) to take more informed (e.g. based on graphical representations), evidence-based decisions on proposed aquaculture developments and the associated opportunities and risks.

At a European scale stakeholders raised an insufficient marine spatial management as one obstacle for expanding aquaculture activities (Gimpel et al., 2016). Policies or national strategies such as the German National Strategic plan for Aquaculture (BVAQ, 2014) should allow for an a priori consideration of aquaculture in spatial planning processes. The German EEZ case study scenarios exhibit on both, i) areas of potential compatibility between uses at a large scale (German EEZ) and ii)

allocated zones at a small scale (German coastal zone) where production is intensified. This corresponds to the issues mentioned at the German stakeholder workshop, where untapped scientific resources (related to offshore aquaculture) and high spatial conflict potentials were criticised.

Interpreting the site-specific results for seabass, scenario 12 exhibits for instance a low risk of disease spread, a relatively low conflict potential, a low impact on touristic attractions, low Nitrogen values and a stable aquaculture suitability. Such a scenario would comply with the expectations of the German stakeholders (due to a low conflict potential and a low risk of disease spread) and could further contribute to a better image of aquaculture. Nevertheless, scenario 14 presents in comparison an even lower Nitrogen level and water depth. Instead, it offers more profit and a higher RoFTA. Interpreting the results for blue mussel, the highest aquaculture suitability is given at scenario 27. In contrast, spatial synergy with low water depth, wave height specific exposure and visual impact is given at scenario 21. Nevertheless, the highest profit is for instance achieved in scenario 18. Distance to port-related comparisons of selected AquaSpace tool indicator values illustrate the variability of location-specific data (exemplified in Fig. 5). In contrast to environmental and socio-cultural input data, the variability of the economic index 'opportunity costs' is barely visible. Nevertheless, a clear distinction can be made when comparing species-specific results, as the opportunity costs for aquaculture with European seabass exceed the ones for blue mussel considerably.

The application of the AquaSpace tool informs a systematic process for calculating and comparing risk and opportunities of alternative scenarios of a proposed aquaculture site in a multi-use environment. In the first case, the outcomes are a transparent and spatially explicit risk assessment of co-location scenarios which could be provided to the German planning authority to inform the upcoming revision process of the MSP. In the second case, the outcome is a comprehensive evaluation of the production increase scenario including all relevant management aspects which could be provided to all relevant players: the administrative, the social and the business operator ones. Both of the scenario sets demonstrated the importance of adequate assessments of aquaculture operations, which need to be facilitated to decision makers, community stakeholders and other stakeholders such as NGOs (and other non-profit organizations) that want to ensure that aquaculture operations benefit local communities such that it promotes sustainable development, equity, and resilience of interlinked socio-ecological systems. This gains on importance in the light of the challenges and risks aquaculture companies face in establishing and operating an aquaculture site. Gaining and maintaining stakeholder support by demonstrating economic benefits on a proactive and periodic basis can help to limit overall project risks (Plumstead, 2012).

Currently, stakeholders can choose in between using the pdf-report output (Appendix E.1), the scenario comparison (exemplified in Appendix E.2) or the trade-off assessment (Fig. 6a,b) for decision support. In this way, complex licensing processes might be eased, which would match with expectations of stakeholders mentioned at the German stakeholder workshop. The authors refrained from synthesising the results further than done during the spatially explicit trade-offs on the base of standardised data, due to a risk of over- or underestimating indicator values. In the future, additional templates could allow for further, user-specific aggregations of indicators. An individual weighting scheme could speed up an end-user driven visualisation of risks and opportunities of aquaculture planning scenarios.

The AquaSpace tool currently presents a static GDB. Although a link to Web Feature Service (WFS) datasets was envisaged to address up-front limited data availability, the response still needed a high amount of time loading the data, which slowed down tool performance. Further, open data available are currently not comprehensive at EU extent (e.g. EUNIS habitats as a baseline for habitat vulnerability mapping) while lacking of updates. The area designated for the expansion of wind farms in Germany decreased for instance from approximately

6200 km² (effective 2013) to approximately 1800 km² (effective November 2016), but an update of the shapefiles provided online is missing.

In application of the AquaSpace tool a range of environmental indicators such as the cumulative pressure indicator or the habitat vulnerability indicator is offered. Nevertheless, temporal aspects were only considered indirectly (i.e. vulnerability assessments by Alkiza et al. (2016)). While the temporal resolution needs to be included directly (e.g. by weighing human pressure loads according to their frequency), the spatial resolution and the extent of those data describing the level of sustainability need to be increased (i.e. vulnerability mapping). Another kind of impact assessment likewise hard to resolve spatially is the economic impact assessment. The most economic indicators are driven by 'distance to port' calculations and should be improved in future. In summary, a definition of standards for the edit and use of open access data related to aquaculture planning and management in EU waters is highly recommended.

Considering the current and future obstacles for the expansion of aquaculture, examined in the EU project AquaSpace, the risks of pollution and eutrophication through finfish aquaculture were issued as being highly important. Being aware of the current regime for the southern North Sea, respective functions would have only been implemented as rule of thumb models (equivalent to the risk of disease spread), allowing for uncertainty in the system and therefore in the tool output. With the AquaSpace tool a first screening tool was developed, setting the focus on an overall assessment of management effects of planning with aquaculture and therefore on the post phase of suitability assessment based solely on ecological indicators. Nevertheless, in order to improve collaboration in aquaculture science and research, the coupling with other models such as growth models is encouraged. In the future, the AquaSpace tool would therefore directly profit from standards regarding the data format required to enable free data access, the type of data required for the designation of suitable sites (e.g. quantified eutrophication effects of fish farms from spatially explicit predictive models), the type of data required for the monitoring of aquaculture activities (e.g. pelagic and benthic nutrient and oxygen concentration, benthic keystone species etc.) and the visualisation of spatially explicit data (geographic representation, object categories, symbols etc.). Nevertheless, several tools already do address environmental carrying capacity analysis such as BLUEFARM-2 or the SMILE model.

The broader applicability of the AquaSpace tool is currently tested in six European case studies. While applications located in Northern Europe are mostly related to finfish in offshore areas, applications in the South are rather related to oyster and mussel cultures nearshore. In the course of the Integrated Maritime Policy (IMP) and the Europe 2020 strategy tall orders are placed with the European countries. The member states are faced with multiple objectives such as Good Environmental Status (GES) or Blue Growth (EC, 2012; EC, 2014b). Concrete, place-based tools such as the AquaSpace tool allow a transparent evaluation of spatial management options and their consequences under the EAA. This enables authorities to account for a range of principles of good MSP practice as mentioned by the EU commission in its roadmap to MSP in practice: (1) Using MSP according to area and type of activity, (2) Defining objectives to guide MSP, (3) Developing MSP in a transparent manner, (8) Incorporating monitoring and evaluation in the planning process, and (10) A strong data and knowledge base (EC, 2008). Following the EAA as proposed by the FAO and World Bank (2015) might facilitate spatial planning with aquaculture. This process should be aided by spatial planning tools and spatially explicit assessments of planning trade-offs as demonstrated in this study. Nevertheless, aquaculture planning tools such as the AquaSpace tool need to be used responsibly to address the key issues constraining or strengthening the growth of aquaculture in an effective way (Corner and J., 2017). This gains even on importance switching from single sector perspectives to more comprehensive ones. Integrating aquaculture in MSP processes constitutes a

challenge for European countries. Issues not related to investment security or environmental impact are unfavourable production conditions or a negative image of both aquaculture production and aquaculture products. Further the price competitiveness with imports still shows the risk of failing to compete on the market (Gimpel et al., 2016). The majority of European aquaculture enterprises are micro-enterprises with less than 10 employees, located in Greece, Spain, France, Italy and the United Kingdom (Remotti and Damvakerak, 2015). Nevertheless, aquaculture is one of the five sectors of the EU blue economy which should be promoted in future in order to ensure sustainability, food security and employment (EC, 2017).

6. Conclusion

The AquaSpace tool is one of the first open-source GIS-based planning tools that allows for a spatially explicit and integrated assessment of indicators reflecting the economic, environmental, inter-sectorial and socio-cultural risks and opportunities for potential aquaculture systems. The tool builds on open datasets at a European scale, improving reproducibility and collaboration in aquaculture science and research. It supports the planning and management of sustainable aquaculture development and helps to reduce uncertainty around new investments. Its technical concept and implemented functionality was led by a bottom-up approach reflecting stakeholder needs. The tool outputs comprise detailed reports and graphical outputs. Given that tool settings and datasets can be freely changed, the tool has proven to be flexible. With this paper we presented the context, decisions on functionality and some initial results of a first application of the tool showcased based on the example of the German Bight of the North Sea.

The computation of aquaculture planning scenarios and the assessment of their trade-offs in the Southern North Sea showed that it is feasible to identify aquaculture sites, that correspond to multifarious potential challenges, for instance by a low conflict potential, a low risk of disease spread, a comparable high economic profit and a low impact on touristic attractions. Further, the tool application is demonstrated at multiple spatial scales, taking account of different aquaculture systems and development constraints. The broader applicability of the AquaSpace tool is currently tested in six European case studies.

The co-assessment and mapping of a series of indicators describing ecological, economic and social features of species-specific aquaculture planning units enables a transparent assessment of trade-offs. This allows key stakeholders (e.g. industry, marine planners, and licensing authorities) to take more informed, evidence-based decisions on proposed aquaculture developments and their associated consequences. Specifically shedding light on the socio-economic dimension may increase the acceptance of new developments by local communities and society-at-large.

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The tool was customised, applied and further developed in collaboration with several AquaSpace partners and case studies operating at different spatial scales. The expertise of the AquaSpace consortium contributed to implemented tool functionality in relation to stakeholder requirements, case study issues, and current state of the art of the assessment of risks and opportunities of planned aquaculture activities. Further, such collaboration encouraged the amendments of the tool

functionalities, the test phase by case studies, the development of the tool manual and the promotion of the tool.

Information contained here has been derived from several data sources which are listed in the in Appendix B. While tool indicators, thresholds and functions are standardised, the utility and applicability of the geodata rely heavily on the quality of the data available and the users' interpretation of the results. Information contained here has been derived from several data sources which are listed in the in Appendix B. While tool indicators, thresholds and functions are standardised, the utility and applicability of the geodata rely heavily on the quality of the data available and the users' interpretation of the results.

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