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Spatial Suitability Analysis for Finfish Aquaculture: A Jurisdictional Review

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Executive Summary

Determining the capacity of coastal waters to support finfish aquaculture with negligible environmental impacts and minimal multi-user conflicts is critical for the sustainable development and management of aquaculture. In recent years, aquaculture jurisdictions around the world have applied Spatial Suitability Analysis (SSA) which combines Geographic Information Systems (GIS) with Multicriteria Decision Analysis (MCDA) to generate outputs for decision-makers, to delineate the optimal or suitable areas for aquaculture based on multiple criteria.

This report presents the findings of a jurisdictional review of available information on existing SSA initiatives in coastal salmonid aquaculture jurisdictions around the world. This review explores approaches among jurisdictions including suitability potential, criteria applied, objectives, and methodology.

SSAs have been developed and applied in select finfish producing countries such as Norway, the United Kingdom, Australia, and Finland to guide aquaculture development, zoning, and site selection, and to inform wider coastal planning initiatives. While a limited number of jurisdictions actively incorporate SSA into regulatory and management frameworks, many are in early stages of development and implementation.

Most existing SSAs are developed in the context of industry expansion and sector development, although the impact of implementing SSA systems remains undetermined. While most focus on estimating biophysical suitability for fish growth and health, some jurisdictions prioritize environmental sustainability to mitigate potential environmental impacts on natural habitats and wild fish populations. Less common are considerations for social values and multi-use conflicts, which are challenging to quantify and constantly changing.

Three crucial implications of existing SSA applications are identified in this jurisdictional review and include considerations around: i) the scope and scale of applications, ii) how to adapt to uncertainty, and iii) data limitations and challenges. Choice of methodology, including decisions around the number and type of criteria, standardization process, and weighting is critical for application of SSA outputs to decision-making. While SSAs have been formally integrated within government management and regulation in few cases, they are often of limited scale and scope, raising concerns over the legitimacy and acceptability of such SSA systems for attaining multi-dimensional sustainability. Still, this report highlights how SSA is a flexible methodology that can provide decision-support for aquaculture planning and management through the consideration of multiple, overlapping criteria to meet ecological, social, and biophysical sustainability goals.

Glossary

Boolean	A data type that is binary in nature, having only two possible values either as “true” or “false”
Constraint	A type of criterion / parameter that serves to limit the spatial scope of suitability area; element or feature that represents restrictions and / or limitations that would preclude the activity under consideration
Criteria	Attributes that reflect principles or standards by which decision-making objectives can be measured.
Factor	A type of criterion / parameter that enhances or detracts from the suitability of a specific alternative for the activity under consideration
Geographic Information System (GIS)	Computer system for capturing, storing, analyzing, and presenting geographical data
Multi-criteria Decision Analysis (MCDA)	A collection of formal approaches to explicitly account for multiple criteria in decision-making environments
Parameter	Refers to specific measures agreed to be important in achieving a criteria’s objectives and goals
Resolution	The dimensions represented by each cell (pixel) within a GIS environment
Spatial Suitability Analysis (SSA)	A GIS-based process used to determine the appropriateness of a given area for a specific use
Standardization	Process by which criteria values are rescaled to a dimensionless score denoting relative suitability for the given criterion
Suitability scale	The range of suitability scores assigned to a given criterion / parameter
Suitability score	a numerical value indicating an area’s suitability for a given parameter / criterion
Weight	The relative importance of a given criterion / parameter compared to other criteria / parameters

1 Introduction

For the sustainable production of finfish aquaculture, selecting suitable areas for the growth of fish in marine and coastal waters is critical. Traditionally, licensing and leasing for finfish aquaculture sites is predominantly guided by localized site selection processes. Yet, with growing multi-use conflicts, and broader, cumulative environmental challenges in ocean and coastal areas, many jurisdictions are investigating the development and implementation of systems for the classification of areas to inform zoning, planning, and site selection for aquaculture.

In the context of this review, Spatial Suitability Analysis (SSA) can be used to describe any process or strategy that seeks to designate and / or classify an area(s) with a given ranking based on the suitability of desired criteria to meet one or multiple management or planning objectives for aquaculture. SSA is a distinct category of suitability analysis that uses GIS-based processes for analyzing and visualizing the appropriateness of an area for a particular use. SSA provide industry, decision-makers, and interest holders with spatial tools to visualize potential areas for aquaculture development and guidance / support for decision-making regarding planning, site selection, or lease and licensing. While several jurisdictions apply zoning exercises for aquaculture development and planning, not all zoning use SSA, but rather infer an area's suitability for aquaculture activities.

The goal of the jurisdictional review was two-fold. First, it aimed to identify any existing government policies, programs, or projects that have evaluated and mapped the suitability of finfish aquaculture in its coastal waters. Consequently, this review examines the objectives and decision-pathways of such initiatives, the criteria included, data gathered, and tools mobilized, where evidence is available. Second, this review examines how suitability is framed, measured, and assessed to identify common strengths for wider suitability assessment. It analyzes the scope, impact, and strengths of the SSAs from leading jurisdictions and concludes with key challenges and priorities.

2 Spatial Suitability Uses and Applications

Current SSA applications from a variety of jurisdictions were examined. Select jurisdictions including Norway, the United Kingdom, Australia, and Finland have implemented SSAs to guide sector development and / or relevant government zoning, management, and industry siting decisions for finfish aquaculture. SSAs have also been applied to generate suitability maps as part of larger Marine Spatial Planning (MSP) exercises, or in research projects to assess environmental challenges and growth opportunities in many jurisdictions around the world. Examples of jurisdictions employing suitability analysis include:

- **Guiding sector development** – Norway, Scotland, and England
- **Zoning / designating aquaculture development areas** – Australia and England
- **Aquaculture siting / planning** – Finland, England
- **Aquaculture within coastal planning** – Finland, Portugal / Spain, Germany, and Italy

2.1 Norway

In 2017, Norway introduced a new spatial planning management regime, the Traffic Light System (TLS) for the adjustment and expansion of production capacity for Atlantic salmon (*Salmo salar*) aquaculture, based on the exposure of wild salmonids to sea lice (*Lepeophtheirus salmonis*). The objective of the TLS is to provide authorities with a predictable decision-making tool for aquaculture expansion while accounting for environmental sustainability (Ministry of Trade Industry and Fisheries, 2015). This system ranks each of the nation's 13 production areas[1] based on environmental criteria to determine whether industry growth (i.e., production capacity) would be allowed, maintained, or reduced for the next two years (refer to Table 1 for criteria applied to classify areas). Using a combination of models, data analysis, and expert assessments, environmental suitability of each production area is determined through a single measure of exposure of wild salmonids[2] to sea lice, based on lice-induced mortality estimates, using three pre-defined categories (Figure 1) of:

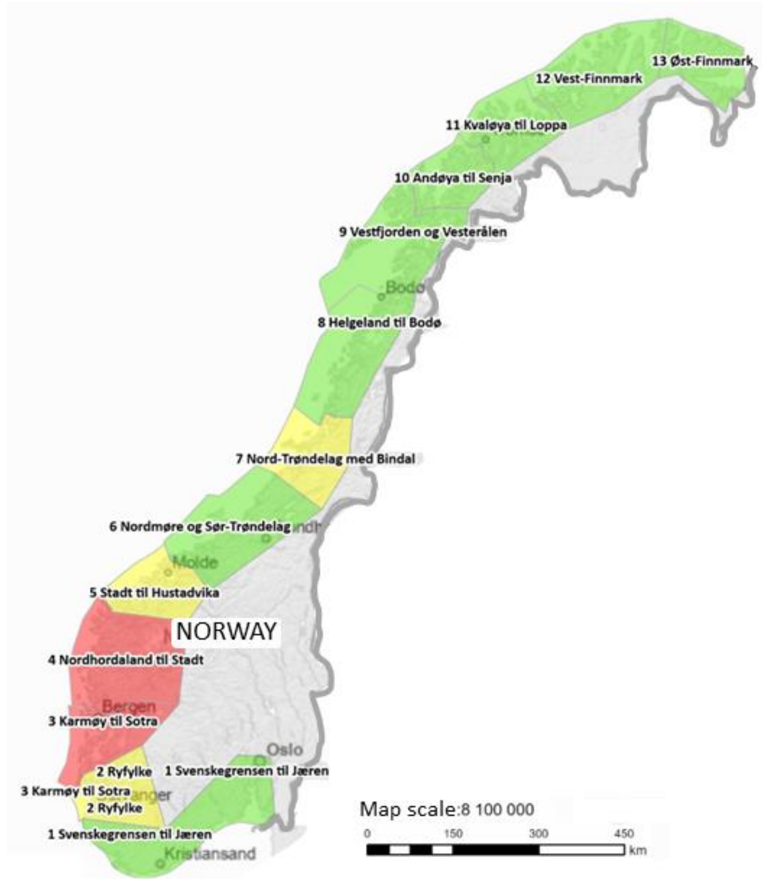

Figure 1 Classification of Norway's production areas based on wild salmonid sea lice mortality estimates (obtained from the online GIS portal by the Directorate of Fisheries (n.d.) – last updated November 16, 2022).

- Red (above 30%) = production capacity must be reduced by 6%
- Yellow (between 10-30%) = production capacity must remain constant
- Green (less than 10%) = production capacity can increase by 6%

[1] Coordinated production zones established by the Norwegian Ministry of Trade, Industry and Fisheries in 2017 to coordinate disease management controls for aquaculture (Ministry of Industry and Fisheries, 2017).
[2] Includes salmon, trout, and rainbow trout

2.2 United Kingdom

2.2.1 England

In England, the spatial potential for aquaculture development was carried out and adopted as policy by the Marine Management Organization (MMO). In 2013, regional spatial potential for aquaculture was calculated for the East and South Marine Plan Areas (MMO, 2013a), categorizing areas suitable for development[3] based a combination of natural resource modelling, planning and infrastructure constraints analysis, and proximity to supporting services[4] (Figure 2).

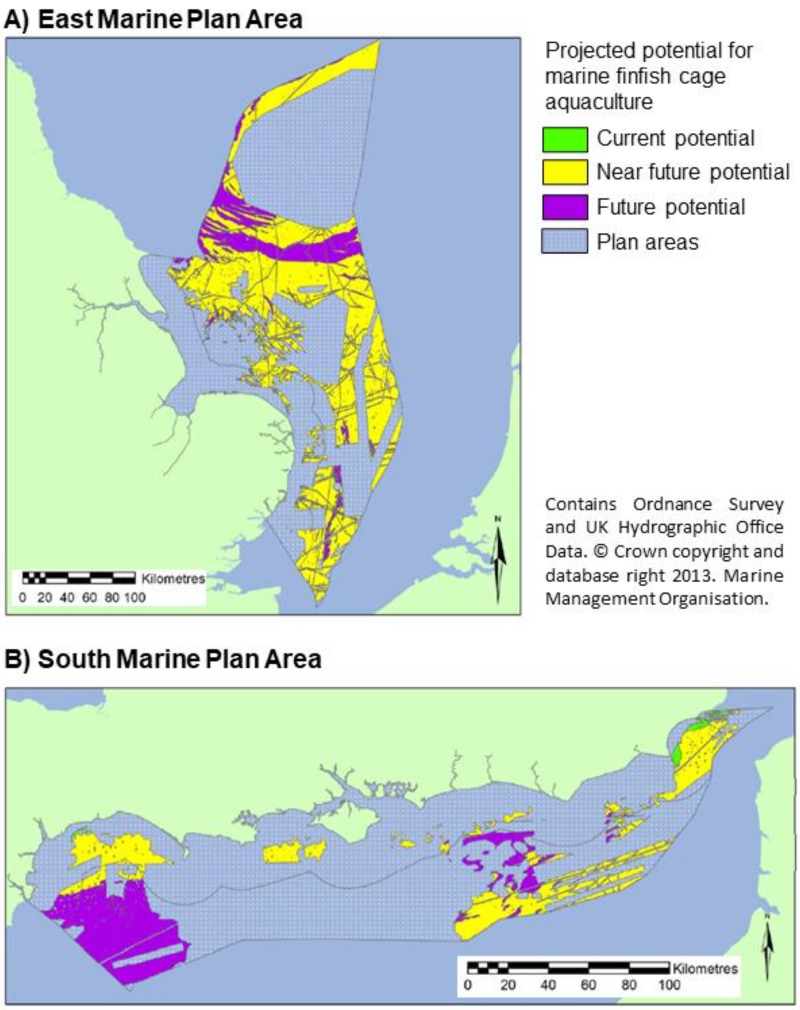

Figure 2 Suitability maps for intersection of natural resource modelling and areas of lease planning and infrastructure constraints in the A) East Marine Plan Area and B) South Marine Plan Area in England in 2013 (MMO, 2013a).

In 2019, aquaculture suitability was also calculated for various shellfish, seaweed, and finfish species across all English waters (MMO, 2019b; MMO, 2020). The final suitability model was based on a continuous suitability scale from 0 to 1 representing a combined calculation of different biological, technical, and planning suitability scores (Table 1). For example, biological criteria were classified in a three-tier system:

- Unsuitable: conditions considered unsuitable for aquaculture growth or fish survival
- Suboptimal: cultured species can grow, but potentially lower growth rate, and/or yield
- Optimal: most optimal conditions for growth of species

[3] Based on current potential (0-5 years), in the near future (5-10 years), and in the future (10-20 years)
[4] Proximity to essential infrastructure through distance to landing ports was mapped but not assigned specific suitability scores or modelled.

2.2.2 Scotland

Scotland's 2014 "*National Marine Plan*" sets out guidelines for aquaculture planning and development, emphasizing the importance of spatial planning and environmental suitability in siting finfish aquaculture (The Scottish Government, 2014). Every quarter, Marine Scotland Science[5] updates its Locational Guidelines for the Authorization of Marine Fish Farms in Scottish Waters (Marine Scotland Science, 2022), using predictive modelling to estimate a combined environmental sensitivity index of nutrient enhancement and benthic impact in sea lochs supporting aquaculture (Gillibrand et al., 2002). These combined indices are used to define suitability categories guiding sector development (Figure 3):

- Category 1: Caution against further fish farm developments (score 7 to 10)
- Category 2: Precaution should be applied in consideration of further fish farm development (score 5 to 6)
- Category 3: Fish farm developments are likely to be acceptable, subject to other criteria being satisfied (score 0 to 4)

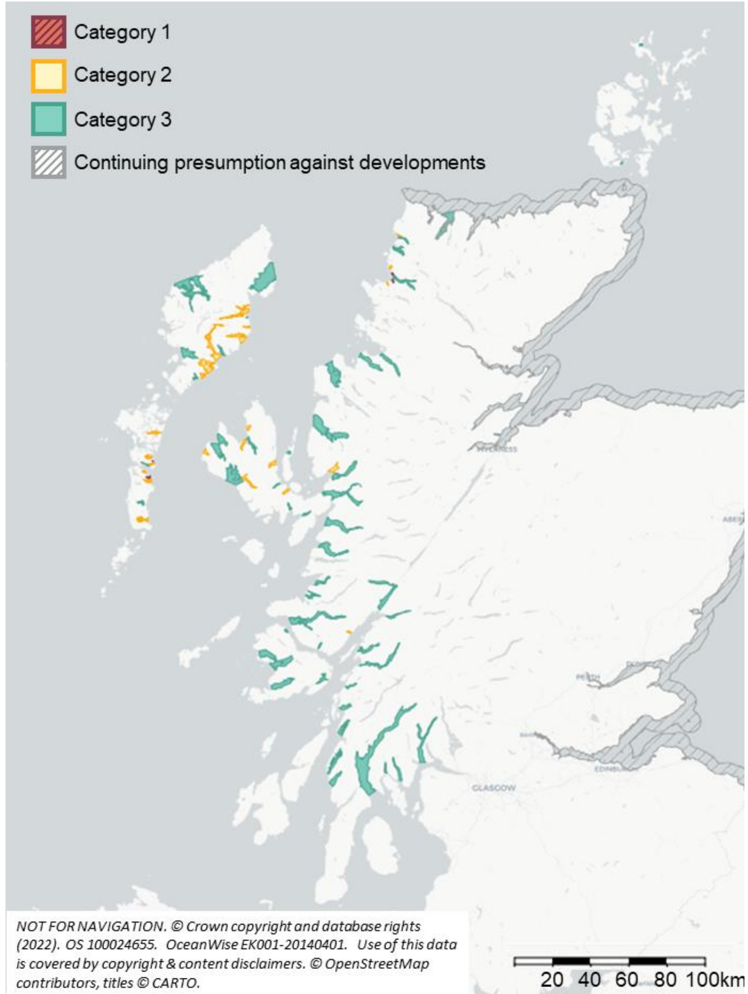

Figure 3. Classification of select sea lochs for aquaculture in 2022 based on nutrient enhancement and benthic impact, as part of the Scottish Government locational guidelines. Map extracted from public interactive mapping tool available (Scottish Government, 2022).

[5] Marine Scotland Science is the scientific division of the Marine Scotland Directorate supporting the Scottish Government assessments and guidelines.

2.3 Australia

In Tasmania, The Tasmanian Government generated "*The Sustainable Industry Growth Plan 2017*" (Tasmanian Government, 2017) which details the vision and priorities for the salmon farming industry and identifies proposed 'grow' zones where salmon farming may take place now (yellow) and in the future (green), and 'no grow' zones that will be banned for salmon farming (Figure 4). The designation of these zones was not based on quantitative suitability calculations, but rather based on participatory approach considering a combination of biophysical and environmental suitability recommendations[6] and community concerns over amenity and use values. 'No grow' areas were determined to be unsuitable for finfish farming, including either areas already dedicated to shellfish culture, areas without existing marine farming development plans, or specified areas to protect important reef habitats.

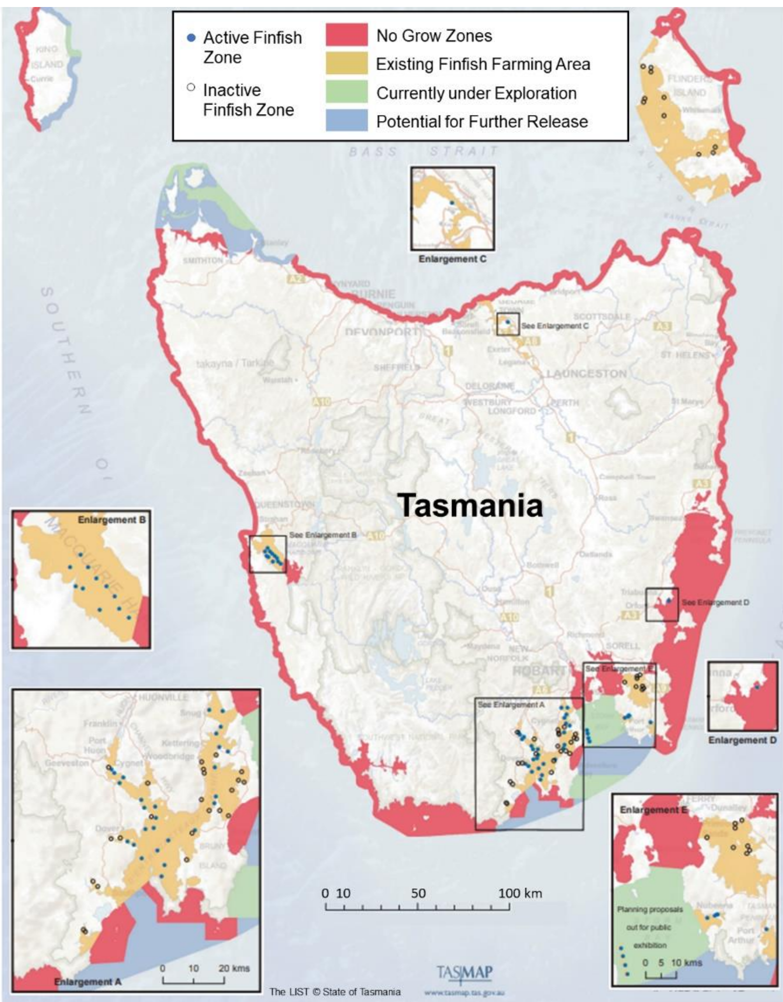

Figure 4. Proposed 'grow' and 'no grow' areas outlined in Tasmania's "*Sustainable Industry Growth Plan 2017*" (Tasmanian Government, 2017).

Additionally, in 2021, a project in Tasmania conducted a statewide assessment of the biophysical suitability (Table 1) for finfish aquaculture. This assessment identified areas for potential aquaculture development (Lacharité et al., 2021), in the context of wider spatial planning across multiple activities in the marine environment (Ross et al., 2020). In Queensland, the State Government also established nine aquaculture development areas for 'land-based marine aquaculture'[7] using a combination of physical, environmental, and planning criteria (State of Queensland, 2018).

[6] From advice provided by government and industry.

[7] Suitable for the culture of marine species like shrimp and finfish (e.g., barramundi, cobia) in earthen ponds with access to seawater.

2.4 Finland

In accordance with Finland's Aquaculture Strategy 2022, a National Location Management Plan outlines criteria guiding the determination of suitable areas for aquaculture, which includes the need to combine broad environmental and socio-economic considerations (Gray, 2019). Adoption of the National Location Management plan is voluntary, and thus SSA is developed and applied on a regional basis; for example, in South-West Finland (Figure 5). Researchers at the Natural Resources Institute Finland have developed a spatial tool (FINFARMGIS) to identify areas which are best suitable for fish farming. The application has been used by local planners and companies to determine optimal locations for farms prior to applying to the permitting process (Natural Resources Institute Finland, n.d.).

Additionally, in 2020, Finland adopted a Maritime Spatial Plan 2030 outlining 'significant and potential' areas for multiple coastal and marine uses, including aquaculture (European MSP Platform, 2022). Potential areas for aquaculture were using FINFARMGIS considering eight environmental criteria, one economic criterion, and two social criteria (See also Section 3.3, Table 1).

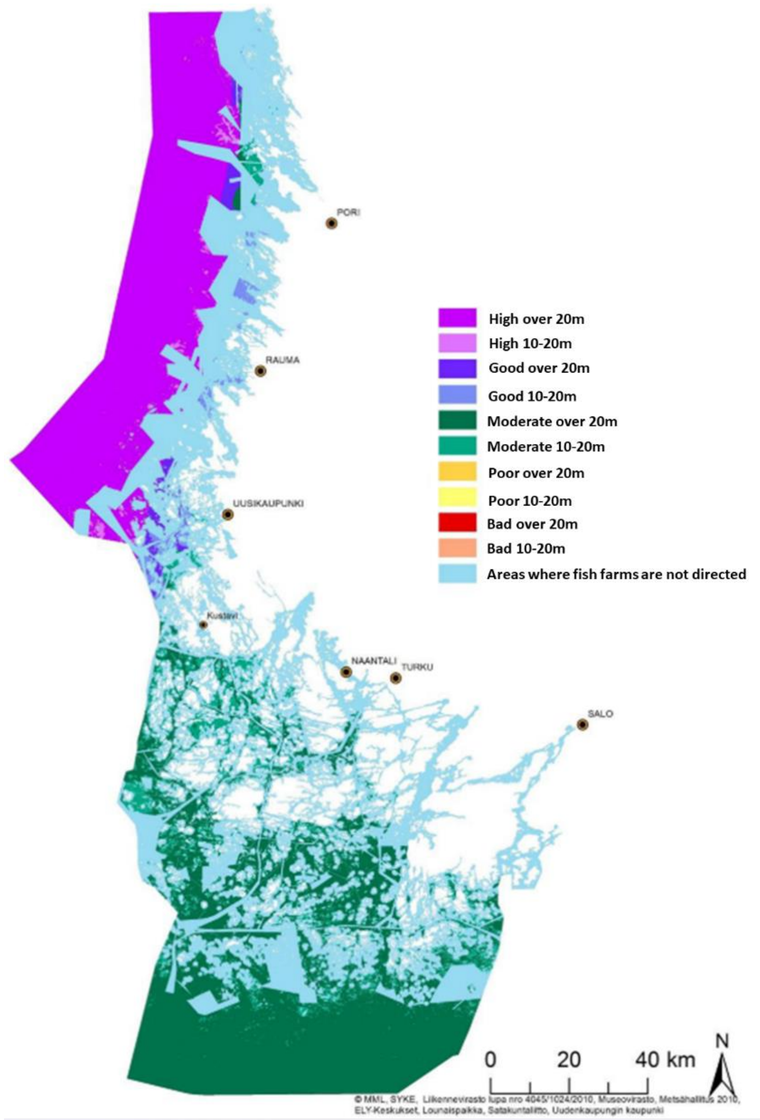

Figure 5. Suitable areas for aquaculture in South-West Finland (Setälä et al., 2012).

3 Spatial Suitability Analysis Applications

3.1 Motivations and Decision-Making Applications

Spatial Suitability Analysis (SSA), including the relevant Geographic Information System (GIS) and Multicriteria Decision Analysis (MCDA) tools been used for site selection and aquaculture planning for multiple culture systems and species globally (See Section 2). SSA can provide planners and industry with products, data, and decision-support tools to identify potential areas of interest, which may be used by government for planning and licensing processes and industry to identify and test growth opportunities. The outputs of SSA are also easily incorporated into interactive online mapping tools that allow various end users, including the public and other interest holders to explore suitability results, as has been done in Norway (Directorate of Fisheries, n.d.), Scotland (Scottish Government, 2022), and England (MMO, 2019a).

In most jurisdictions, SSAs were conducted in the context of informing sector development and expansion. For example, the Norwegian TLS was established largely to meet the national goal of expansion of aquaculture following a 2012 report anticipating a five-fold expansion of the industry by 2050 (Olafsen et al., 2012). In some countries, area classification systems have been mobilized to identify regulatory aquaculture development zones or areas allocated for the growth / expansion (e.g., Australia and United Kingdom). These applications were predominantly guided by biophysical and economic considerations, to meet national or regional goals of sector expansion.

Some SSA applications aim to reduce environmental risk to surrounding marine systems as a guiding principle in their licensing and development processes. In Scotland and Norway, SSA applications are used directly in the aquaculture licensing process, guiding conditions by which expansion (either through physical or production growth) of existing sites or licensing of new sites can proceed. In these applications, constraints are set for areas identified as less suitable, aiming to restrict industry development in areas that are environmentally unsuitable or have greater risk of impacting the environment.

Several jurisdictions acknowledge the relevance and benefits of developing SSA applications for aquaculture planning, zoning, and site selection, but are in early stages of development and implementation. For example, in Canada and Chile, the development of a classification system for aquaculture based on the suitability of the marine environment has been identified as an important policy objective (Doelle and Lahey, 2014; Soto, 2022). The European Commission also acknowledges the importance of spatial planning for aquaculture, which is considered a key issue outlined in the 2013's "*Strategic Guidelines for Aquaculture*" (European Commission, 2013). As a result, spatial suitability exercises have been investigated in several European countries including Portugal and Spain (Vaz et al., 2021), Italy (Porporato et al., 2020), Scotland (Falconer et al., 2013), and Germany (Gimpel et al., 2018), although these applications are not formally integrated into government zoning or planning processes.

Spatial suitability analysis has also been integrated as a part of larger spatial planning projects, such as in Finland's Maritime Spatial Plan (European MSP Platform, 2022) or as a deliverable of the European COEXIST project (COEXIST Project, 2022) aimed at providing a roadmap for the integration of aquaculture and fisheries with other coastal zone activities (Stelzenmüller et al., 2013). Regardless of the intent of spatial analysis (i.e., sector expansion, coastal marine planning, or siting), these tools can inform decision-making by identifying potential areas of suitability for sustainable development and management of aquaculture.

Yet, whether the outputs of SSA applications have been effective in meeting their underlying motivations remains complex and poorly understood. The opinions and responses by government, industry and public to SSA applications are not widely available, but what exists suggests variability in the perceived acceptance and legitimacy of implemented SSA applications. For example, Norway's TLS system has been scientifically and politically controversial (Berge, 2020; Hersoug, 2022), with skepticism over the objectivity and over-reliance on a single indicator, in addition to industry sentiments that the TLS is key barrier to further production growth in Norway (Dennis and Taranin, 2020). Still, most SSA systems are relatively new (implemented in the last five years), and so industry development and expansion goals have largely still yet to be realized. Evidence from local applications of SSA decision support tools suggests that SSA can be effectively used by industry to identify optimal sites for development (e.g., Nordic Trout in Finland) and by communities investigating business opportunities in their area (e.g., Uusikaupunki, Finland) (Natural Resources Institute Finland, n.d.).

3.2 Methods Used

The majority of SSAs employ a form of MCDA[8] to determine the relative suitability of locations for aquaculture, based on multiple criteria (Box 1). MCDA generally aims to calculate the suitability of multiple cells within a larger area (i.e., grid), which can effectively be mapped using GIS software.

Box 1. General steps involved in MCDA:

1. Define objective and/or problem
2. Define desired criteria (factors and constraints)
3. Identify relevant data layers (e.g., parameters)
4. Reclassify parameters on a scale from unsuitable to most suitable
    - This is often done on a scale with multiple discrete categories, or on a continuous scale from 0 to 1
    - Constraints are often 0 or 1
5. Define weights for the parameters (i.e., ranking in relation to their relevance)
6. Calculate suitability layer by combining parameters, often using a linear equation

SSA often requires two types of criteria, including factors and constraints. Factors are criteria which enhance or diminish the suitability of an area by varying degrees and are often calculated as continuous values that can be categorized into different suitability levels. Constraints, such as coastal buffer or exclusion zones, are criteria which serve to limit areas for aquaculture. Constraints are Boolean, in that they are either possible or not, and are often classified as a "0" (exclusion) or "1" (included).

[8] Also referred to as Multi-Criteria Evaluation (MCE)

Reclassification of criteria into numerical scales is necessary for combining data and determining final suitability in a process known as standardization. Standardization into suitability classes is predominantly done through user-defined categories with hard boundaries (Gimpel et al., 2018), or through gradual suitability scales (continuous) (MMO, 2019b; MMO, 2020). Many SSAs categorize data into two[9] or three[10] discrete levels that can provide decision-makers with easily applied suitability ratings, while a broader number of categories (e.g., five in Finland's FINFARMGIS model) can provide more flexibility to allow for variability and uncertainty in the data.

Defining weights for the parameters is critical for MCDA and is proportional to the reliability and importance of each parameter. Yet, weighting has not always been applied in existing SSAs, especially where suitability relies on a single criterion or data layer (e.g., Norway and Scotland). Additionally, many exploratory SSA applications exclude weighting (Falconer et al., 2013; Porporato et al., 2020), recognizing the need for weighting to be a participatory process, and one based on transparent, sound science-based evidence.

Alternatively, parameters may be simply added or multiplied linearly (Falconer et al., 2013). For example, in England, classified layers were overlaid, with the final suitability index (between 0 and 1) calculated as the number of 'optimal' criteria divided by total number of criteria, with grid cells containing any unsuitable criteria given a "0" rating (Figure 6). Selection constraints can also be merged into a single data layer representing the addition of all constraint parameters, which then gets superimposed with other suitability layers (Porporato et al., 2020). Selection constraints are thus not commonly incorporated to SSAs through weighting process but included after suitability ratings are aggregated. Rather, the final suitability applications and maps often visualize only constraint-free areas.

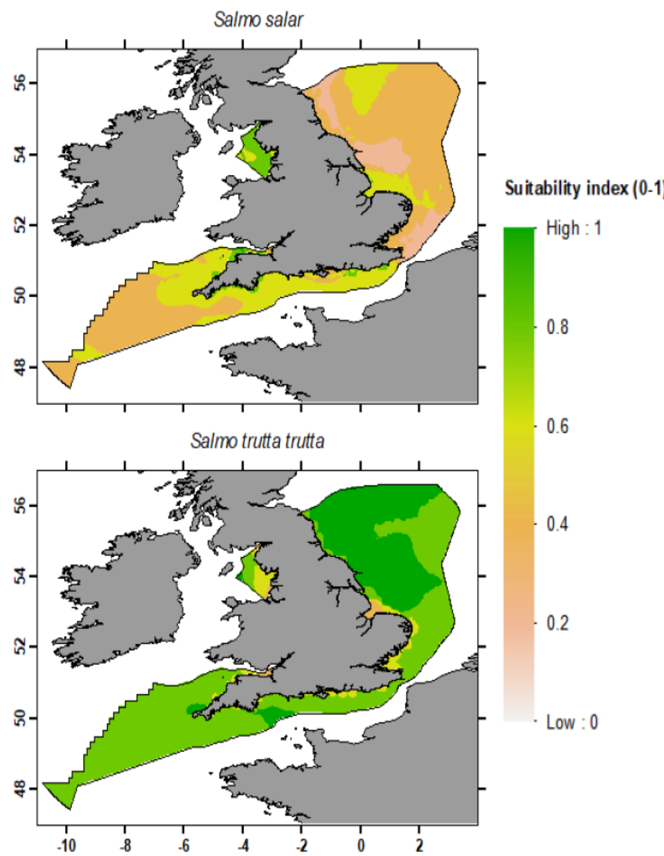

Figure 6. Suitable areas (optimal and suboptimal combined) identified for growth of two salmonid species in England (MMO, 2019b).

[9] Such as dividing areas into 'grow' or 'no grow' areas in Tasmania
[10] As applied in Norway and the United Kingdom

3.3 Criteria and Parameters

SSA presents a useful method for decision-makers and industry to evaluate multiple criteria to address both environmental and socio-economic objectives for aquaculture management and development (Table 1). Largely motivated by national and regional expansion goals, SSAs have focused predominantly on biophysical and environmental parameters outlining requirements for fish production and protecting environmentally significant areas. A few jurisdictions (England, Australia, and Finland) also consider social criteria which include multiple human uses of marine areas like recreation and capture fisheries. In addition, few jurisdictions also consider infrastructural constraints (i.e., accessibility considerations incorporating parameters like distance to infrastructure and exposure risk). Constraints often include governance / regulatory considerations to prevent overlap with other marine uses (e.g., shipping lanes) or ecologically significant areas (e.g., Marine Protected Areas).

Biophysical criteria are the most frequently applied as standardized factors, dividing parameters into distinct suitability classes. Conversely, other criteria rely more on buffer zones and exclusion constraints. Many parameters, with the notable exception of growth suitability criteria, are included through distance-based considerations, such as classifying appropriate distances to specific features, or excluding buffer zones based on an assigned distance like proximity to ecologically important areas or marine structures (i.e., submerged pipelines). In a few jurisdictions, the suitability of criteria is designated based on a more complex process including multiple models, data, and expert assessment (e.g., Scotland and Norway). This is commonly applied for environmental sustainability and sensitivity considerations, incorporating environmental carrying capacity estimations and indices.

Table 1. Criteria applied to area classification systems in select jurisdictions globally.

Type of suitability	Criteria - Qualitative goals	Data layers	Suitability values (and rating)	Application
Biophysical	Environmental sensitivity	Combined 'nutrient enhancement' and 'benthic impact' indices*	7-10 (1), 5-6 (2), 0-4 (3)	Scotland [1]
	Critical habitat - Protect environmentally significant areas	Distance to high biological areas (km)	Buffered by 1 km (exclusion)	Tasmania [2]
		Fish nursery and spawning areas	100 m buffer herring spawning grounds (exclusion)	Finland [3]
			Graduated score between 0 and 1	England [4]
		Sensitive benthic habitats	low pressure (0.5), medium pressure (1), high pressure (2)	England [5]
		Distance to bird islands (m)	25 – 100 (1), 100 – 200 (2), 200 – 300 (3), 300 – 500 (4), > 500 (5)	Finland [6]
		Distance to underwater reefs (m)	> 100 (1), 100 – 200 (2), 200-300 (3), 300 -500 (4), > 500 (5)	Finland [6]
		Distance to ecologically valuable areas (m)	> 100 (1), 100 – 200 (2), 200 – 300 (3), 300 – 500 (4), > 500 (5)	Finland [6]
	Growth suitability - Meet biophysical requirements for growth of finfish	Water temperature (°C)	> 22 (0), 21-22 (1), 20 – 21 (3), 19 – 20 (4), 18 – 19 (7), < 18 (9)	Tasmania [7]
		Water depth (m)	> 10 (0), 10-15 (3), > 40 (9)	Tasmania [7]
			25-50 (Optimal), 10-25 (Sub-optimal), >50 or < 10 (Not suitable)	England [8]
			<20 and >50 excluded	England [5]
			15-50 (1), < 15 and >50 (0)	Scotland [9]
			< 10 (0)	Finland [3]
			< 5 (1), 5 – 10 (2), 10 – 15 (3), 15 – 20 and > 50 (4), 20 - 50 (5).	Finland [6]

Type of suitability	Criteria - Qualitative goals	Data layers	Suitability values (and rating)	Application
Biophysical (cont'd)	Growth suitability (cont'd)	Current speed (m/s)	<0.01 (0), 0.01 – 0.02 (1), 0.02 – 0.04(3), 0.04 – 0.08 (5), 0.08 – 0.2 (7), >0.2 (9)	Tasmania [7]
			0.25 - 0.5 (Optimal), 0.02 - 0.25 or 0.5 - 0.75 (Sub-optimal), < 0.02 or > 0.75 (Not suitable)	England [8]
			0.025 - 0.8 (1), > 0.8 (0)	Scotland [9]
		Current speed (cm/s)	< 5 (1), 5 – 7.5 (2), 7.5 - 10 (3), 10 – 15 (4), > 15 (5)	Finland [6]
		Significant wave height (m)	>11 (0), 9 – 11 (1), 7 – 9 (3), 5 – 7 (5), 3 – 5 (7), <3 (9)	Tasmania [7]
			0 - 3.5 (1), > 3.5 (0)	Scotland [9]
			<9 (Optimal), 9 (Not suitable)	England [8]
		Substrate type	Suitability ranking between 0 and 1 for different types	Scotland [9]
			Coarse sediment, Sand, Sandy mud, Muddy sand, Fine mud (Optimal), Mixed Sediment, Rock and Hard seabed (Sub-optimal)	England [8]
	Potential disease exposure - Environmental sustainability	Lice-induced mortality in wild salmonids (%)*	< 10 (Green), 10-30 (Yellow), > 30 (Red)	Norway
		Distance from existing fish farms (m)	< 100 (1), 100 - 500 (2), 500 - 1000 (3), 1000 - 2500 (4), > 2500 (5)	Finland [6]
Socio-economic	Suitability for recreation - Maintain recreational activities	Coastal accessibility to beaches, marinas, wharves, boat ramps (km)	>20 (3), 10 - 20 (5), 5 - 10 (7), 0 -5 (9)	Tasmania [2]
		Recreational boat launches	Buffer 500 m	England [4]
		Recreational boat intensity (AIS)	Graduated score from 0 to 1	England [4]
		Fishing hotspots	Other (5), Reef areas (9)	Tasmania [2]
		Maximum significant wave height (m)	>3 (3), 2-3 (5), 1-2 (7), 0-1 (9)	Tasmania [2]

Type of suitability	Criteria - Qualitative goals	Data layers	Suitability values (and rating)	Application
Socio-economic (cont'd)	Lifestyle and cultural - Minimize noise and light pollution	Distance to residential buildings (km)	1 km buffer (exclusion)	Tasmania [2]
		Distance to summer homes (m)	500 m buffer (exclusion)	Finland [3]
		Density of summer cottages (per km^2)	Over 50 (1), 15-50(2), 5-15(3), 1-5(4), none (5)	Finland [6]
	Sea visibility	Sea visibility from land	Graduated score between 0 and 1	England [4]
	Capture fisheries - Reduce fishery use conflicts	Fishing intensity	Graduated score between 0 and 1	England [4, 5]
	Existing human uses - Prioritize existing human water uses	Shipping and boating routes	Routes and their buffers (exclusion)	Finland [3]
		Shipping lanes	Exclusion	England [4, 5]
		Excluded areas	National parks, government and private protected areas, seal conservation areas, military areas, protected wrecks, navigation routes and areas (exclusion)	Finland [6]
Infrastructural	Functional distance - Accessibility to infrastructure	Distance from shore (km)	0 to 20 (1), >20 (0)	Scotland [9]
			> 20 (1), 15-20 (2), 10-15 (3), 5-10 (4), under 5 (5)	Finland [6]
			< 6 (Optimal), 6 to <30 (Sub-optimal), >30 (Not viable)	England [4]
	Exposure - Navigational and environmental risks due to exposure	Wave exposure grid	Classification: Extremely sheltered, sheltered, open, extremely open.	Finland [6]
		Combined energy* model using wave, wind, current velocity, and turbulence	High energy areas (Exclusion)	England [5]
Type of suitability	**Criteria - Qualitative goals**	**Data layers**	**Suitability values (and rating)**	**Application**

Governance/ regulatory	Conservation goals - Protect environmentally significant areas	Existing marine conservation areas/protected sites	Exclusion	Tasmania [2]
			250 m buffer zone (exclusion)	England [5]
			Presence (0) or absence (1)	England [4]
		National parks	Exclusion	Finland [6]
		Bird areas	500 m buffer zone of protected areas during nesting period (exclusion)	Finland [6]
			Areas with more than 1 seabird species (constraint 1)	England [5]
	Historic sites	Protected shipwrecks	100 m buffer (exclusion)	Finland [6]
			Exclusion	England [5]
		Wrecks, debris, and paleolandscapes	500 m buffer	England [4, 5]
	Legislative boundary	Distance from shore (NM)	> 3 NM (exclusion)	England [5]
	Existing aquaculture	Existing sites	Exclusion	England [5]
	Resource structures	Oil and gas structures (platforms and well heads)	Buffer 500 m (exclusion)	England [5]
			Buffer 100 m (exclusion)	England [4]
		Nuclear power stations	Buffer 500 m (exclusion)	England [4]
		Surface/sub-surface infrastructure	Buffer 200 m (exclusion)	England [4]
		Underwater cables and pipelines	Buffer 250 m (exclusion)	England [5]
			Buffer 500 m (exclusion)	England [4]
		Offshore wave and tidal developments	Exclusion	England [4,5]

[*] Values and subsequent suitability rating draws from multiple datasets and methods such as models, risk assessment, expert judgement etc.

[1] Gillibrand et al. (2002) ; [2] Ross et al. (2020); [3] Setälä et al. (2012); [4] MMO (2020); [5] MMO (2013b); [6] FINFARMGIS-Niskanen (2018); [7] Lacharité et al. (2021); [8] MMO (2019b); [9] Falconer et al. (2013)

4 Considerations and Implications of Applying SSAs

4.1 Scope and Scale of SSAs

SSA enables the integration of multiple potentially diverse parameters, generating outputs that are useful for planners, managers, and investors across a range of criteria. While criteria can be combined for the final output, individual criteria can also be visualized in isolation, providing intrinsic value to the end-user as well (MMO, 2013a). Yet, many existing SSAs only incorporate a limited set of criteria, emphasizing biophysical factors and governance constraints. Most apply distance-based parameters, and only few jurisdictions use complex models that calculate measures of relative pressure or risk on the environment in some form of environmental carrying capacity estimation (e.g., Scotland and Norway). Economic benefits has been previously considered during suitability analysis but limitations and availability of input data inhibited its application in England's final SSA (MMO, 2013b). Other important criteria for decision-making, like multi-use conflicts and cultural values have been difficult to quantify, and thus not well incorporated into SSA. Only within the last couple of years have SSA applications assigned suitability scores for social criteria (MMO, 2020; Lacharité et al., 2021). Typically, key areas for recreation or commercial fisheries are identified and certain distance-based parameters are established to define suitability or set exclusion areas. So far, measures of social values relevant to discussions around social carrying capacity have not been explored within SSA applications.

Many SSA applications are constrained to high-level decision-making due to their relatively low spatial resolution, providing a single suitability metric for a region or bay (e.g., Norway and Scotland). This is often done when the areas for analysis are pre-determined through policy processes. For example, the Scottish government's categorization system only includes select sea-lochs and does not extend to include all coastal Scottish waters. Few SSAs (Norway and Scotland) include procedures for regular updating of classification ratings, enabling a dynamic and adaptable system useful for guiding aquaculture management decisions. Reducing the spatial resolution and number of criteria considered, can decrease the computational complexity of the SSA and minimize the information and data required during re-evaluations. However, coarse spatial resolutions may not adequately consider local-scale dynamics and variations that drive some parameters (Posen et al., 2020).

SSA applications are challenged with adequately balancing political, scientific, and practical considerations in the selection of criteria and parameters. Limiting the number of criteria can reduce complexity and avoid potential weighting limitations (see Section 4.3) but may not reflect multiple dimensions of sustainability or provide an overly simplistic model of the environment. Furthermore, selection of relevant criteria may be biased by data availability or swayed by political priorities. For example, Norway's TLS indicator was largely tied to policy decisions that prioritized reducing sea lice interactions with wild salmonids (Bailey and Eggereide, 2020). In the creation of the TLS system, some interest holders criticized the lack of consideration for social sustainability, raising concerns that the process was swayed by environmental goals over industry development considerations (Michaelsen-Svendsen, 2019).

4.2 Adapting to New and Changing Information

A major benefit of using GIS and MCDA in SSA applications is the ability to incorporate new or updated data / information as they become available, to create new suitability maps. Where SSAs are incorporated into planning or management guidelines (e.g., Norway and Scotland), areas can be effectively re-classified as new information changes or becomes available[11]. Both Scotland and Norway have systems in place for regular review and updating of area suitability classifications, which is necessary for incorporating SSA analysis into management and site selection processes. Yet, many SSA applications conducted as part of broader identification of aquaculture development zones are often static, 'one-off' maps at a given point in time, and often do not have formal processes to adapt zones based on changing information. Furthermore, there is little evidence of considerable changes in the classification of parameters used. For example, an evaluation of the scientific validity of Norway's TLS system recommends regular reassessment of the mortality thresholds used, in part due to lack of empirical basis for thresholds (Eliasen, 2021).

4.3 Data Challenges and Constraints

The usefulness of the SSA often depends on relevance, completeness, and resolution of datasets. Data may not always be 'fit-for-purpose'[12] and thus unable to be incorporated in SSA (Box 2). Required datasets may be unavailable, dated, or in unsuitable formats (e.g., qualitative or descriptive). For example, the use of vector data (points or lines) in SSA can underrepresent an actual area occupied or being used and so data layers should ideally be expressed as polygons (MMO, 2013b). In addition, the most useful data layers are those that can be reclassified on a continuous scale for suitability analysis. However, not all data can be easily grouped into continuous scales, and there may be data limitations in having the scientific knowledge to assign suitability categories to data. Furthermore, the availability and spatial resolution of underlying datasets can be variable, which can result in a loss of precision when multiple criteria are aggregated (a constraint recognized in MMO (2020)).

Box 2. Data challenges involved in SSA development

- Descriptive nature of data
- Unsuitable data types used to describe data
- Adequate spatial coverage of data
- Scale or resolution is too coarse
- Knowledge gaps and uncertainties
- Change and variability of criteria

Lack of access to adequate data, the inherent variability of parameters, and changing environmental and / or social contexts can all add uncertainty to SSA calculations and outputs. For example, in England's 2019 SSA exercise, interpolation of data or indirect observational data was often required to generate full spatial coverage of suitability (MMO, 2020), suggesting variability in the quality of data across areas. Properly handling uncertainty of SSA methods and data becomes critical in ensuring the legitimacy of SSA systems (Eliasen, 2021). In addition,

[11] Areas are re-assessed every two years in Norway and every three months in Scotland

[12] i.e., did not represent the feature or criteria sufficiently

communication of uncertainty is essential for policy makers and end-users to understand how suitability was calculated and effectively use the outputs in decision-making.

Furthermore, the number of criteria and the process of weighting selected can affect the relative influence of individual criteria and subsequently influence the complexity of outputs. Applying variable weights to criteria has been applied in some exploratory research (Porporato et al., 2020; Lacharité et al., 2021; Vaz et al., 2021) but not commonly applied to existing SSAs. Exploratory research emphasizes that selecting weights in a variable weighting process requires input from scientific literature and carefully designed participatory processes that consider the role and influence of different decision-makers and interest holders. The process of assigning variable weights to multiple criteria also has limitations since the overall score may be less sensitive to changes in lower weighted criteria. Thus, most implemented SSAs within policy processes apply equal weighting to criteria or are based on a single parameter and subsequently do not requiring weighting. However, even with equal weighted criteria, inclusion of additional criteria can reduce the contribution of individual parameters to the overall score (Figure 7), potentially diminishing the influence of nominally more important variables. Alternatively, addition of more parameters may have little influence on suitability scores despite added computational complexity. Therefore, models must carefully balance inclusion of most relevant parameters and complexity required for given decision-making purposes.

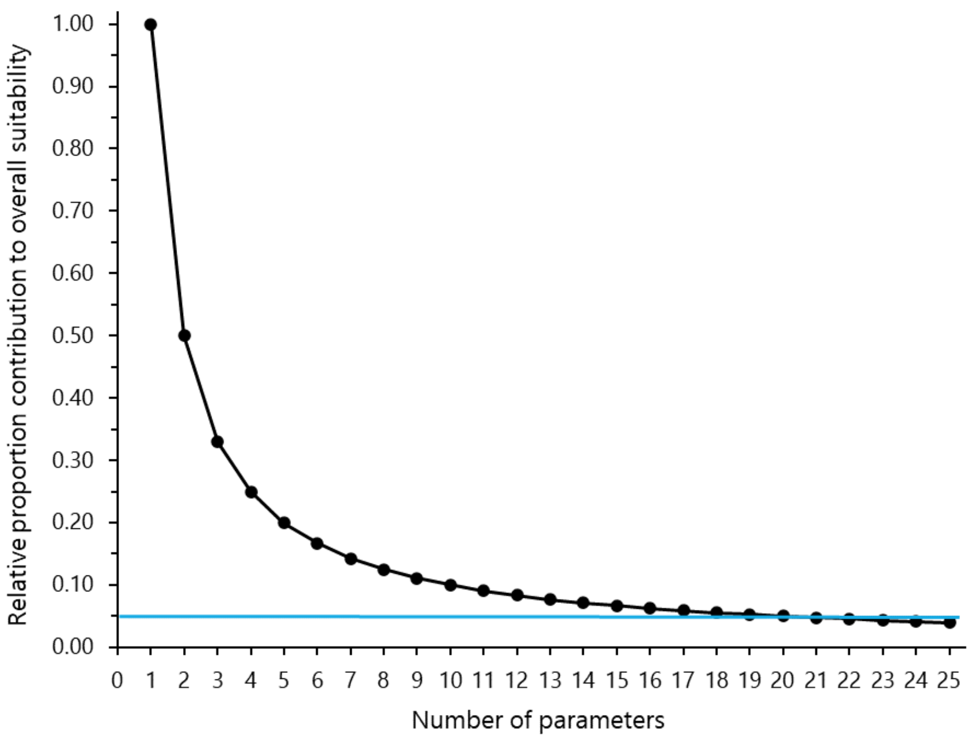

Figure 7. In an equal weighting process, as number of parameters increase, the proportion of each parameter to the overall suitability score decreases. At 20 or more parameters, each would contribute 5% or less to the overall score (as indicated by the blue line).

5 Conclusion

Current SSA applications for finfish aquaculture are only incorporated into mandatory licensing / leasing or management processes in a few jurisdictions. Rather, most current SSA applications and tools are largely still in development, with many jurisdictions actively conducting large research projects to identify suitable areas for aquaculture development and management. The criteria, suitability scales, and weights included in SSA will depend on the objectives, policy goals, and information available for the given area. Key decisions on the method of standardization, whether criteria are included as selection factors or constraints, the total number of criteria and the weighting process are critical in determining the output of the SSA. Finally, managing uncertainties in the data will also be important to incorporate the confidence of datasets and potentially add flexibility and adaptability to new information or changing criteria.

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