Tools for Assessment and Planning of Aquaculture Sustainability

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COORDINATOR:	**Prof. Trevor Telfer**
ORGANISATION:	**University of STIRLING, UK**
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Integrated spatial framework for a representative number of case study areas

Contributing Authors:

Lynne Falconer, Trevor Telfer; University of Stirling

Stephanie Palmer, Laurent Barillé, Pierre Gernez; Université de Nantes

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SUMMARY

This report presents an overview of the site selection frameworks developed as part of the Tools for Assessment and Planning of Aquaculture Sustainability (TAPAS) project, an EU H2020 research project. TAPAS aims to promote the sustainability of European aquaculture and alleviate bottlenecks by providing tools for key stakeholders at local, national, and EU levels. The report outlines the general framework that has been established as a foundation for European aquaculture development, and also highlights how it can be used for different types of aquaculture. Freshwater cage aquaculture and offshore shellfish production are used as examples to illustrate the site selection process. The spatial framework provides structure and an additional level of decision support and enable more targeted site identification. In doing so, it can support wider planning and management initiatives such as Integrated Catchment Management, Marine Spatial Planning and the Ecosystem Approach to Aquaculture.

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1. Introduction

Site selection is one of the most important decisions in aquaculture, as the location influences many aspects of production (**Falconer et al., 2018; 2019b**). However, although many studies have focused on aquaculture site selection, there are no common modelling frameworks for site selection and regulation, which leads to fragmented approaches to planning. The lack of common modelling frameworks is likely due to the nature of site selection and the requirement to fulfil specific biological and environmental conditions, which vary depending on the species and farming system, and the different regulations and policies that aquaculture producers must adhere to within specific areas. However, there are fundamental considerations that are common to all types of aquaculture and can provide guidance to stakeholders when selecting a suitable site for aquaculture.

Site selection is the identification of the most appropriate location to establish an aquaculture system. Once the site has been selected, the aquaculture producer will then perform more detailed assessments as part of the licensing process. Based on the information provided in the application, the relevant decision makers will determine if a license should be granted or not. Therefore, it is important to remember that site selection is the start of the licensing process and does not guarantee that aquaculture will be permitted in that specific area.

This report outlines a spatial framework which is then adapted for different types of aquaculture system used in Europe.

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2. Site selection considerations

Many factors should be considered when identifying and selecting a site for aquaculture. Generally, they can be summarised in three broad categories: 1) regulation and policy, 2) availability of an area, and 3) suitability of an area. First and foremost, regulation and policy will play a key role in outlining the type of aquaculture that can take place within a jurisdiction, as this will ultimately define what can take place. Regulations may be set and overseen at a national level, but could also be at a more local level depending on the legal system within the country. Assuming regulation permits a specific type of aquaculture, it is then necessary to assess availability and suitability. Not all available locations are suitable for aquaculture, while the opposite is also true; not all suitable locations are available for aquaculture. Depending on data, availability and suitability of a location may be assessed sequentially or in parallel. However, it is important to note that data collection and analysis may be time consuming and require a considerable amount of resources depending on the level of detail required.

2.1. Regulation and policy

Regardless of the environmental suitability of the location, policies and regulations will usually dictate the type of aquaculture system that can be established and the species that can be used (Ross et al., 2013; Sanchez-Jerez et al., 2016). There may be restrictions or moratoriums in place that prevent aquaculture from being established, or regulations may prohibit or specify types of aquaculture, which can influence species and technologies that will be used. Consequently, the first step in assessing site suitability and the potential for aquaculture development should be to consult national and regional regulations to ensure such systems can be established. There are different considerations depending on the type of aquaculture.

With regard to spatial management, legislation and policies regarding the use of space are at the heart of the aquaculture site selection process. Aquaculture is not the only activity that takes place in the coastal and marine environment and there is often competition for space, access, and resources. Marine spatial planning (MSP) is widely acknowledged as a useful approach for planning and managing multiple users and activities (Douvere et al., 2008). The EU adopted the Maritime Spatial Planning Directive in 2014 and each member state must develop their plans by 2021. As part of this process, they must identify management objectives for the area and identify the existing activities and components of the environment to enable more coordinated and sustainable use of the ocean. Cross-border cooperation is a key component of the directive, and the long-term expectation is that MSP in Europe will be region-specific rather than country-specific (Friess and Grémaud-Colombier, 2019). In many countries, aquaculture will have a key role in marine spatial plans as it is considered an important area for Blue Growth. However, in some countries, or some locations, other activates may be prioritised.

For freshwater cages and pond systems, the surrounding area and other activities can affect the suitability of an area for aquaculture. Activities upstream can affect downstream locations, while inputs to the aquatic system from adjacent land use may have negative effects on aquaculture production or the health and welfare of the farmed animals. The management of water resources within a catchment to maximise benefits and minimise impacts is sometimes referred to as integrated catchment management (ICM), integrated water resource management (IWRM), natural resource

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management (NRM), or river basin management (RBM) (Fenemor et al., 2011). The surrounding environment and land use are therefore important considerations for aquaculture site selection in freshwater environments.

For ponds and land-based systems, such as flow-through tanks and recirculating aquaculture systems (RAS), it is important to assess regulations covering the use of water with regard to abstractions and discharges to identify the type and scale of system that could be established, as there may be restrictions on the amount of water that can be used and there may also be fees and financial obligations which must be considered in the capital or operation costs.

For multi-user areas or locations where the environment may be particularly sensitive, there may be a need for more co-ordinated planning. The use of Allocated Zones for Aquaculture (AZAs), where the development of aquaculture is prioritised over other activities can be a useful approach for managing aquaculture in areas where there is competition for space and resources (Sanchez-Jerez et al., 2016). Zones should be based on the suitability of the area for aquaculture, with consideration of the biological requirements of the potential farmed species and characteristics of the environment. It is also important to identify constraints to production and areas where aquaculture development is not allowed. Potential constraints include areas prioritised for other activities or protected areas. However, it is important that the relevant authorities provide clear guidelines about what can and cannot take place within a zone or a defined area. For example, Marine Protected Areas (MPA) are often considered to be exclusionary zones for aquaculture, but this is not always the case, as there are different categories and management objectives of MPAs such that aquaculture can take place in some, and may even have positive effects that are compatible with the MPA goals (Le Gouvello et al., 2017). Although zones are often discussed when referring to marine aquaculture, they are also relevant to other types of aquaculture, and can play an important role in managing shared resources.

Some countries have implemented management areas, where companies work collaboratively on some farm strategies and health issues. An example of this is salmon farming in Scotland, where Farm Management Areas (FMAs) and Disease Management Areas (DMAs) are used for spatial management and disease mitigation (Murray and Gubbins, 2016). DMAs are used for the control of serious notifiable diseases, such as Infectious Salmon Anaemia, and are based on separation distances and simple hydrodynamic processes around active fish farms (Murray and Gubbins, 2016). The DMAs are updated and revised regularly to consider active and inactive farms, and new farms cannot be established in areas which bridge DMAs (Scottish Government, 2019). Consequently, this has implications for site selection. In FMAs, farms collaborate on management issues and coordinated action, such as fish health strategies, movement, fallowing, and harvesting (Murray and Gubbins, 2016). Similar management strategies take place in other countries. They are usually voluntary, and their operation will depend on the organisations involved. For site selection, it is important to be aware of existing management agreements within areas of interest, which may affect the establishment of a farm, but also the operation of a farm once developed. Discussion with the regulatory authorities, and perhaps even local stakeholders may be useful at this stage.

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2.2. Availability and suitability of a location

It is important to assess the availability of locations for aquaculture. There may be permanent or temporary restrictions that make an area unavailable for use, and will therefore affect the potential use for aquaculture, regardless of the suitability of that location. Such limitations that prevent aquaculture from being established are often referred to as constraints. For all types of culture, other activities and potential conflict between resource users can affect the availability of a location for aquaculture. If an area is already occupied, then it is unlikely it is available for development. For land-based culture, ownership of the land or water-rights can also restrict potential areas for development.

Policies or legislation may be in place which prevent development due to environmental or other concerns. For example, in Scotland there is a moratorium on salmon aquaculture on the north and east coasts to protect wild salmon stocks (Slater, 2016). Given the cultural and economic importance of salmon fisheries in Scotland, it is unlikely that this moratorium will be lifted in the near future, thus attention and resources should be focused assessing the suitability of other locations where aquaculture is not banned.

Some areas may not be suitable for a specific technology or system. The physical conditions of the environment may render a location unavailable, for example, a coastal location may be too shallow for a cage system to be established, or there may be an inadequate water supply for a pond system.

2.3. Site selection

Following analysis of the regulatory feasibility, availability, and suitability of the area, potential sites can be selected. This may be one site or a number of sites that show potential and should therefore be assessed in more detail. These sites should be the most appropriate location that is available and also suitable for development. To obtain a licence to farm at these sites, more detailed and site-specific analysis will be required as part of the planning and licensing process.

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3. Framework for site selection and regulation

There are many different steps within the site selection process. As discussed previously, it is difficult to establish a detailed common framework as there are specific needs and requirements depending on the species, system, and area that are under assessment. However, there are common elements that each site selection assessment should consider, and we have developed a broad framework, which is outlined in Figure 1. This is relevant for coastal, marine, freshwater, and land-based production, and can be used for fish, shellfish, and seaweed.

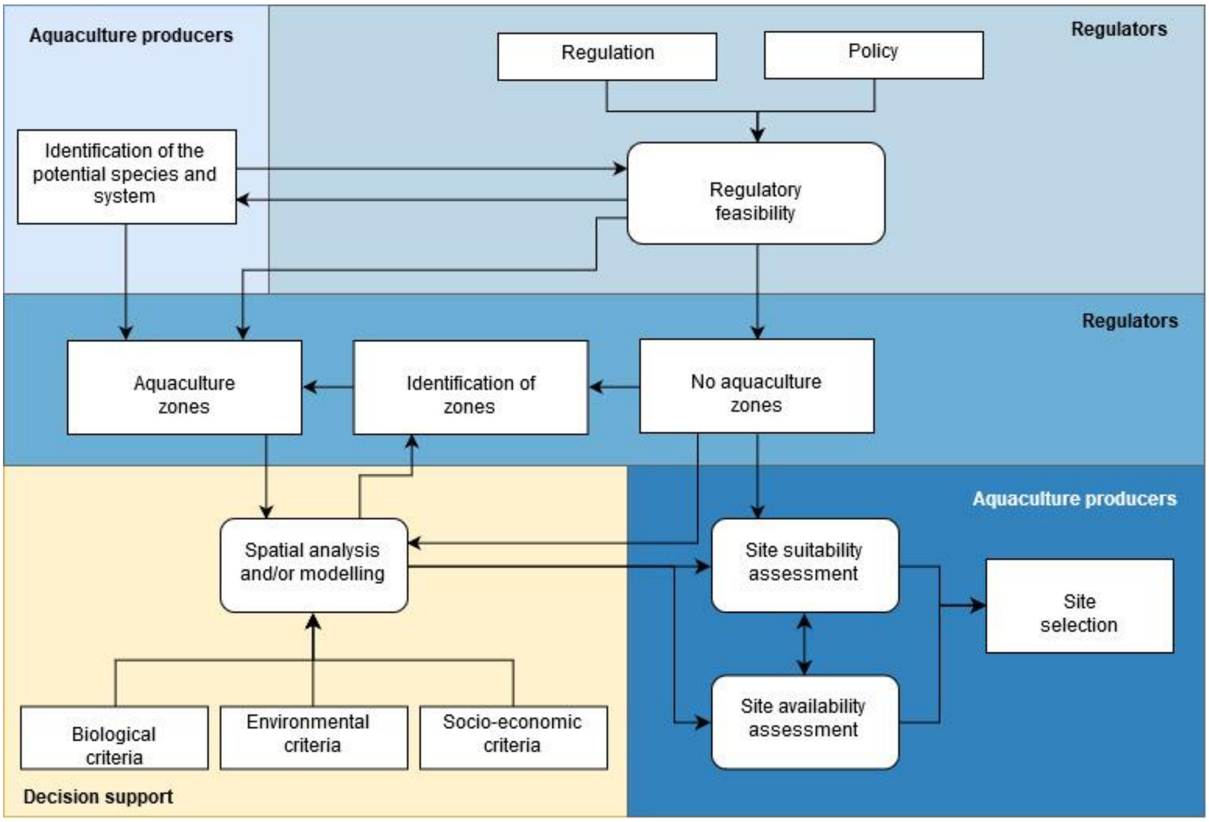

Figure 1: Overview of the broad spatial framework for site selection and regulation.

The first step in the site selection process involves the prospective aquaculture producer deciding which species to farm and the system to use. In many cases, this will be a simple decision based on existing aquaculture practices within the country and experience of the producer. For commonly farmed species within a country there is usually an established planning and regulatory framework. However, for a new species or system, there may be a need for regulatory authorities to evaluate the existing regulatory regime, to ascertain whether a new species or system should be allowed, and, if so, whether the licensing and regulatory approach should be revised and updated. In Norway, research and development licences have been introduced to encourage innovation in the sector and are a good example of how a more flexible approach to licensing can be used to support development

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as technology improves and more information is available on farming practices, health and welfare, and environmental impacts.

Once the species and system has been established, the producer can then begin the spatial assessment. Zones are established by planning and regulatory authorities, and, if they exist, aquaculture producers should focus their assessment in such areas. However, if there are no zones, the site selection process is less restrictive, but may first require broad-scale analysis to identify an area or region of interest using coarser-scale data with a spatial resolution of several kilometres before identifying a potential area for more detailed site availability and suitability assessment.

Spatial analysis and modelling has a key role in decision support, facilitating the site selection process by proving information that would otherwise be difficult to obtain. Biological, environmental, and socio-economic data can be evaluated and assessed to identify the locations that are most appropriate for aquaculture development. Trade-offs between different factors can be considered, and a range of different scenarios can be explored. This then allows the identification of areas that are available for aquaculture development and areas that are suitable for aquaculture development. The results should be combined to indicate those areas that are both available and suitable for development, and the most appropriate site can then be selected.

3.1. Spatial analysis and modelling for decision support

3.1.1. Geographic Information Systems (GIS)

In TAPAS Deliverable 5.1 (Falconer et al., 2016), the critical review and evaluation of 'near-field' models for aquaculture site selection and regulation, Geographic Information Systems (GIS) had been shown to play an important role in site selection. Therefore, for this present deliverable, we conducted a thorough review of the primary scientific literature to assess how GIS is used for aquaculture decision support, with the details provided in Falconer et al. (2019b). Our analysis confirmed the importance of GIS, and showed that site selection was the most popular application among the published studies evaluated, with 35% of the 211 articles focusing on site suitability and site selection. Furthermore, the results revealed that site selection studies have been published on a wide range of aquaculture systems throughout the world, as shown in Figure 2.

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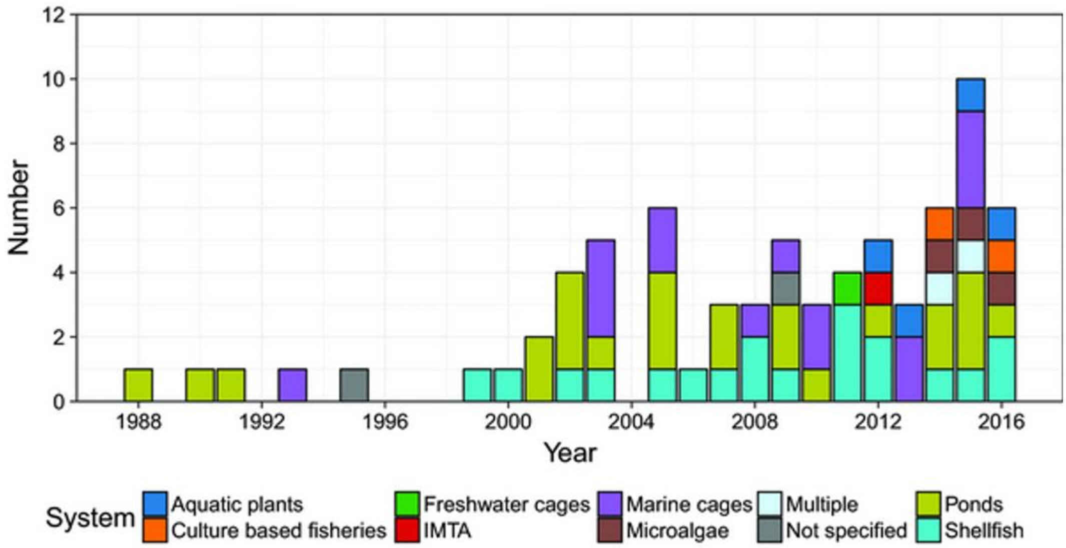

Figure 2: Number of studies in primary scientific literature focusing on site suitability and site selection between 1988 and 2016, from **Falconer et al., (2019b)**.

Most of the GIS-based site selection models have been developed for specific locations and systems (e.g. Dapueto et al., 2015; Pérez et al., 2005; Thomas et al., 2019), although the approaches can be adapted and applied elsewhere if the necessary data are available and the model is relevant. Most studies have common elements, with a number of spatial layers that are reclassified to a common scoring system depending on suitability criteria and are then combined. Combination can be through a weighted multi-criteria evaluation, which is useful since some layers may be more important than others. Falconer et al (2018) describe some of the different approaches available for reclassifying and combining data in more detail. In addition to identifying the suitable sites for producers, GIS can be very useful for participatory planning, and can provide a more transparent approach to why a site was selected and what alternative options are available (Tress and Tress, 2003). This can help communication with local communities and other sectors in the area in terms of why a site is considered to be the most appropriate. As social acceptability can often be a key constraint in aquaculture development, the use of GIS to illustrate where the selected site is and why it is considered a suitable location for aquaculture could be a way of engaging with stakeholders as part of the consultation process, or even prior to a licence application to assess community acceptance. See Section 3.3 for more information on stakeholder engagement.

The literature analysis, together with discussions with experts and stakeholders, was used to develop a spatial framework for developing GIS-based models to support site selection. The logical sequential process is represented in Figure 3, and the spatial modelling framework is provided in Figure 4. These can be used to guide aquaculture producers and/or their representatives in modelling the availability and suitability of an area and then selecting a site.

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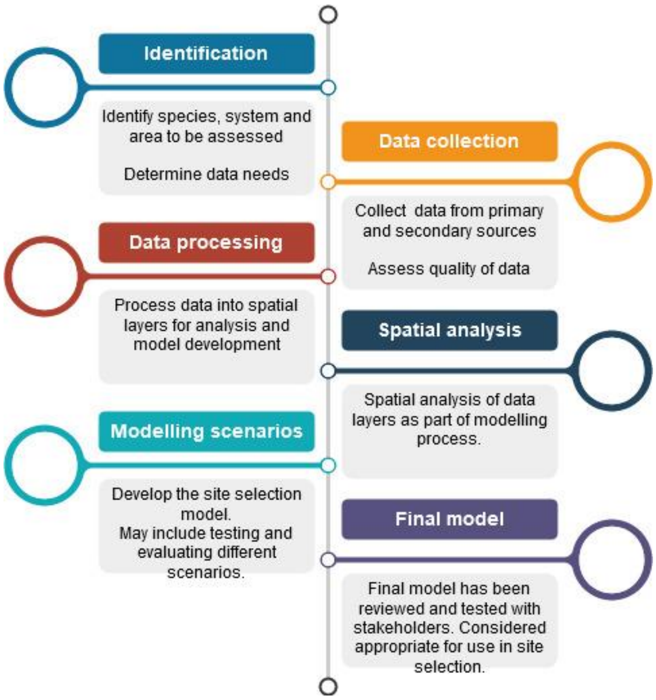

Figure 3: The logical procedural sequence that is followed when developing site selection models.

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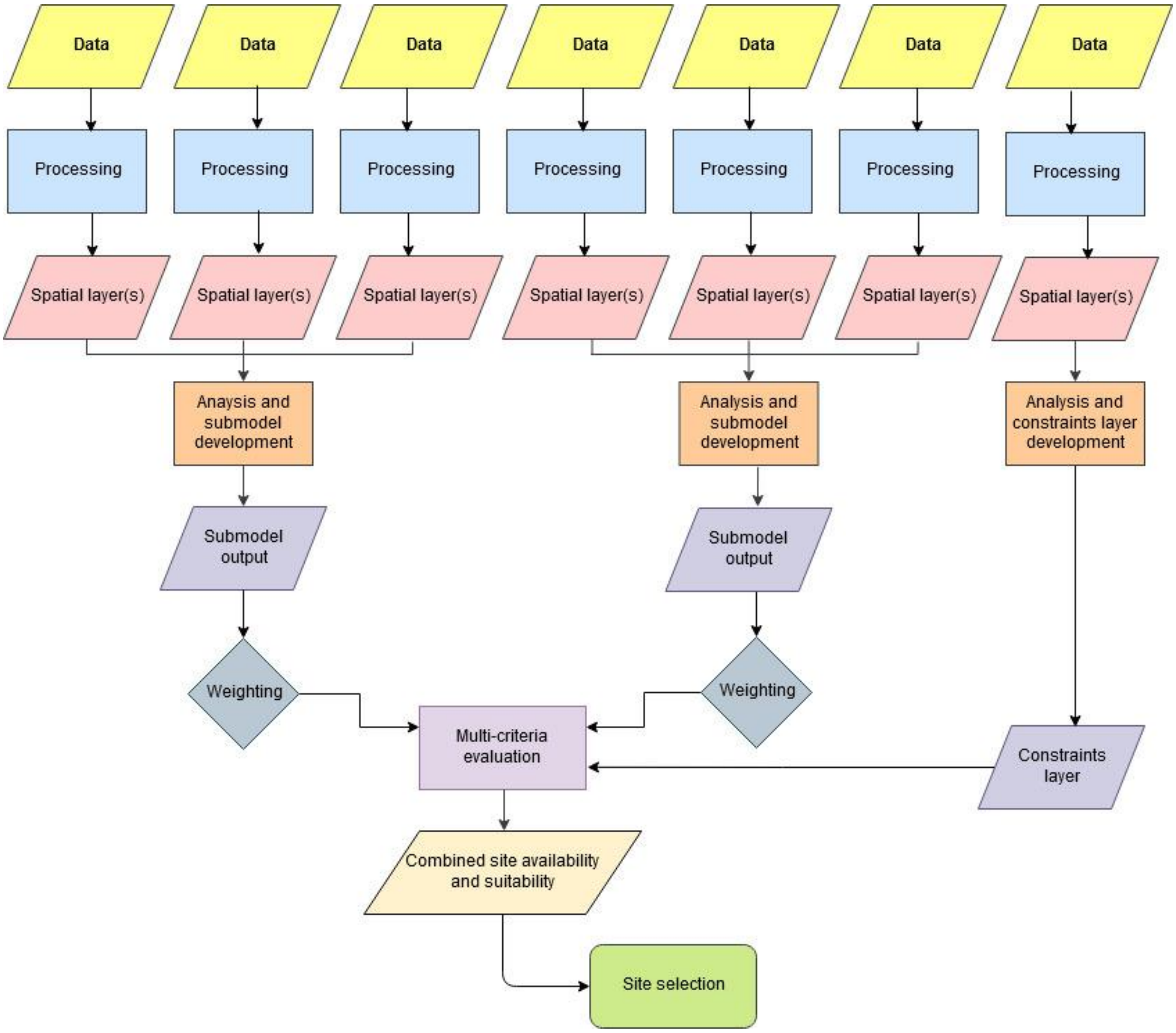

Figure 4: Outline of the framework used for GIS-based modelling approaches for aquaculture site selection.

3.1.2. Other modelling approaches

As shown in TAPAS Deliverables 5.3 and 5.5 (Falconer et al., 2019cd), more complex approaches involving hydrodynamic and/or biogeochemical models are useful for planning and management of marine cage sites and shellfish culture. Such approaches can be used to simulate potential organic waste dispersion, risk of disease spread, and environmental interactions. However, the amount of time and resources involved in such modelling restricts their use in many cases. This may improve in the future as technology advances and more data and information become available. However, for now, it is likely that such approaches will not be used for every coastal or marine site, but may be used if there are particular concerns or issues (e.g. large number of other farms, potential cumulative impacts, or sensitive species), if the scale of the system warrants a more detailed assessment, or if it is a new environment (e.g. moving further from the coast) where potential implications for farming and impact on the ecosystem are unknown.

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3.2. Data availability and quality

The most time-consuming part of a site selection exercise is data collection. Some countries have geospatial databases that are easy to access, regularly updated, and contain a wide variety of layers, while others are more limited. There are also a number of data networks and platforms in Europe and across the global that can be a valuable source of data, such as EMODnet (http://www.emodnet.eu/), and Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu/). Although there are many data resources now available online, in many cases there will still be a need for field visits, either for initial data collection or for validation purposes. Furthermore, it is important to assess whether the data is fit-for-purpose, as the quality can vary and the resolution may not be appropriate for decision making. There is often a trade-off between data that should be included and data that can be included. It is important to acknowledge that the quality of the input data is of vital importance, as this determines the final output of the analysis and modelling.

Regulatory authorities can support the site selection process by providing guidance on the conditions that would be considered good for aquaculture development and those which are unlikely to meet environmental standards. Furthermore, online data portals that share information on existing aquaculture locations, as well as environmental conditions and other activities, are useful. By providing information to support aquaculture producers in the site selection process, regulatory authorities can reduce their workload by decreasing the number of applications for sites in highly unsuitable locations.

3.3. Stakeholder engagement and communication platforms

Stakeholder engagement is an important part of the site selection process. If producers are identifying potential sites for production, they may wish to discuss with regulatory and decision making authorities. Furthermore, they may also wish to discuss with other stakeholders, such as non-governmental organisations or producer organisations. This can provide information on aspects of site selection that may otherwise be difficult to obtain. In Ireland, there is a process known as CLAMS (Co-ordinated Local Aquaculture Management System), which is a non-statutory management system that focuses on management at a bay level and integrates all stakeholders and users of the environment within a group. The initiative involves developing a management plan at bay level, and managing activities in-line with the local plan, as well as national objectives and policies. It provides a strong communication network, as the stakeholders are engaged in the process and conflicts can be avoided or resolved at an early stage. This is useful for aquaculture site selection, as it is a way of planning aquaculture in the most appropriate locations while also considering the needs of other stakeholders. This can facilitate the licensing process by identifying issues quickly and highlighting where potential aquaculture producers may need to provide additional information in an application, if an alternative approach or technology would be appropriate, or providing information on the local area from existing users.

When developing aquaculture zones, regulatory authorities should consider establishing a system such as CLAMS. The advantage of a dedicated group that includes all users and stakeholders in the

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area is that there is an increased sense of ownership, people can have their say, and this encourages local participation. The plans and strategies developed by the group should be adaptable and evolve as things change. Once established, aquaculture producers can co-ordinate farm management practices, such as stocking and disease treatment. Key to the success of the system is the use of an aquaculture liaison officer, who is a dedicated individual that chairs the process and is the point of contact for all involved.

3.4. Framework checklists

Some aquaculture producers will be very experienced in the site selection process, but for those who are less experienced or new to the industry, a framework checklist can be used (Table 1). This allows the user to ensure that each step has been followed and can be used by prospective aquaculture producers (Table 2) and regulatory authorities (Table 3) alike. This is useful to note the roles and responsibilities of the aquaculture producer and also the regulatory authority.

Table 1: Spatial framework checklist to facilitate the site selection process.

Framework checklist	Comment
Identification of species and system	
Regulatory feasibility	
Zones	
Decision support	
Site availability	
Site suitability	
Site selection	

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Table 2: Framework checklist and role of prospective aquaculture producers within the site selection process.

Framework checklist	Description	Required data
Identification of species and system	*The prospective aquaculture producer identifies the species and system they wish to develop.*	*Information on the farming requirements for the species.*
Regulatory feasibility	*The prospective aquaculture producer reviews the regulation to ensure the species and system is allowed in the area. If this information does not exist, the producer should contact the relevant regulatory authority.*	*Information on the aquaculture regulations and licensing process for the area.*
Zones	*If zones exist, then aquaculture development may be limited to these areas and prospective aquaculture producers would need to focus on these areas. Otherwise, the general area of interest should be established prior to spatial assessment.*	*Information on where any aquaculture zones are located.*
Decision support	*The prospective aquaculture producer or representative (e.g. consultant) uses spatial analysis and/or modelling to assess the trade-offs between biological requirements, environmental conditions, socio-economic issues and legal aspects of farming a particular species within an area.*	*Data on the biological requirements of the species, environmental conditions of the area, existing activities and any legislative restrictions. Spatial analysis and modelling can be performed using a range of tools.*
Site availability	*The process of identifying the locations that are available for aquaculture.*	*Data on the biological requirements of the species, environmental conditions of the area, existing activities, and any legislative restrictions. Spatial analysis and modelling can be performed using a range of tools.*
Site suitability	*The process of evaluating the suitability of an area for aquaculture.*	*Data on the biological requirements of the species, environmental conditions of the area, existing activities, and any legislative restrictions. Spatial analysis and modelling can be performed using a range of tools.*
Site selection	*Using the information provided to select the most suitable site that is available for aquaculture development. Once selected, more detailed data collection and analysis may be required as part of the licensing process.*	*Results from the site availability and site suitability assessment.*

Table 3: Framework checklist and role of regulatory authorities within the site selection process.

Framework checklist	Description	Required data
Identification of species and system	*Regulatory authorities should have a list of allowed species and systems, which should be updated as environmental conditions change and new information and technology becomes available.*	*Information on the farming requirements for the species.*
Regulatory feasibility	*For each species and system, the regulatory authorities should provide guidance that defines the regulatory requirements and any limitations.*	*Information on the farming requirements for the species, potential environmental impacts, possible health and welfare issues, disease risk, and food safety.*
Zones	*There are advantages and disadvantages to defining aquaculture zones for development. If a regulatory authority decides to establish zones, they must be identified and demarcated based on the biological and environmental requirements of the species. The decision maker must also provide clear guidance about what can and cannot take place within a zone.*	*Data on the biological requirements of the species, environmental conditions of the area, existing activities, and any legislative restrictions. Spatial analysis and modelling is useful to support the designation of zones in the most appropriate location.*
Decision support	*The regulatory authority may use spatial analysis and modelling to support their decision-making process for the establishment of zones and also the overall planning and consent process.*	*Data on the biological requirements of the species, environmental conditions of the area, existing activities, and any legislative restrictions. Spatial analysis and modelling can be performed using a range of tools.*
Site availability	*The process of identifying the locations that are available for aquaculture.*	*This is the responsibility of the prospective aquaculture producer. The regulatory authority may be able to provide information to support assessment (e.g. a data portal and online visualisation tools).*
Site suitability	*The process of evaluating the suitability of an area for aquaculture.*	*This is the responsibility of the prospective aquaculture producer. The regulatory authority may be able to provide information to support assessment (e.g. a data portal and online visualisation tools).*
Site selection	*The aquaculture producer will select the site and then start the licence application.*	*The regulatory authority may provide guidance but will not select the site.*

4. Case studies

Two case studies are included here to illustrate how the spatial framework presented in Section 3 can be used to support planning and management of aquaculture in Europe. One focuses on site selection for freshwater cage culture and the other considers offshore shellfish production.

4.1. Freshwater cage culture

This case study considers site selection for cages in freshwater lake systems. Table 4 shows the overall process, following the framework outlined in Figure 1. The identified species and system were juvenile Atlantic salmon (*Salmo salar*) in freshwater cages in a lake system in Scotland and there were no regulatory issues for that specific lake and two sites already exist. There are no specific aquaculture zones and the lake system had already been identified as the waterbody to be assessed. Therefore, site availability and site suitability assessment would focus on the entire lake. The lake system is relatively large, and spatial modelling is required for decision support. Stakeholders were consulted regarding what parameters would be relevant for the assessment. Based on the stakeholder response and understanding of the system, it was decided that a modelling approach which considered the availability and suitability of the lake system should be complemented with a catchment-based model to show areas at risk of phosphorus loading from the surrounding land use. Such an approach could be used for integrated catchment management.

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Table 4: Framework checklist for the spatial assessment to support site selection for cages in a freshwater lake system.

Framework checklist	Comment
Identification of species and system	Juvenile salmon in cages in a freshwater lake system
Regulatory feasibility	Yes, salmon production is allowed within the lake system and cages already exist.
Zones	No zones, but a lake has been pre-identified as potentially suitable.
Decision support	Stakeholders and expert opinion suggest the need for a lake-based suitability model and a catchment-based model to assess the risk of phosphorus loading from different land-use types. Data is available to support relatively simple GIS-based modelling, but not dynamic modelling or more complex hydrological modelling.
Site availability	The lake has a dam and is used for electricity generation, which may affect the availability of some areas.
Site suitability	The suitability of the lake will primarily depend on its physical characteristics. Phosphorus levels are a limiting factor for development, but inadequate data exists for the entire lake, therefore this suitability assessment is a first step to identify the potential site, and further analysis would then be required with regards to potential environmental impact.
Site selection	The results can be used to identify a suitable location for cages and then more detailed data collection would be required at the farm level.

4.1.1. Study area

The study area focused on Loch Shin (58°7’N, 4°35’W), a freshwater lake (loch) system in the North West Highlands of Scotland (Figure 5). A concrete and embankment dam was installed in the 1950s, and the water level was raised by approximately 11 metres, making Loch Shin a reservoir as part of a hydro-electric scheme (Scottish and Southern Energy, 2005). It has a large catchment, with a number of rivers feeding into the loch. Land use in the surrounding area is primarily moorland and forestry,

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with a small town at the south of the loch, where the dam is located. Loch Shin has been used for salmon smolt production for more than twenty years, with one site in the north of the loch and another in the south. The most recent River Basin Management Plan, a requirement for the EU Water Framework Directive, considers Loch Shin and catchment rivers to be in poor condition due to water quality and access for fish migration (SEPA, 2015). Action is ongoing to address the barriers to fish migration which are due to the hydroelectricity generation. Although nutrient levels are above the environmental standard set for good status, SEPA (2015) note action is not required for water quality as the levels are not showing adverse effects on the lake ecosystem, but further elevation of nutrient concentrations should be avoided. Therefore, it is important to make sure aquaculture is planned and managed accordingly.

Figure 5: Location of the freshwater lake in the north of Scotland

4.1.2. Lake Model

Discussions with local stakeholders identified depth as the main physical parameter which would affect siting of fish cages (Figure 6A). Due to the surrounding topography and location of the lake, waves are not considered an issue. Within Scotland, visual impact can be a major constraint to development. Therefore, a visibility layer was constructed to identify the locations that would be most and least visible from the buildings within the area (Figure 6B). Areas that were considered highly visible were given the lowest suitability score and areas that were considered to have lowest visibility were given the highest suitability score. Landscape character was not considered within this assessment as all of the lake was considered to have the same visual amenity throughout and there were no outstanding areas of natural beauty. Access to a site is an important factor in site selection. Existing and potential boat access points were identified and a cost function was applied to assess the time it would take to travel from the point (Figure 6C). Areas of the lake which were furthest away from any access point and therefore would take the longest time to reach were given the lowest

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suitability score and areas closest to the access point were given the highest suitability score. Shallow parts of the lake which were not deep enough to site a cage were considered a constraint as were areas within 1 kilometre of the dam, which is in the south of the loch (Figure 6D).

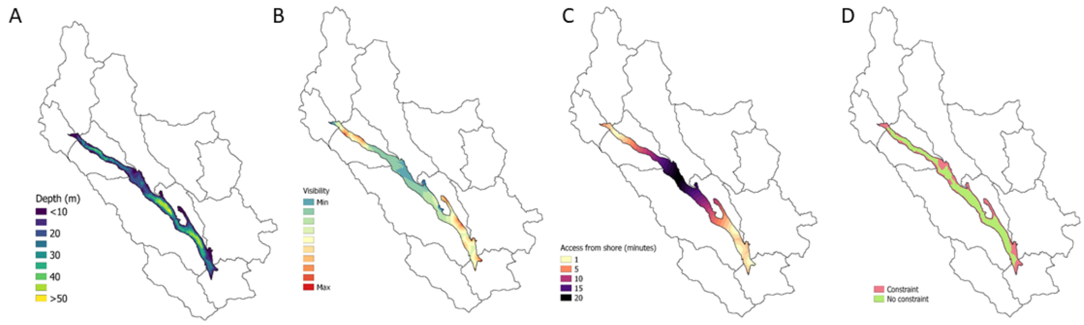

Figure 6: Submodels for the lake model; A) physical suitability based on depth, b) potential social impact based on visibility, c) logistical suitability based on accessibility, and d) constraints based on depth limitations and distance to the dam

A fuzzy reclassification was used for each layer and the thresholds were defined based on literature and experience. The three factors (depth, visibility and access) were combined within a multi-criteria evaluation (MCE). Discussions with stakeholders and experts were used to identify and assign weights. Depth was considered the most important and given a weighing of 0.6, then visibility and access were considered of equal importance to each other and were each weighted 0.2. Constraints were also applied to the output to produce the final result which indicated the most suitable locations to site cages in the lake (Figure7). The results suggest that there are several areas within the lake that could be suitable for cage aquaculture. Areas in the north and in the south appear to have most potential, with the mid-section having lower suitability scores. Some areas are unavailable as they are too shallow.

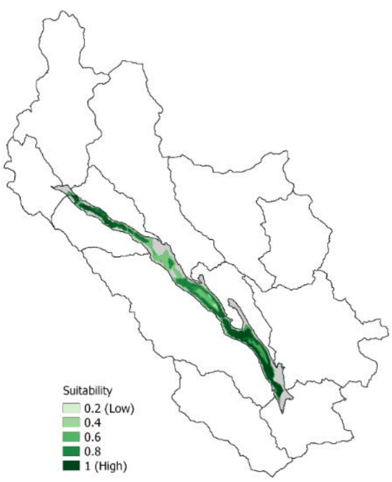

Figure7: Final output for the lake suitability model.

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It is important to note that the lake suitability model indicates potential areas that might be suitable for freshwater cages, but more in-depth site-specific analysis would be needed to determine carrying capacity and production potential at a site, as discussed in TAPAS Deliverable 5.6 (Falconer et al., 2019a). The advantage of the GIS-based modelling process for site selection is that it can be used to identify areas that are potentially suitable based on selected criteria. However, it cannot be used to assess carrying capacity for a specific site. A stakeholder can use the model outputs to select a site, but then more detailed assessment would take place at the potential farm site. This targeted approach is particularly useful in large or complex areas where there is a high degree of spatial heterogeneity and variable conditions. However, data availability is an issue as there may not be data for important parameters that would affect the suitability of the lake for aquaculture. Data collection campaigns can take place, but these can be resource intensive depending on the data and level of detail required. For this case study, depth was a key parameter, but no existing datasets were available, and the size of the lake and resource limitations made a full-scale bathymetric survey impossible. Thankfully, there were historic maps which were digitised, georeferenced and processed alongside up-to-date topography datasets to create the spatial layer. However, in many lake systems this information is unavailable which could limit the application of such models.

Furthermore, it is important to acknowledge that the model structure will also influence the final results, and the weighting process is often subjective. In this example, the model was weighted in accordance with stakeholder views, who were all in agreement but in some cases, stakeholders may disagree, and this can add uncertainty to model outputs, and overall interpretation and use of the results. A way around this is to model different scenarios, but the approach must be transparent so that end users fully understand how the final outputs were derived. This is particularly important when there are large numbers of layers.

4.1.3. Catchment model

The lake suitability model only considers the suitability with regard to conditions within the lake; but the water quality of freshwater systems is affected by surrounding areas and this will also influence carrying capacity and production potential. Within the planning process, this will usually be assessed at the potential farm site and measurements will be taken and carrying capacity can be assessed using predictive models, as evaluated in TAPAS Deliverable 5.6 (Falconer et al., 2019a). However, sampling and water quality analysis requires resources and if there are several potential sites under consideration (as can be identified from the lake suitability model) then additional decision support may be required to target specific areas. Spatial models of the catchment can be used to identify areas that are potentially at risk of higher levels of nutrient loading because of the characteristics of the catchment and land use. One of the advantages of a catchment model, is the potential to simulate different scenarios of land use, so can use the model to assess land use change and support integrated catchment management and the ecosystem approach to aquaculture.

Within this case study, the aim of the catchment model is to assess the potential risk of phosphorus loading into the lake system. There are many catchment models available ranging from relatively simple to complex. Each has their own data requirements and the more complex hydrological models can be time and resource-intensive. One of the issues for site selection is that areas being considered are not always rich in data as complex landscape models are often developed for areas that have been

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studied over many years. This is true for the case study here as there is a lack of publically available detailed datasets. Thus, a simpler and less data intensive modelling approach was required

The potential input of phosphorous from the surrounding environment to the loch was estimated using the InVEST Nutrient Delivery Ratio (NDR) model from InVEST (v3.7.0) suite of tools (Sharp et al., 2018). This uses data on land use (Figure 8A), elevation (Figure 8B) and average annual rainfall (Figure 8C). The NDR uses a mass balance approach and simulates nutrient movement as long-term, steady-state flow using empirical relationships (Sharp et al., 2018). A detailed description is provided in the InVeST User Guide (Sharp et al., 2018).

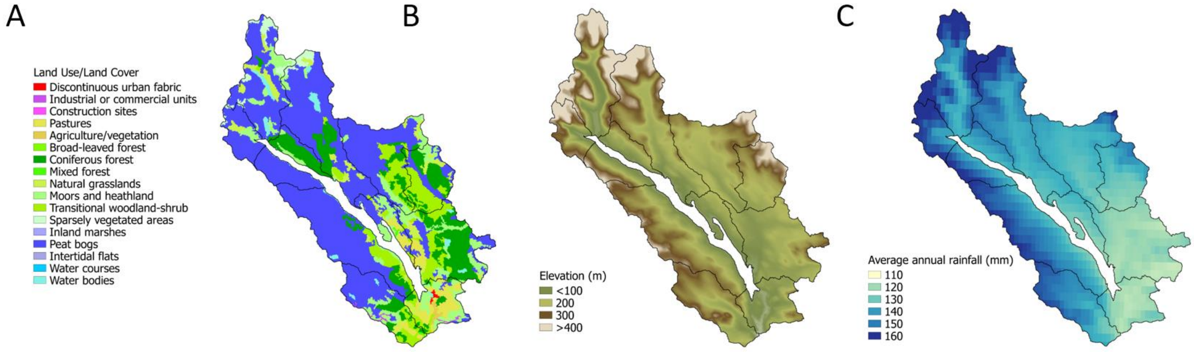

Figure 8: Data layers used within the catchment model, A) Land use/land cover, B) Elevation, C) Average annual rainfall

The results from the catchment model are shown in Figure 9. The model indicates that the highest levels of phosphorus are exported from catchments in the south of the lake, compared to the north. Water flows through the lake system from north to south which also suggests that P loading in the south of the lake is unlikely to affect locations further north. This should not be used to determine overall suitability of the lake for aquaculture or select sites but should be used to identify areas at higher risk of nutrient loading, and those areas with lower risk. This can then help inform data collection and environmental monitoring campaigns.

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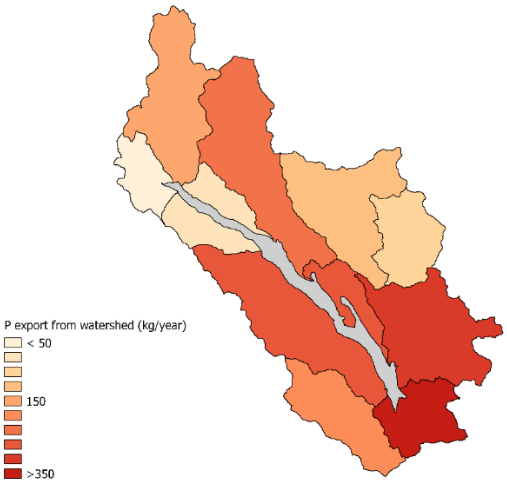

Figure 9: Modelled total phosphorus export from the sub-catchments (watersheds) within the larger lake catchment.

4.1.4. Integrated Lake-Catchment model outputs

Combining the results in an Integrated Lake-Catchment visualisation can allow for a more holistic overview of the ecosystem and potential site selection considerations. The Integrated Lake-Catchment model for the case study are shown in Figure 10. The advantage of a combined approach is that it shows the areas of the lake where a cage could physically be located (lake model) but also considered potential implications for water quality (catchment model). The results show there are areas in the north and south of the lake system that would be suitable for cages, however areas in the south would be at risk of higher Phosphorus loading from the surrounding catchments than those in the north. Field measurement campaigns can then be conducted at the most appropriate sites to assess carrying capacity.

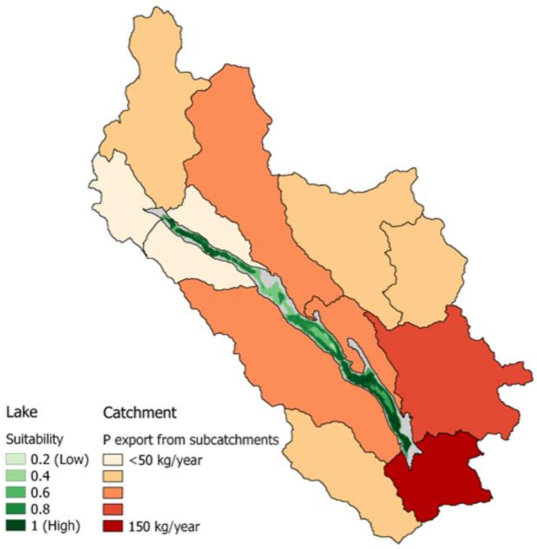

Figure 10: Modelled total phosphorus export from the sub-catchments (watersheds) within the larger lake catchment.

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4.1.5. Summary

One of the challenges for freshwater cage site selection is a lack of data. The use of freshwater cage systems for aquaculture production is not common in Europe, therefore data to support site selection is often unavailable. However, GIS-based models can make use of available data sets to target locations that have potential and should be investigated further, and more detailed data collected at the local-scale. Using the spatial framework that has been outlines in the previous section, this case study, demonstrates how spatial models can be used for freshwater cage site selection. The modelling approach (Figure 4) is used with the data that was considered appropriate by stakeholders and was available for use. If more data becomes available, then it is possible to expand the model.

The integrated loch-catchment model provides an overview of the entire system and provides information that would otherwise be missed if only a single component (lake or catchment) was modelled. The case study presents a relatively simple approach for the catchment due to data availability, however in some catchments, if data are available then a more complex approach could be used, e.g. QSWAT.

It is important to note that the modelling approach is designed as a first step in the planning process and should be used to assist decision makers in site selection. Other factors which were not included in the model may also be important and the site selection model forms part of the process rather than the whole procedure. Furthermore, site suitability assessment is often more of an abstract concept other modelling approaches, therefore a transparent approach such as the one presented here (Section 3) is required to guide the user in interpreting the result.

4.2. Offshore bivalve production

This case study considers site selection for offshore Pacific oyster (*Crassostrea gigas*) cultivation over a large (~5000 km^2) area off the French Atlantic coast (Fig. 10). Table 5 shows the overall process, following the framework outlined in Figure 1. Although a limited number of offshore farms currently exist in France, mainly for mussel production, no offshore aquaculture zones have been designated as of yet; however, Strategic Coastline Documents to provide planning in support of the national obligations under the EU Marine Spatial Planning Directive (MSPD; 2014/89/EU), including for aquaculture, are being prepared. Although the offshore licensing process has been documented as being deterrently complex and lengthy (Barillé et al., 2020), there remains interest by small-scale producers in moving production offshore from the overcrowded intertidal zone. Experimentation to demonstrate the biological appeal and technical feasibility, along with environmental suitability, at any given site is the first step in applying for an offshore license. Experimental leases have been granted for single offshore sites in the past (2008 and 2010). Here, several spatialized data sources and modelling are used to leverage and expand upon the results from these individual sites. Information pertinent to this first licensing step is provided so as to identify potential zones or sites of interest over the large area considered. Constraints and other factors impacting site availability and suitability were identified and defined in consultation with producers and industry professionals and

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used with modelled oyster growth in a regional spatial multi-criteria evaluation (SMCE). Such an approach and the resulting information is expected to facilitate this crucial first step of the licensing process for applicant producers and regulators.

This section provides a brief overview for information. For details of this case study, and further explanation of model structure and application, please see Barillé et al., (2020).

Table 5: Framework checklist for the spatial assessment to support site selection for offshore Pacific oyster cultivation.

Framework checklist	Comment
Identification of species and system	Pacific oyster in offshore bottom cage and longline systems.
Regulatory feasibility	Technically feasible under current regulatory framework, but cumbersome.
Zones	No zones at present; Strategic Coastline Documents to support implementation of national strategy to fulfil EU Marine Spatial Planning Directive (MSPD; 2014/89/EU) currently being developed and to include aquaculture.
Decision support	A variety of vector- and raster-type data needed for spatial modelling and analysis is available; a framework and training for carrying our such analyses for different sites or under different scenarios is currently being developed as a tool to support the regulatory authority and interested parties.
Site availability	Constraints limiting site availability related to existing uses, sensitive areas, and technical requirements for proposed systems identified and mapped.
Site suitability	Relative suitability of the available study area, in terms of growth potential and other limiting or enhancing factors, have been combined and presented as suitability indices under various scenarios.
Site selection	The results can be used to identify suitable and most optimal locations for Pacific oyster cultivation, which can be used to designate potential aquaculture zones, or select farm sites to consider in further detail and present as part of the first step of the licensing process.

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4.2.1. Study area

The study area is the ~5000 km^2 offshore area surrounding Bourgneuf Bay, which is located just south of the Loire estuary in the French *Pays de la Loire* region off the Atlantic coast (Figure 11). Bourgneuf Bay (~340 km^2) itself currently and historically hosts dense *C. gigas* farming in the ~100 km^2 of its intertidal zone, whereby the 283 mostly small-scale farms can access their concessions during low tide. However, there is no room for further aquaculture expansion there. Bourgneuf is a macro-tidal bay, with a tidal range varying from 2 to 6 m throughout the year, and a high turbidity gradient, ranging from extremely turbid (i.e., suspended particulate matter (SPM) occasionally exceeding 1000 mg m^{-3} (Gernez et al., 2014; 2017)) nearshore in the intertidal zone to relatively clear (i.e., SPM typically less than 30 mg m^{-3}) in the centre of the bay. Although less extreme, there is a spatially-similar gradient in water column productivity related to the combined effects of microphytobenthos resuspension in the shallower depths of the intertidal zone and nutrient loading that dilutes with distance from nearshore. Experimental results (Glize and Guissé, 2009; Glize et al., 2010; Louis, 2010) comparing *C. gigas* growth at an intertidal site with that in bottom cages offshore within the bay have suggested much faster growth offshore, supported by recent modelling efforts using satellite image data to assess growth across the bay (Palmer et al., 2020), and provides further incentive for producers to consider offshore production.

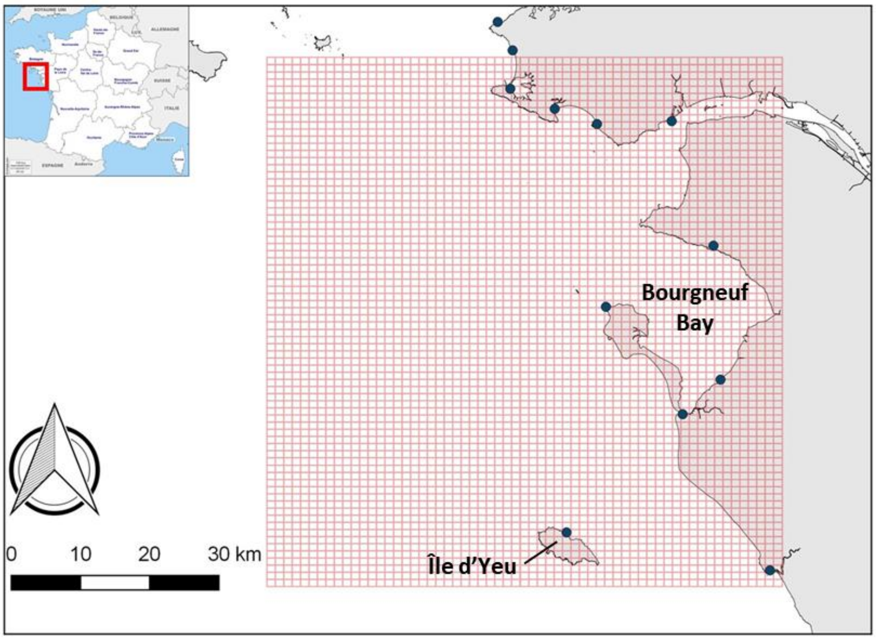

Figure 11: Location of the French Atlantic *Pays de la Loire* study site, with locations of existing harbours indicated (blue dots) and with the 1 km grid used in the current work overlain.

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4.2.2. Spatial Multi-Criteria Evaluation

Identified first were those factors that limited the availability of the area considered (i.e., constraints; Figure 12). Several of these were related to precluding existing activities or habitats: seabed mining, sand deposits, commercial traffic, and areas protected as sensitive habitat or for fishing (Barillé et al., 2020). Two further constraints identified were from a producer or technical perspective, including bathymetry (the cage and longlines under consideration are only appropriate within certain depth ranges; 5-10 m and 10-20 m respectively) and distance from a harbour (5 nm, beyond which larger vessels and associated operating licenses are required) (Figure 13). Areas found to be unavailable or unsuitable related to any of the above criteria were not considered in further analyses. Three categories of variable were then identified to calculate suitability indices and complete the SMCE (Figure 12): environmental interactions (bottom and surface currents, substrate type, Natura2000 habitat, and sole nursery grounds); socio-economic (fishing and tourism activity, militarized zones, and underwater pipes); and optimal oyster growth (considering indicators of growth itself, as well as interannual variation).

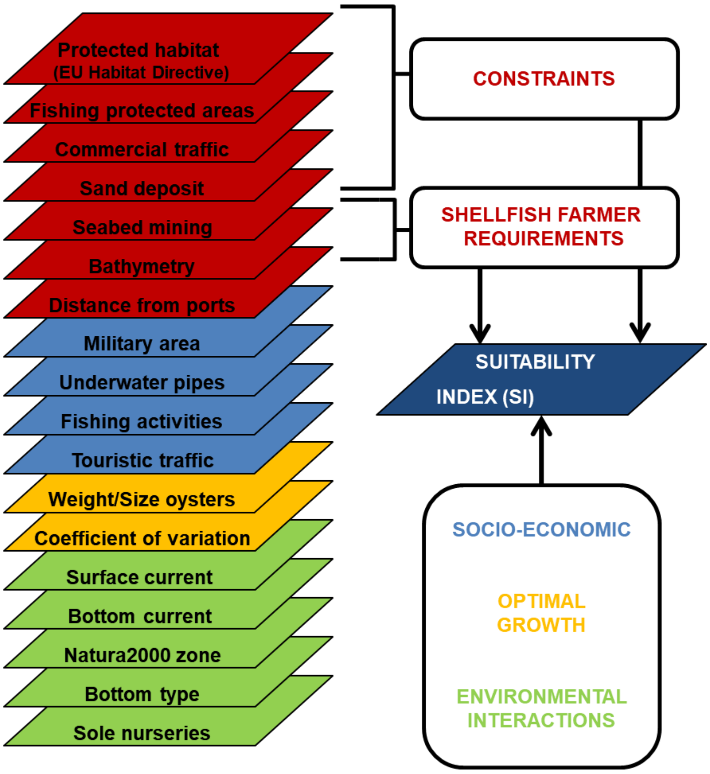

Figure 12: Constraint, socio-economic, optimal oyster growth, and environmental variables identified and included in the SMCE site selection. From **Barillé et al. (2020).**

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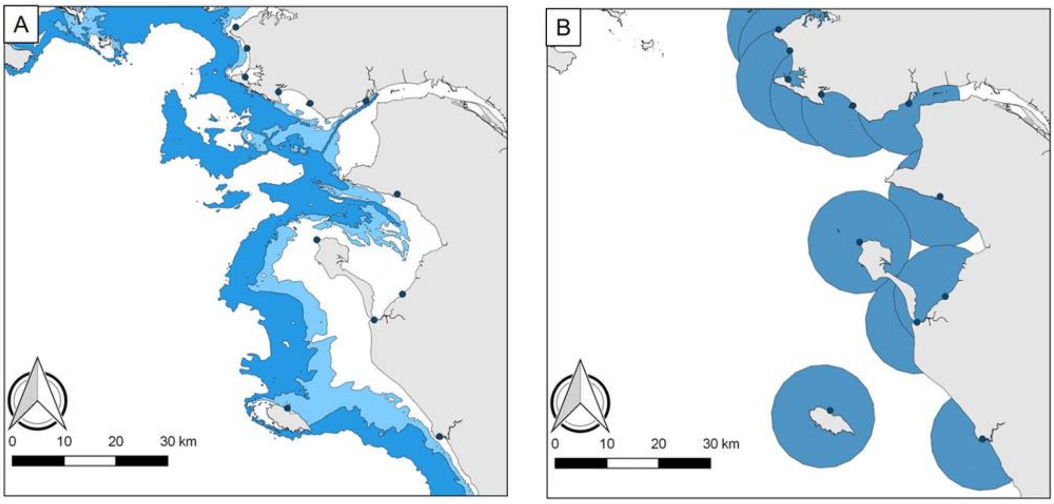

Figure 13: Maps of (A) bathymetric limitations for offshore cage (5-10 m depth; light blue) and longline (10-20 m depth; dark blue) oyster production, and (B) areas within five nautical miles (large blue circles) of existing harbors (dots). From Barillé et al. (2020).

Following data compilation, SMCE comprised three steps: (1) scaling all data to a common spatial grid and normalizing values for each criterion. Whereas all other data layers were in vector format, optimal oyster growth indicators were generated by applying Dynamic Energy Budget (DEB) modelling to input satellite image data of sea surface temperature and chlorophyll-a (representative of available food). DEB outputs were of the same format as the input data; raster-type with 1 km spatial resolution. This same grid was then applied to all other data layers and the SMCE was performed for each 1 km cell (Figure 11). Likewise, for the environmental, socio-economic, and optimal oyster growth variables, since these either favourably or unfavourably influence the potential for aquaculture at any given site rather than preclude, these must be normalized to a common scale (between 0 and 1, with 0 being least favourable and 1 being most favourable for a given variable) to reflect this influence at a given location. (2) Different scenarios whereby one of the three categories was favoured, or where they were prioritized equally, were considered. Each category was weighted through the application of coefficients. Finally, (3) all weighted criteria were aggregated to obtain the final suitability index (SI; Figure 13), whereby all available sites (i.e., 1 km cells) were rated either highly suitable (0.75 < SI < 1), well-suited (0.5 < SI < 0.75), somewhat suitable (0.35 < SI < 0.5), low suitability (0.25 < SI < 0.35), or unsuitable (0 < SI < 0.25).

From the results presented in Figure 14, it is clear that the category of variable prioritized (i.e., step 2 described above) greatly influences the total area and spatial distribution of sites well-suited to offshore Pacific oyster aquaculture (i.e., the final output from step 3 above), within the 800 km^2 found to be available and suitable (i.e., no constraints present) of the total 5000 km^2 considered (Barillé et al., submitted). This ranges from 81.1% of the area with a SI > 0.5 when none of the scenarios is prioritized over the others, to 64.6% of the area for environment, 66.2% for optimal oyster growth

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(note, however, that approximately half of this area was found to be highly suitable (SI > 0.75)), and only 32.7% for socio-economic. Areas generally found to be suitable are within the offshore Bourgneuf Bay, around Île d'Yeu, and – except in the socio-economic scenario – to the north of the Loire estuary. A framework for undertaking SMCE using an open source GIS platform, and including a knowledge transfer and training component, is currently planned such that regulatory authorities and industry professionals and organizations can adapt this approach to their specific needs and questions to facilitate the site selection step of licensing.

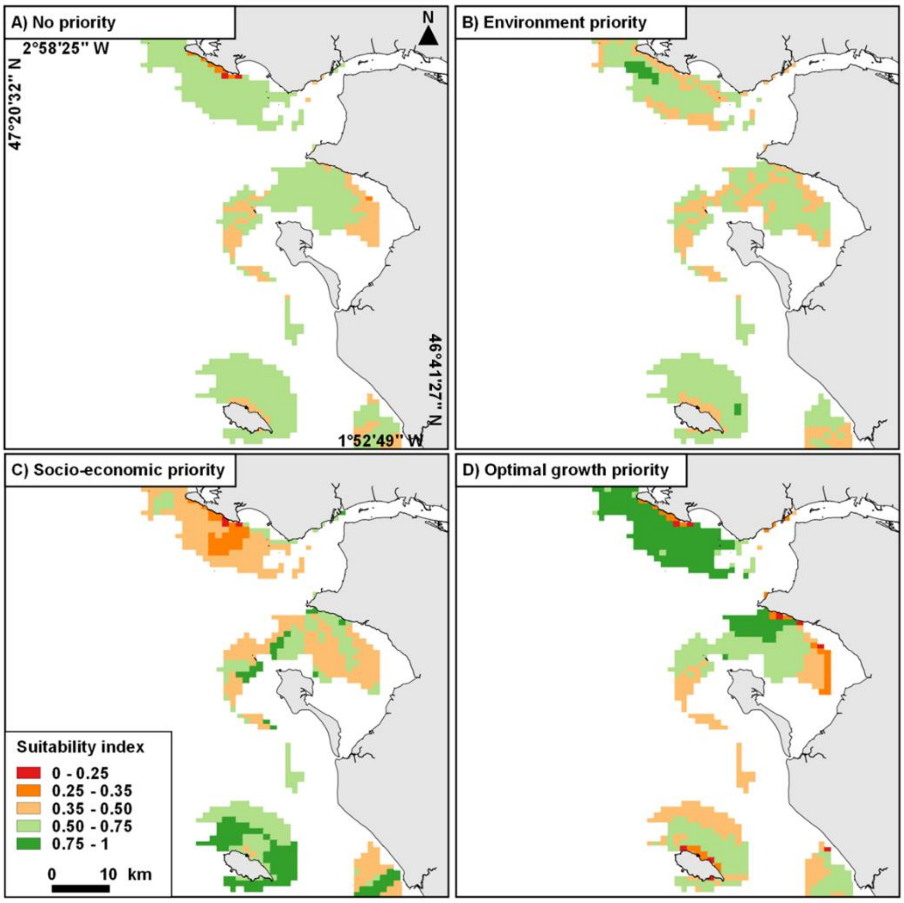

Figure 14: Suitability index maps for the four scenarios: (A) without specific priority (equal 33% weighting for all categories), (B) priority (75%) to environmental interactions, (C) priority (75%) to socio-economic activity, and (D) priority (75%) to optimal oyster growth. In B-D, those categories not prioritized each receive a 12.5% weighting. From Barillé et al. (2020).

4.2.3. Summary

Although extending Pacific oyster cultivation to the offshore environment would open an extensive potential area for aquaculture, many conflicting uses and constraints limit space availability and suitability. Spatial multi-criteria evaluation of the availability and suitability of oyster aquaculture, using 18 vector and raster spatial data layers, has been demonstrated here as an example of the general framework outlined in Section 2. This can help producers and regulatory authorities to identify possible sites of greatest potential so as to facilitate licensing and eventually contribute to farm

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success and sustainability. The initial area considered, of approximately 5000 km^2, was reduced to an 800 km^2 suitable and available area, within which between 260 and 650 km^2 was found to be well-suited to highly suitable (i.e., suitability index > 0.5) to Pacific oyster culture, depending on variable prioritization and weighting.

5. Summary conclusions

The spatial framework presented here provides a structured approach for site selection. This would be the first step of the planning process, but it is important to note that it should be used to support decisions rather than make a decision as there may be other factors which are not modelled but would also influence the suitability of a site. Furthermore, once a site is identified, more detailed site-specific analysis would take place to determine carrying capacity, environmental impact and production potential. Examples of these models are discussed in other TAPAS deliverables (including Falconer et al., 2016; 2019a; 2019d). However, such models usually require site specific data in their implementation and use, therefore can only be used in locations for which this data is available. Data collection can be resource intensive, especially for more complex models or those that require data over a number of different time-points. Therefore, the advantage of spatial site selection models is that there is already some consideration of the suitability of the site. However, this depends on the factors included in the model and the model developers are responsible for ensuring the model is fit-for-purpose.

Model results are highly dependent on the input data and model structure. If data of poor quality is used as input, then this will affect the results. Therefore, it is important to highlight potential limitations of data and data quality issues to the end users. Furthermore, the common approach of combining reclassified data within an MCE must also be used with caution as the processes involved in structuring the model can highly influence the model results. Stakeholder engagement and consultation is important as it is necessary to establish criteria that are relevant to their needs, so the model outputs are representative and useful. A design-thinking approach (Falconer et al., 2019b), where stakeholders are consulted throughout the process is key for development and can address some of the uncertainties that arise during model construction. Furthermore, different scenarios, as implemented here in the shellfish case study (Barillé et al., 2020), and by other authors (Brigolin et al, 2017) is useful as it provides further information on different priorities. This is also useful for stakeholder engagement as it can be used in trade-off analysis.

The spatial framework is not intended to replace more in-depth site-specific analysis, instead it provides structure and an additional level of decision support and enable more targeted site identification. Spatial analysis is powerful and can reveal information that would otherwise be difficult to obtain and can provide a more holistic overview of a system, supporting broader planning and management approaches such as Integrated Catchment Management, Marine Spatial Planning and the Ecosystem Approach to Aquaculture. This is particularly important in the complex environments in which aquaculture often operates, where it can be difficult to identify the most suitable locations based on biological, environmental, social and administrative criteria without some extra analysis.

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