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Identification of North Sea areas suitable for cultivating *Saccharina latissima* as an alternative source of protein

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Abstract

Demands for food resources are increasing with the growing human population and the impacts of climate change on agricultural land. Protein is an essential macronutrient for human well-being and supplies are likely to face a global security crisis in the foreseeable future. However, research has shown that the brown seaweed species *Saccharina latissima* (*S. latissima*) could be an alternative plant-based source of protein for human consumption that can be sustainably farmed under North Sea conditions. Yet seaweed farming currently remains an underexploited resource in the United Kingdom (UK). This study aims to identify areas suitable for *S. latissima* cultivation in the exclusive economic zone of England's North Sea, to help decision-makers adapt to challenges in finding sustainable ways to feed the population. A multi-criteria decision analysis was used to identify twenty planning, technical and environmental constraint variables and their criteria for developing an *S. latissima* aquaculture site. The integrated methodical approach then used a geographical information system to perform a Boolean modelling technique that spatially mapped out constraints across the study area to create a suitability map. Results identify and illustrate the whereabouts of ~2.05 million hectares (~20,500km^2) in the English North Sea that have the capacity for *S. latissima* cultivation. Findings conclude there is enough scope within the established Boolean areas for *S. latissima* yields to make meaningful contributions towards the UK's protein supply. However, analysis indicated that *S. latissima* should be regarded as a high-quality food source rather than being viewed solely for potential protein content. It is recommended that future work investigates the Boolean areas in further detail by adding a weighted suitability overlay to identify between suitable and optimal areas for *S. latissima* aquaculture, which will strengthen site selection decision-making.

Keywords: Aquaculture, Boolean, cultivation, GIS, macroalgae, MCDA, North Sea, plant-based protein, Saccharina Latissima, seaweed, site selection, sugar kelp, sustainability, UK.

Introduction

Project rationale: Global food security challenges

Agricultural land, climate change and resource demands

A staggering 50% of Earth's habitable land is used to produce food for human consumption (Roser *et al.,* 2019). These agricultural practices are contributing towards the acceleration of climate change (Carter *et al.,* 2017). Meanwhile, climate change is diminishing the yields from agricultural practices (Malhi *et al.,* 2021). This relationship is subsidising a network of positive feedback loops that are pushing climate change towards a threshold whereby any human intervention to reverse consequences will be trivial (IPCC, 2021).

The increased magnitude and frequency of extreme weather events have conspicuously changed previously stable seasonal cycles and decreased the fertility of agricultural land or destroyed it completely (Qiu *et al.,* 2022; Cogato *et al.,* 2019). This is challenging farmers to plan harvests and produce high yields impacting food security and socio-economics on a global scale (Mbow *et al*., 2019). The deterioration of agricultural productivity is also being amplified by increasing occurrences of saltwater inundation in coastal regions, due to flooding caused by sea level rise (Lindsey, 2022; Duarte *et al*., 2020; Spencer *et al*., 2015) which is reducing the quality of agricultural soil (DEFRA, 2022).

Since 2005 the global population has been rising by approximately 83 million people per year and the United Nations (2019) anticipates figures to reach 8.6 billion by 2030, and 9.8 billion by 2050. In addition, long-term trends show growth in the global gross domestic product (FAO, 2021) which correlates to a growing consumption of resources (Alper, 2018). Including the global per capita daily energy and protein intake (Roser *et al*., 2019) (figure 1), which is further increasing the pressure on food supplies to meet their demand. This is concerning as the world will need 60% more food by 2050 assuming there is no reduction to the current amount of food waste (FAO, 2012).

Bottom-up consumer food demands

Debating which food source is a better or worse burden on the environment is subject to conscious and subconscious bias and can be assessed from many different perspectives (Murphy, 2020). However, as the landmass available for agriculture is shrinking and becoming increasingly unreliable, a workable solution could be to sustainably utilise the ocean's resources to produce an alternative source of protein (Cicin-Sain, 2015). Moreover, it is agreed that primary productivity supports the metabolic requirements of every species above in the food chain and that 90% of energy is lost when transferred to the next trophic level (only 10% is converted into biomass) (Eddy *et al*., 2021). Therefore, transfer inefficiency problems arise. However, if people replaced the consumption of higher trophic levels with primary producers' energy could be conserved (Eddy *et al*., 2021).

Recent decades have brought demands that would support this transition towards protein alternatives to dairy, meat, and fish, as shown in figure 1 which illustrates a growing consumption of plant-based protein in the UK.

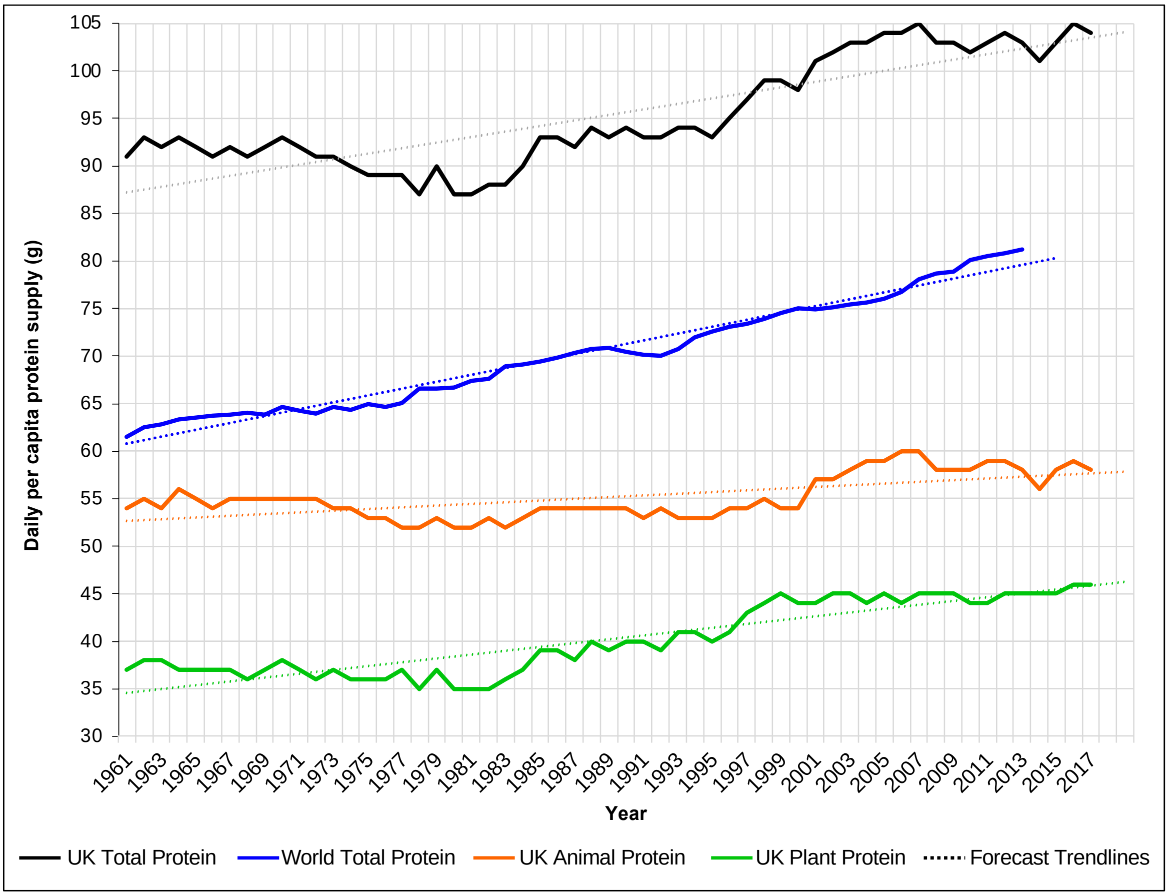


Figure 1: Daily per capita protein supply, measured in grams per person per day. This figure illustrates time series data of the origin (animal or plant) of the UK's per capita protein supply, along with the total (animal and plant combined) daily protein supply for the UK and world. Animal protein includes protein from all meat commodities, eggs, dairy products, fish, and seafood. Data was acquired from the FAO (2018).

For instance, the number of vegans living in the UK was ~600,000 in 2019 which was a 300% increase from 2014 (Howard, 2021). Additionally, 14% of UK adults currently follow a meat-free diet and the number of omnivores eating meat-free meals is also increasing (Nilsson, 2019). Protein extraction using an environmentally sustainable yet feasible method that complies with a plant-based diet is required to feed this request. Yet challenges arise as although for multiple reasons including poor dietary choice anyone can develop malnourishment, people who consume plant-based diets are more susceptible to regularly lacking in essential amino acids (Kiely *et al*., 2021) and micronutrients, including iodine (Fallon *et al*., 2020; Groufh-Jacobsen *et al.,* 2020) and vitamin B-12 (Kapoor *et al.,* 2017). Furthermore, vegans may ingest higher volumes of pesticides when compared to non-vegans (Van *et al*., 2009).

However, macroalgae can contain an abundance of micronutrients and proteins (Patarra *et al.,* 2011) and its cultivation alleviates many terrestrial-based farming issues as it does not require fresh water, fertiliser or rely on arable land that could be diminished by intense precipitation and droughts (Stanley *et al.,* 2019). It may also not require pesticides; however, farm infrastructure could still utilise a form of antifouling (Zheng *et al*., 2019).

Theoretical background to macroalgae cultivation

Macroalgae

Seaweeds are benthic multicellular algae taxonomically classified based on their photosynthetic pigment combinations (Pereira, 2016). They are usually restricted to relatively shallow coastal waters as they must receive adequate sunlight to photosynthesise whilst simultaneously anchoring their holdfasts (a root-like structure) to a substrate (Yesson *et al*., 2015). Brown seaweeds can inhabit the subtidal zone as they contain dominant ancestry photosynthetic carotenoid pigments such as, xanthophyll (yellow pigment) and fucoxanthin (brown pigment, responsible for their brown characteristics), which enables them to absorb light in parts of the spectrum where chlorophyll is less efficient (O'Sullivan, 2010). This wide absorption range allows brown seaweed to grow at greater depths than green (Pereira, 2016).

Saccharina latissima

The demand for seaweed-derived products in Europe is increasing (Kim *et al*., 2017). However, harvesting seaweed is not an environmentally feasible method to meet the growing demands as wild seaweed stocks may become overexploited (Callaway, 2015). Though, seaweed aquaculture would alleviate this risk whilst yielding ecosystem services and socio-economic benefits (Buck and Grote, 2018).

Kelp (phylum Ochrophyta, order Laminariales) is a category of brown seaweed which is a dominant type of macroalgae in aquaculture, and *Saccharina latissima* (*S. latissima*) also known as Sugar Kelp, is a brown kelp species commonly spread throughout Europe (Portugal to Norway) (Stanley *et al*., 2019). It is also the most cultured European seaweed species because it has a rapid biomass growth rate (Bak *et al*., 2018; Handä *et al*., 2013), and commercially important tissue content for food applications (Stévant *et al*., 2017; Marinho *et al*., 2015). Such as, the structural carbohydrate alginic acid (a complex polysaccharide used as a stabilizer and emulsifier) (Harmsen, 2014), and the storage carbohydrate mannitol (used as a sweetener), along with containing proteins (Stanley *et al*., 2019). However, despite *S. latissima* proven to be successfully farmed under North Sea conditions (Kieckens, 2021; Broch *et al*., 2019; Van den Burg *et al*., 2013), UK seaweed cultivation remains an underexploited resource (Cai, 2021).

Cultivating S. latissima as a source of protein

There are many methods for farming *S. latissima* and depending on the farm site characteristics different approaches to spore production, seeding, harvesting and post-harvest treatment are used (Forbord *et al.,* 2020; Stanley *et al*., 2019; Blikra *et al.,* 2019). However, a pH-shift extraction method (Harrysson *et al.,* 2018) and the use of sonication and enzymes have proven to be effective methods for extracting proteins from *S. latissima* (Klyve, 2020). Furthermore, though the total protein content of *S. latissima* depends on environmental conditions, season, and processing methods (Marinho *et al.,* 2015a), *S. latissimas* protein content has shown to be highest when out planted in autumn and harvested in early spring (Bak *et al*., 2019), giving *S. latissima* the potential to be a suitable choice for producing an alternative source of protein (Pereira, 2016).

Additionally, *S. latissima* contains an abundance of iodine (Aakre *et al*., 2021), a vital mineral for the secretion of thyroid hormones triiodothyronine and thyroxine (Zimmermann, 2011; Opazo *et al*., 2020). This is significant as, a study on UK individuals following omnivore, vegetarian and vegan diets found that vegans and vegetarians had a significantly higher risk of iodine deficiency when compared to omnivores (Eveleigh *et al*., 2022). Furthermore, *S. latissima* also contains photosynthetic bioactive compounds that are absent from terrestrial plants (Brown *et al*., 2014) such as fucoxanthin, which has antioxidant and anticancer properties (Wang *et al*., 2019; Pangestuti and Kim, 2017).

Aim and objectives

This paper aims to identify suitable areas for *S. latissima* cultivation as an alternative source of protein for human consumption within England's North Sea exclusive economic zone (EEZ), an area where seaweed cultivation has potential but is currently underexploited. The outcomes of this research aim to provide a valuable decision-making tool that involves stakeholders to implement an English North Sea *S. latissima* farm, that ultimately could contribute towards sustainable protein production.

This study’s objectives to achieve the aim are:

- To examine the main requirements for *S. latissima* aquaculture.
- To identify and set appropriate criteria parameters for each requirement through a multi-criteria decision analysis.
- To conduct geographical information system (GIS) modelling to map out the parameters of each variable into constraint layers within the study area (English North Sea EEZ).
- To identify any areas that have the potential for *S. latissima* cultivation using a Boolean modelling technique and analyse the feasibility for suitable areas to produce a source of protein.

Methodology

Study procedure

The main parameters which need to be considered to determine the location for an aquaculture site include technical, planning and biological suitability variables (MMO, 2020; Buck *et al*., 2018). Every variable within these parameters was identified to evaluate if the constraint could jeopardise the instalment of an aquaculture site. Next, a multi-criteria decision analysis (MCDA) which has been approved as an effective method for geovisualisation studies (Malczewski and Rinner, 2015), was conducted to determine the relevant criteria for each factor. The selected constraints were then mapped out and overlayed using a Boolene modelling technique, which meant that only places that met every criterion were classed as an appropriate area for *S. latissima* cultivation. Then the Boolene modelling results were analysed to assess the area's potential feasibility to yield a source of protein. This study process has been depicted throughout the flow diagram in figure 2a, b, c and d.

Model description

The Boolean data logic is that there can only be two possible values (true or false) meaning that an area either is or is not suitable. Boolean modelling was the chosen technique as it has been verified as an appropriate method by other spatial analysis studies' including: Jahangiri *et al*., 2016; Eskandari *et al*., 2016; Longdill *et al*., 2008; Al-Adamat *et al*., 2010; Thomas *et al*., 2019 and Machiwal *et al*., 2015. Additionally, Boolean results will clearly illustrate areas that have or do not have a capacity for *S. latissima* farming which will reduce potential stakeholder conflicts (Eastman, 2006).

Software and materials

Scientific literature, secondary data, and GIS software were used to conduct the MCDA and map out constraints for the Boolean assessment. ArcGIS was the selected computer program as it is a powerful tool that supports input, visualisation, and modelling for spatial data (Malczewski, 2010). The data search focused on ArcGIS compatible datasets and for this data availability and cost-free access were factors that influenced the selection of datasets (table 1).

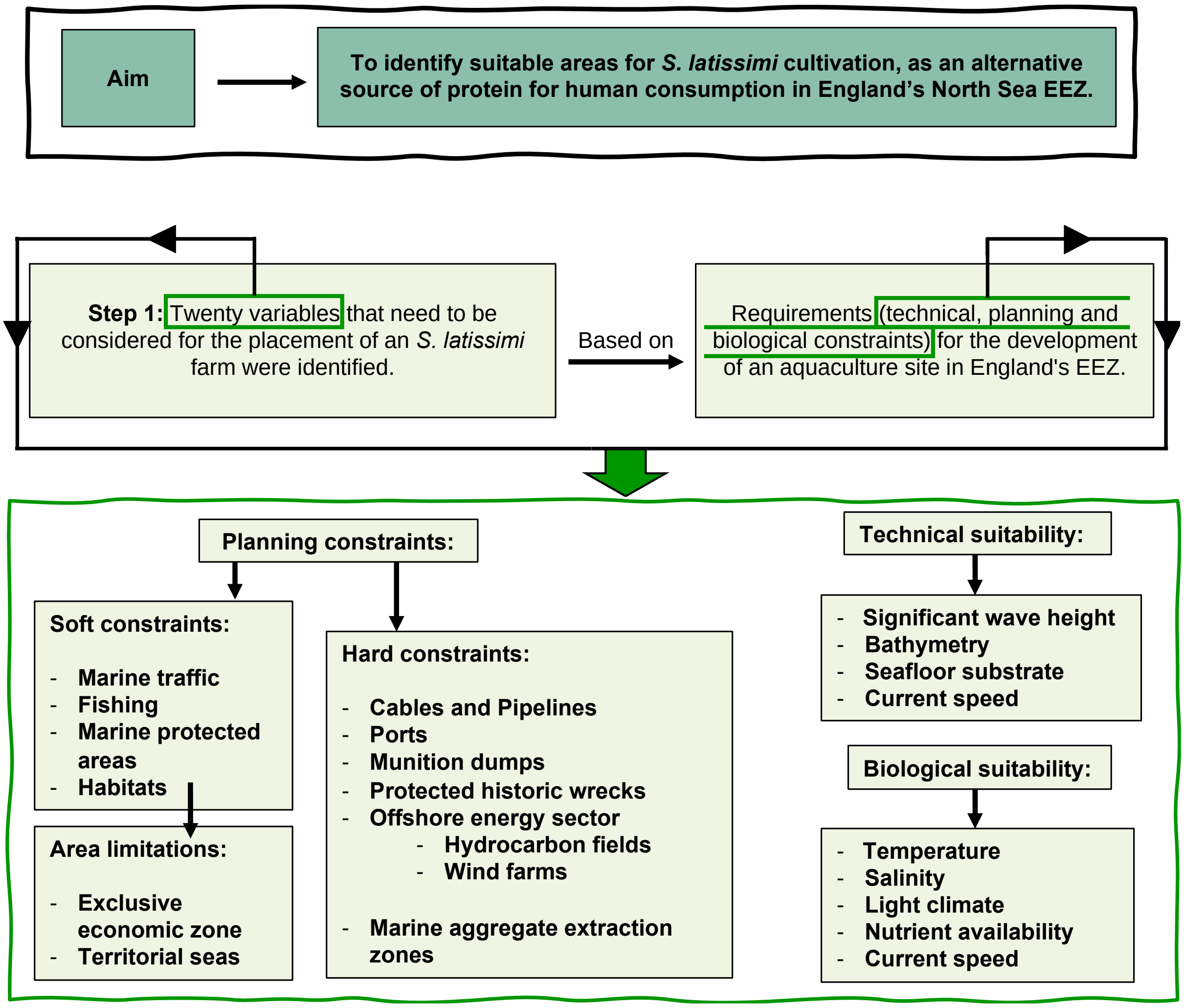
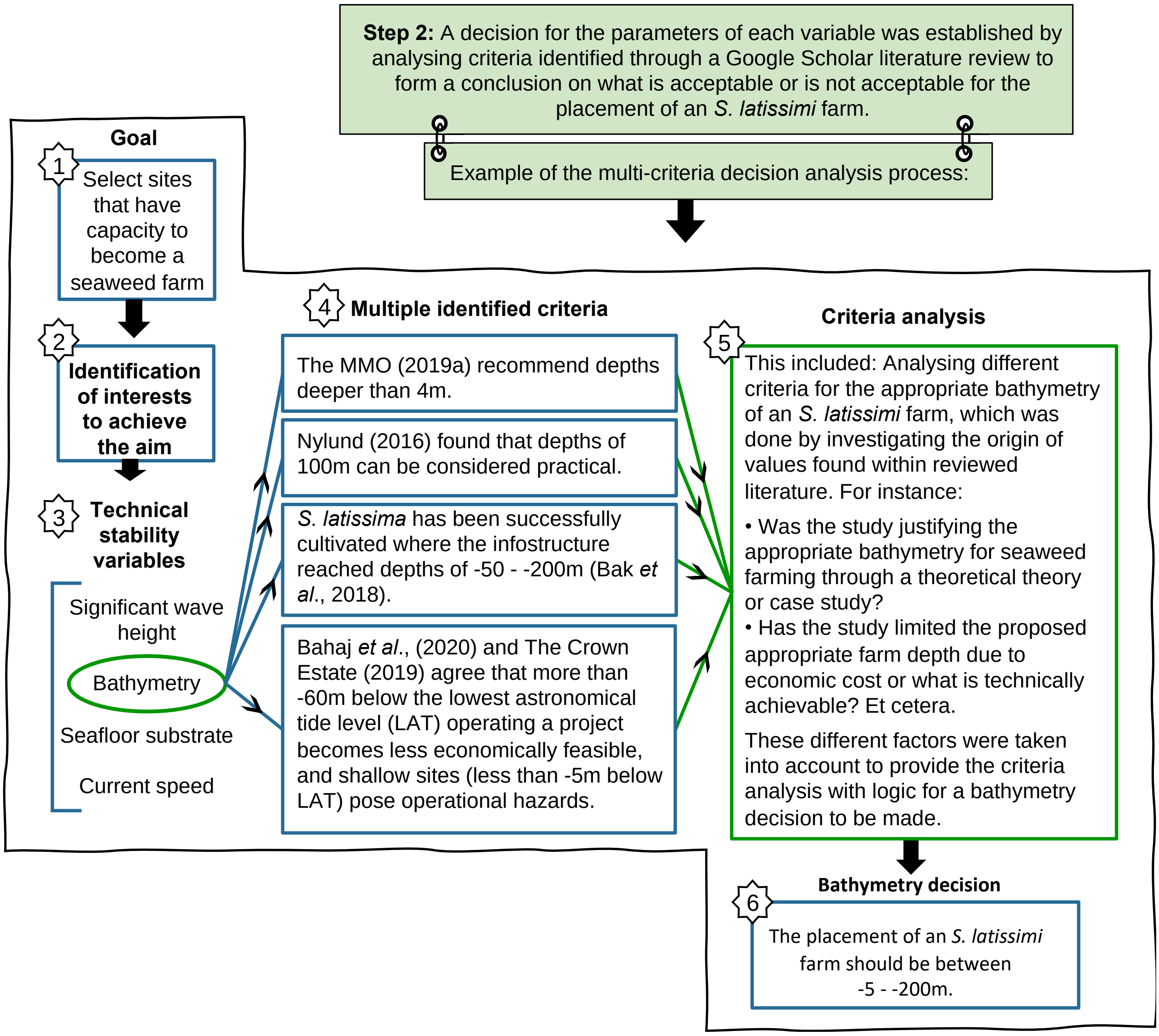


Figure 2a: Step 1, illustration of the aim and identification of variables, within the sequence of steps taken in the methodological procedure to establish the research aim. *S. latissima* refers to *Saccharina latissima*, EEZ refers to exclusive economic zone.



Step 2: A decision for the parameters of each variable was established by analysing criteria identified through a Google Scholar literature review to form a conclusion on what is acceptable or is not acceptable for the placement of an *S. latissimi* farm.

Example of the multi-criteria decision analysis process:

The MMO (2019a) recommend depths deeper than 4m.

Nylund (2016) found that depths of 100m can be considered practical.

S. latissima has been successfully cultivated where the infostructure reached depths of -50 - -200m (Bak *et al*., 2018).

Bahaj *et al*., (2020) and The Crown Estate (2019) agree that more than -60m below the lowest astronomical tide level (LAT) operating a project becomes less economically feasible, and shallow sites (less than -5m below LAT) pose operational hazards.

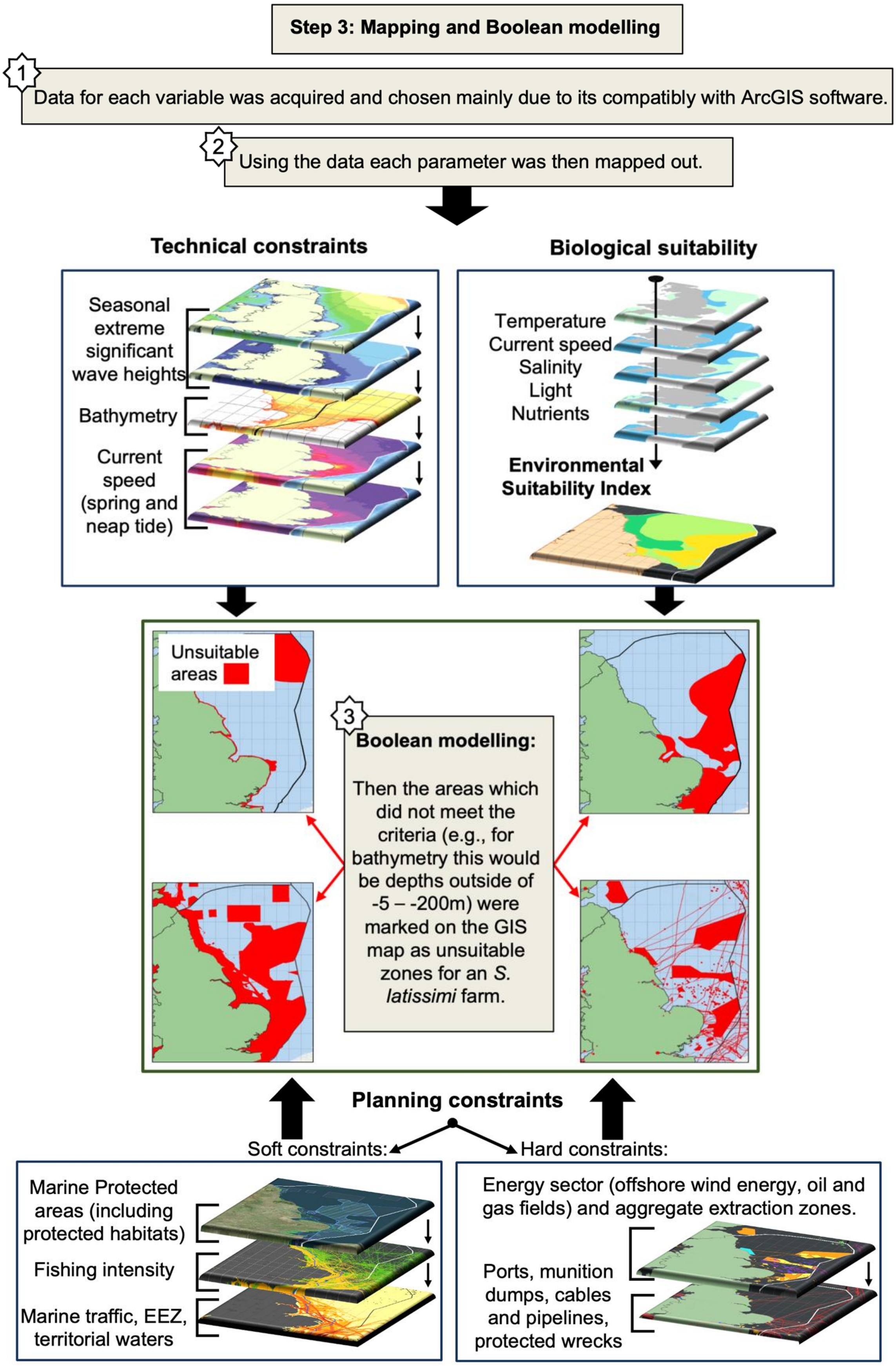
This included: Analysing different criteria for the appropriate bathymetry of an *S. latissimi* farm, which was done by investigating the origin of values found within reviewed literature. For instance:

- Was the study justifying the appropriate bathymetry for seaweed farming through a theoretical theory or case study?
- Has the study limited the proposed appropriate farm depth due to economic cost or what is technically achievable? Et cetera.

These different factors were taken into account to provide the criteria analysis with logic for a bathymetry decision to be made.

The placement of an *S. latissimi* farm should be between -5 - -200m.

Figure 2b: Step 2, illustration and explanation of the sequence of steps taken in the multi-criteria decision analysis within the methodological procedure to establish the research aim. *S. latissima* refers to *Saccharina latissima*, EEZ refers to exclusive economic zone.



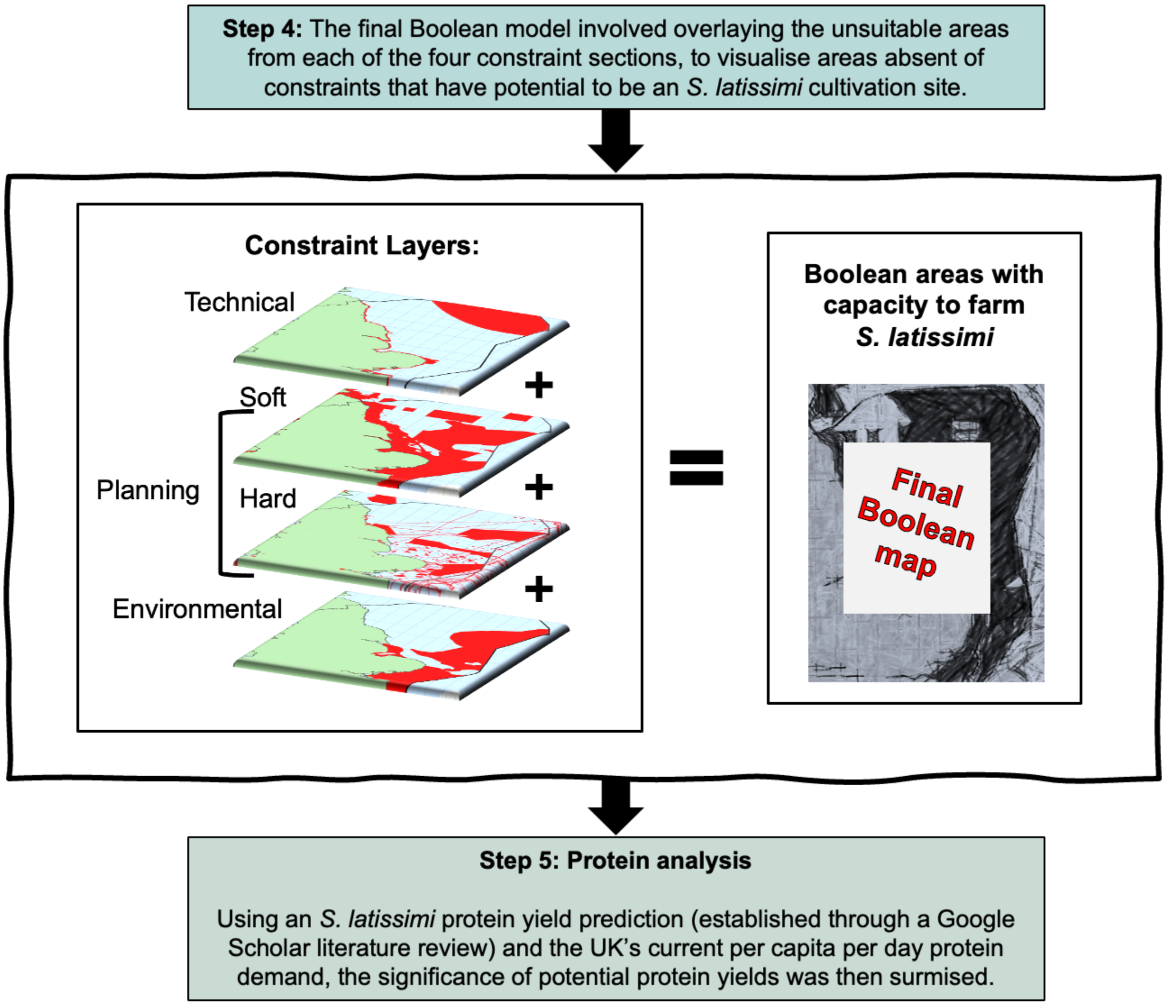
Step 3: Mapping and Boolean modelling

1 Data for each variable was acquired and chosen mainly due to its compatibly with ArcGIS software.

2 Using the data each parameter was then mapped out.

3 **Boolean modelling:** Then the areas which did not meet the criteria (e.g., for bathymetry this would be depths outside of -5 – -200m) were marked on the GIS map as unsuitable zones for an *S. latissimi* farm.

Figure 2c: Step 3, illustration of the sequence of steps taken in the methodological procedure to establish the research aim. *S. latissima* refers to *Saccharina latissima*, EEZ refers to exclusive economic zone. Graphic contributions based on materials from: MMO (2019); EMODnet (2016); and ABPmer (2008).



Step 4: The final Boolean model involved overlaying the unsuitable areas from each of the four constraint sections, to visualise areas absent of constraints that have potential to be an *S. latissimi* cultivation site.

Step 5: Protein analysis

Using an *S. latissimi* protein yield prediction (established through a Google Scholar literature review) and the UK's current per capita per day protein demand, the significance of potential protein yields was then surmised.

Figure 2d: Step 4, illustration of the Boolean model overlay of all variables. **Step 5** shows the protein analysis, within the sequence of steps taken in the methodological procedure to establish the research aim. *S. latissima* refers to *Saccharina latissima*.

Uncertainties

The Boolean approach has no trade-off as it is a straightforward overlay of all maps. Thus, the Boolean model assumes that each criterion has equal significance but, not all layers will have the same impact on the suitability of an aquaculture site.

Decision making

To carry out the GIS-based MCDA all chosen criteria their justification and the setting of their parameters was reliant upon decision-making, this implies there will be uncertainties related to human error. To conclude a MCDA is an individual tool thus, by applying different reasoning and interpretation of data the choices made throughout this study are subject to discussion.

Data sources

All GIS databases (table 1) have been quality controlled by the platform authoriser (ArcGIS, 2021). However, this report acknowledges that it had no control over the accuracy of data quality inspections.

Table 1: Data source selection of the chosen ArcGIS and other geodatabase layers. The environmental suitability index layer is an intersection of salinity, temperature, light climate and nutrient variables which has been used to establish areas suitable for *S. latissima* growth.

Layer	**ArcGIS geodatabase source**
Authorised (2022) seabed aggregate extraction sites	The Crown Estate, 2022
Cables and pipelines	Infrapedia, 2018; TeleGeography, 2016
Exclusive economic zone	UK Hydrographic Office, 2018
Fishing density	The Maritime and Coastguard Agency, 2020
Marine protected areas	JNCC, 2022
Marine Traffic	The Maritime and Coastguard Agency, 2020
Munition dumps	EMODnet, 2018
Offshore wind cable area agreement	The Crown Estate, 2021
Offshore wind energy sites	Esri, 2017
Offshore wind farm development zones	Global Offshore Wind Farm Database, 2019; OSPAR, 2016
Oil and gas fields	Leeuwarden, 2021
Shipping ports	National Geospatial Intelligence Agency, 2018
UK territorial limit	Seafish, 2021
Layer	**Data source**
Bathymetry	EMODnet, 2016; North Sea Observation and Assessment of Habitats, 2014
Environmental suitability index	MMO, 2019
Mean peak current speed	ABPmer, 2008
Mean significant wave height	ABPmer, 2008
Protected wrecks	Maritime & Coastguard Agency, 2020

Results

Tables 2a – 2d provide the criteria decision for each variable (a limitation or conflicting use of the North Sea) and the logic behind the decision, which was concluded by analysing multiple existing criteria for the site selection of an *S. latissima* farm. After the MCDA the established criteria for each variable (either defined as a constraint or factor) was then used as the parameters to create a Boolean suitability map. The Boolean model outcome was achieved by identifying areas that did not meet the criteria parameters (table 2a – 2d) for each variable and programming those locations as not suitable, which generated the spatial whereabouts of zones that are either suitable or unsuitable for the placement of an *S. latissima* aquaculture site.

- *S. latissima's* biological suitability (table 2a) shows that all environmental variables are fundamental for the growth of *S. latissima* thus, areas which have unsuitable conditions cannot be considered for the placement of a seaweed farm.

- All soft and hard planning variables (tables 2b and 2c, respectively) will influence the placement of a seaweed farm. However, the MCDA showed that hard planning variables were mainly constraints, meaning that a potential cultivation site cannot coexist among the location of these variables. Whereas table 2b showed that the criteria parameters for soft planning variables were more factor-based.
- Table 2d identified the criteria for culture-specific technical suitability and found that to an extent the ability for a seaweed cultivation site to withstand offshore conditions relies upon the selected farm infostructure, rather than the prevailing environmental conditions. For example, table 2d showed that when considering bathymetry although the seaweed itself will usually be in the top 15m of the water column, the farm can be situated in deeper waters as anchors and floats hold the kelp vertically in place. Every location within the study area that did not meet the criteria of the technical parameter decisions was programmed as unsuitable within the Boolean GIS modelling.

Table 2a: Multi-criteria decision for environmental variables that are all based on the natural growth of *S. latissima* bar current speed which represents values for cultivation.

Variable	Decision	Criteria	Reason
Sea Surface Temperature (SST) (°c)	Factor	Prohibit cultivation from areas where the annual extreme SST is <2°c and / or >18°c	• The environmental threshold for the growth of *S. latissima's* is between 2°c - 18°c (Bolton and Lüning,1982; Kerrison *et al.*, 2015).
Salinity parts per thousand (ppt)	Factor	Prohibit cultivation from areas where the annual extreme salinity is <15 ppt	• Because of effects on osmotic processes salinity <15 ppt is not suitable for the growth of *S. latissima* (Kerrison *et al.*, 2015; Smale *et al.*, 2016).
K_d Photosynthetically active radiation (PAR) 10% light depth (m)	Factor	Prohibit cultivation from areas where there is <1 K_d (PAR) 10% light depth (m)	• Due to photosynthetic requirements <1 K_d (PAR) 10% light depth (m) is unsuitable for *S. latissima* growth (MMO, 2019; van der Molen *et al.*, 2018; Guo *et al.*, 2015). • However, when cultivating kelp there is scope to enhance light climate conditions by optimising the infostructure position in the water column (MMO, 2019).
Winter total oxidised nitrogen (TOxN mmol/m^3)	Factor	Prohibit cultivation from areas where the annual extreme TOxN is <4 mmol/m^3	• Nitrates are essential for seaweed growth and although during winter kelps can store nitrogen to make proteins in spring (Van den Burg *et al*., 2013), a TOxN <4 mmol/m^3 is unsuitable for the environmental threshold of *S. latissima* (Broch *et al*., 2013; Kerrison *et al*., 2015).
Current speed (m/s)	Factor	Prohibit cultivation from areas where the annual extreme current speed is >1.5 m/s or <0.1 m/s	• Buck *et al.,* (2005) and the MMO (2019) recommend current speeds of <1.5m/s for the biological suitability of farmed *S. latissima*. • Current speeds <0.1m/s may not be suitable to support the growth of *S. latissima* (MMO, 2019).

Table 2b: Criteria for the planning suitability regarding soft constraint variables for *S. latissima* cultivation.

Variable	**Decision**	**Criteria**	**Reason**
Marine traffic	Factor	Prohibit cultivation from areas with >20.1 vessels crossing per week (these areas include commercial shipping lanes)	• Thomas *et al*., (2019) and Nunes da Silva Ramos (2016) agree that areas with a vessel traffic density of < 20.1 vessels crossing per week are suitable for macroalgae cultivation site selection. • Aquaculture areas should not coincide with commercial shipping lanes due to socio-economic impacts (Roesijadi *et al.,* 2011; Siddiqui, 2018).
Fishing intensity	Factor	Avoid cultivation in fishing grounds, identified by fishing vessel tracks (≥10h fishing / km^2 / month)	• Seaweed cultivation should be restrained from fishing and trawling grounds (Siddiqui, 2018), which can be identified by analysing GIS-based fishing vessel track density (Mendo *et al.,* 2019; Jennings and Lee, 2012). • For instance, EMODnet (2020) has depicted areas of ≥ 10 hours of fishing activity per km^2 per month as significant fishing grounds.
Marine Protected Areas (MPA's)	Constraint	Prohibit cultivation within MPA's	• Existing legal framework does not automatically authorize aquaculture in MPA's (Wood *et al.,* 2017; Capuzzo *et al.,* 2016). • However, dependent on the outcome of site-specific surveys permission may be granted (Wood *et al.,* 2017).
Habitats	Factor	Prohibit cultivation within protected habitats (MPA's) Assess local habitats upon site selection	• Protected habitats can be avoided by prohibiting cultivation within all MPA's (JNCC, 2021; Wood *et al.,* 2017). • After a proposed farm site is selected the surrounding habitats need to be assessed (e.g., this could include an environmental impact assessment) (Wood *et al.,* 2017).
Area limitations	Constraint	Prohibit cultivation within territorial seas and outside of the English EEZ	• An English cultivation site is restricted to within the English exclusive economic zone (EEZ) (MMO, 2019a). • Options for the selection of a farm site may be limited within territorial seas (MMO, 2019a) due to stricter planning regulations for example, those posed by The Crown Estate. Thus, legally permitting farming in these waters can be challenging and it also has a greater risk of stakeholder conflicts (Wood *et al.,* 2017).

Table 2c: Criteria for the planning suitability, regarding hard constraint variables for *S. latissima* cultivation.

Variable	**Decision**	**Criteria**	**Reason**
Cables and Pipelines	Constraint	Prohibit cultivation on and above cables and Pipelines	• Cultivation infostructure (e.g., anchors) that drift or are deployed onto a cable or pipeline can cause displacement and breakages resulting in high economic damage for repair costs (European Subsea Cables Association, 2020; Anderson, 2017). • This is partially concerning in the North Sea due to the significance of electricity cables transporting energy from offshore wind farms to the mainland (European Commission, 2021; Office for National Statistics, 2021a).
Ports	Factor	Restrain cultivation in and around close proximities to ports	• Sites near a port may act as an auxiliary to cultivation efficiency by providing loading and unloading facilities (Roberts *et al.,* 2021). • However, farms in a very close proximity can cause marine traffic associated obstructions due to the overcrowding of sea space (Thomas *et al*., 2019).
Munition dumps	Constraint	Prohibit cultivation over munition dumps	• Munition dumps are a human and marine health hazard risk and thus should be avoided (Beck *et al.,* 2018; Wilkinson, 2017).
Protected historic wrecks	Constraint	Prohibit cultivation over protected wrecks	• In the absence of a licence granted by the Secretary of State it is a criminal offence to deploy equipment (e.g., anchors) or obstruct access to protected wreck sites (Historic England, 2015).
Offshore energy sector	Constraint	Prohibit cultivation within licenced energy sector areas	• Although the use of sea space can be optimised by co-locating offshore wind farms or oil platforms with aquaculture sites (Lee, 2020; Jansen *et al.,* 2017), permitting this involves risks (Lacroix and Pioch, 2011) and requires stakeholder collaborations that cannot be guaranteed. Subsequently, farm site authorisation within the energy sector is not ensured (Van den Burg *et al.,* 2020). • Consequently, for this analysis energy sector areas were not considered appropriate for a farm site.
Marine aggregate extraction zones	Constraint	Prohibit cultivation within marine aggregate extraction zones	• Areas of current licensed marine aggregate extraction zones will need to be avoided due to a conflict of interest and the release of surplus sediment into the water column which affects seaweed growth (Kenny *et al.,* 2018).

Table 2d: Multi-criteria decision for culture-specific technical suitability variables for S. latissima cultivation.

Variable	Decision	Criteria	Reason
Significant wave height	Factor	Prohibit cultivation from areas where the significant wave height can exceed 2.5m	• Cultivated *S. latissima* in the North Sea and Faroe Islands have shown to have a peak wave height tolerance of approximately 6.5m (Buck and Buchholz, 2005) and 8m (Buck *et al.,* 2018), respectively. • The MMO (2019) considers an optimum farm wave height of <4. • The Crown Estate (2019) and Bahaj *et al.,* (2020) suggests that significant wave heights exceeding >2.5m create unsafe working conditions. • Zhu *et al.,* (2021 and 2020) found that *S. latissima* aquaculture attenuates waves, suggesting that suspended canopies could tolerate high energy wave environments.
Bathymetry	Factor	Prohibit cultivation from areas where the bathymetry is less than -5m or greater than -200m	• The MMO (2020 and 2019a) recommend depths deeper than 4m. • Nylund (2016) found that depths of 100m can be considered practical. • *S. latissima* has been successfully cultivated where the infostructure reached depths of -50 - -200m (Bak *et al.,* 2018). • Bahaj *et al.,* (2020) and The Crown Estate (2019) agree that, at depths >-60m below the lowest astronomical tide level (LAT) operating a project becomes less economically feasible, and shallow sites (less than -5m below LAT) pose operational hazards.
Seafloor substrate	Factor	Infostructure dependent	• Although a firm substrate may be the most suitable for the use of moorings for long-lines, cultivation anchors are selected depending on the type of seafloor substrate thus, substrate will not restrict the positioning of a seaweed farm (Cardia *et al.,* 2015).
Current speed	Factor	Prohibit cultivation from areas where the current speed is >1.5 or <0.1 (m/s)	• Despite limited research on the recommended current speed for seaweed cultivation it is considered a critical technical factor as it exerts stress on aquaculture infostructure (Cardia *et al.,* 2015). • Buck and Buchholz (2005) found the infostructure current speed tolerance of a North Sea *S. latissima* farm was ~1.5m/s before the kelp holdfasts became displaced. • The MMO (2019) recommends a current speed of between <1.5 - >0.1m/s for the biological suitability of farmed *S. latissima.*

Tables 2a – 2d: For this study the criteria decisions for each variable were considered a constraint if all the geographical areas of the variable are unsuitable. That is, if they completely constrained or physically prevented the development of an aquaculture site. For example, this could be legislative or political boundaries (e.g., marine protected areas and exclusive economic zones) or barriers (e.g., oil platforms). Whereas the criteria decisions for each variable were considered as a factor, if out of all the geographical regions where the variable can be found some of the areas were suitable, but in other areas where the same variable is present the location is unsuitable. For example, this could be environmental variables (e.g., salinity, where areas <15 ppt are unsuitable but areas >15 ppt are suitable) or planning variables (e.g., marine traffic, where areas that have >20.1 vessels passing per week are unsuitable but areas of <20.1 are suitable).

Main findings

The North Sea is an intensively utilised and crowded area with many socio-economic activities competing for space. Figure 3 acknowledges the influence of the variables from each layer (environmental, planning and technical suitability factors) on the site selection for *S. latissima* cultivation. Ultimately, figure 3 shows that soft constraints are the most limiting in terms of space availability. However, tables 2a – 2d indicated that hard planning variables (figure 3) have the highest restrictions in terms of physical constraints preventing the implementation of an *S. latissima* farm. Yet, many of the restrictions posed by technical variables (figure 3, table 2d) can be mitigated by decisions such as the choice of structural design and cultivation technology.

Key results

The Boolean model is the result of overlaying areas that did not meet the criteria of every input layer (to view individual layers involved in creating the Boolean model please refer to this paper's supplementary material). Figure 4 is a geovisualisation of the Boolean model results showing there is scope for the growth and farming of *S. latissima* in the English EEZ within the North Sea region. The suitable regions are all spatially distributed offshore in exposed areas and can be divided into a few smaller isolated sections and one more extensive zone. However, when combined suitable areas cover ~2.05 million hectares (~20,500km^2).

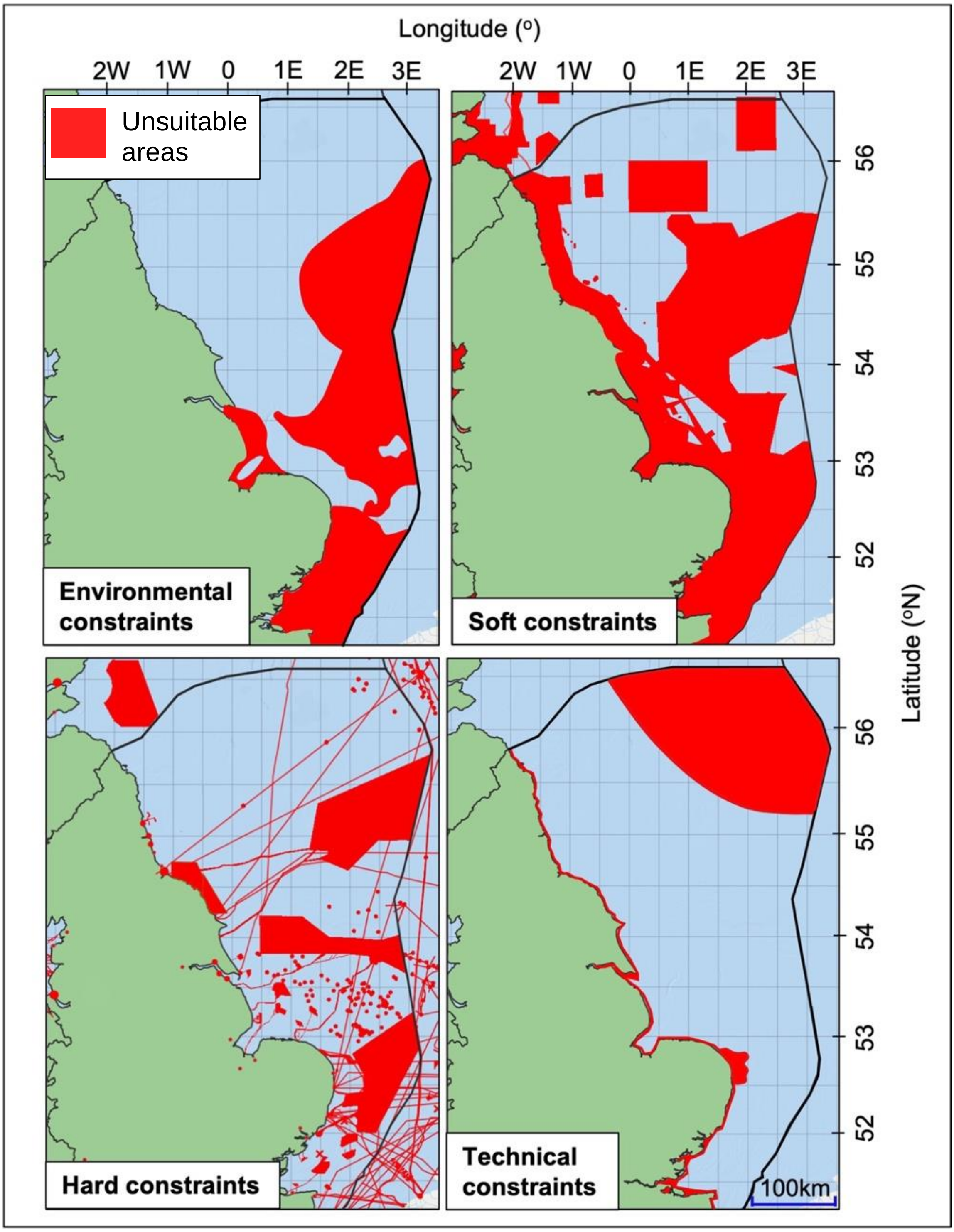


Figure 3: Boolean areas within each section (environmental, technical and planning) that will confine the development of an *Saccharina latissima* farm. These results have been formed from the Boolean modelling of each criterion (established through a multi-criteria decision analysis in tables 2a – 2d) from the four constraint categories: Environmental variables, technical variables, soft planning variables and hard planning variables. Made using ArcGIS with all data and base layer sources from table 1.

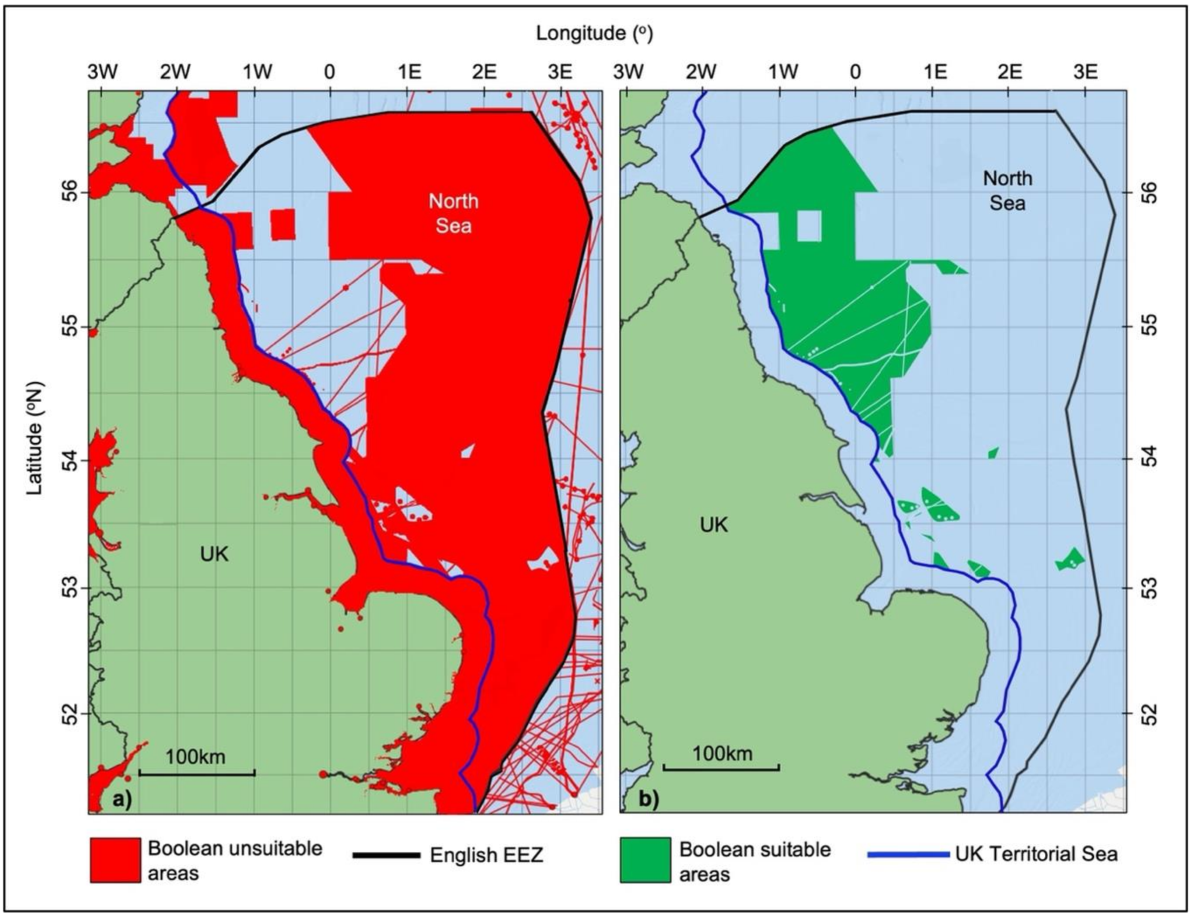


Figure 4: Suitability map of all areas combined from each section (environmental, technical and planning variables) that are either unsuitable (a) or suitable (b) for *Saccharina latissima* cultivation. This figure incorporates the layering of multi criteria from the planning, environmental and technical variable datasets, that together have created the spatial index of the Boolean suitable areas. Made using ArcGIS with all data and base layer sources from table 1.

Discussion

The aim of this investigation was to identify suitable areas to cultivate *S. latissimi* as an alternative source of protein for human consumption in England's North Sea EEZ. This study has produced a Boolean suitability index for *S. latissimi* farming that incorporates planning, technical and environmental constraints, which to the best of the author's knowledge has not been attempted before within the chosen study area. Results from the Boolean model have clearly demonstrated the whereabouts of ~2.05 million hectares (~20,500km^2) where there is scope for *S. latissima* cultivation. This area is roughly equivalent to the land coverage of Wales (~20,780 km^2) (figure 6) which indicates there is large capacity for cultivation within the North Sea. These results will potentially act as a valuable geographical decision-making tool that could help to reduce stakeholder conflicts when selecting areas for the implementation of a North Sea *S. latissima* farm; that could produce a more sustainable source of protein in comparison to traditional UK aquaculture and agriculture methods.

Evaluation of *S. latissima* cultivation within Boolean areas

The next sub-sections (potential biomass production – amino acid profile and quality) investigates previous findings and current statistics. The reasoning behind this is to establish a baseline so that results from this study's Boolean modelling can be related to the present state of knowledge within the existing field of *S. latissima* cultivation.

Potential biomass production

There are large variations in the predicted biomass that an *S. latissima* farm can produce (table 3). For instance, under optimum conditions 57.5 tonnes (t) of dry weight (DW) *S. latissima* could be produced per hectare (ha) (0.01km^2) per year (Sharma *et al*., 2018) (table 3). In contrast, other trials have estimated the annual DW production of *S. latissima* at 4.2 (t ha^{-1}) (Pechsiri *et al*., 2016) (table 3).

Table 3: Previously published yield estimates for *S. latissima* cultivation, by fresh weight biomass potential in different geographical regions. Skjermo *et al.,* (2014) has approximated that *S. latissima* biomass is 85% water weight, so the dry weight (15%) has been calculated for every fresh weight reference using this value. Literature was reviewed using Google Scholar with key search terms: *S. latissima*, cultivation and biomass. t ha^{-1}, refers to tonnes per hectare (0.01 km^2), IMTA is integrated multi-trophic aquaculture and per year relates to one cultivation cycle.

Fresh weight biomass yield (t ha^{-1}) per year	**Dry weight (t ha^{-1}) per year**	**Location**	**Remark**	**Reference**
28	4.2	Sweden	Upscaled from small-scale field trials.	Pechsiri *et al.,* 2016
29	4.4	New England, North East USA	Estimations of a 1 ha hypothetical kelp farm, based on years of *S. latissimi* cultivation yields.	Yarish *et al.,* 2017
40	6	Galicia, Spain	Estimates from trial site biomass values.	Peteiro and Freire, 2013
45	6.8	Western Norway	Upscaled potential, form the IMTA of Salmon and *S. latissima.*	Fossberg *et al.,* 2018
75	11.3	Norway	Model based estimate for average within entire Norwegian baseline.	Broch *et al.,* 2019
95	14.3	Eastern Canada	Recalculated by Broch *et al.,* (2019) from a yield of 19.95t per 0.21ha.	Reid *et al.,* 2013
170	25.5	Norway	Predictions from an analysis on seaweed biobased products.	Skjermo *et al.,* 2014
200	30	Norway	Based on values that have been upscaled.	Masson *et al.,* 2015
220	33	Scotland	Upscaled from small scale field trials in IMTA.	Sanderson *et al.,* 2012
230	34.5	Norway	Model-based estimate for a (September deployment) maximal yield in the entire Norwegian baseline.	Broch *et al.,* 2019
383	57.5	Central Norway	Upscaled by Broch *et al.,* (2019) from yield reports of 38.3kg / m^{-2} from February - June.	Sharma *et al.,* 2018
Mean value = 138 Standard deviation = 113	**Mean value** = 21 Standard deviation = 17			

This is because variables such as time of out planting, harvesting, the depth and spacing of long lines and nutrient availability, differ between sites and approximations. However, the mean DW value among reviewed literature (key Google Scholar search terms: *S. latissima*, cultivation and biomass) is 21 (t ha^{-1}) (table 3). This potential production is over double in comparison to some of the UK's most cultivated arable primary producers such as wheat (DEFRA, 2020) (figure 5).

Potential protein production

Research has highlighted that the composition of macronutrients in *S. latissima* is subject to debate (Stanley *et al*., 2019). For instance, values of the percentage of protein in *S. latissima* have been found to considerably range between 4.3% - 26% (Bak *et al*., 2019; Pereira, 2016). This is partly due to factors such as the timing of harvest as *S. latissima's* composition fluctuates throughout different seasons (Tiwari and Troy, 2015) for instance, *S. latissima* reaches its highest protein content in autumn – early spring while peak carbohydrate content and biomass yields occur in the summer months (June – August) (Bak *et al*., 2019; Schiener *et al*., 2015). Furthermore, different offshore cultivation sites can have unique environmental conditions including nutrient availability which impacts *S. latissima's* biochemical composition thus, protein percentage (Slegers *et al*., 2021). Moreover, there is a lack in understanding of how different *S. latissima* ecotypes respond to environmental changes, which makes quantifying protein content for the species across a large geographical range inexact (Broch *et al*., 2019). Additionally, contradicting estimations could originate from the different nitrogen-to-protein conversion factors that can be relied on for total protein content determination, which can result in an under or over estimation (Bak *et al*., 2019). Furthermore, some studies use different methods altogether such as a quantitative amino acid analysis (Bak *et al*., 2019).

The protein composition of *S. latissima* cultured in the UK, Norway and North Sea area has been valued at ~10% (Nielsen *et al.,* 2020; Monteiro *et al*., 2020; Marinho *et al.,* 2015a) if deployed in autumn and harvested in spring (March – May) (Nielsen *et al.,* 2020; Marinho *et al.,* 2015a). Based on the mean DW biomass production of 21t per ha^{-1} (table 3, figure 5), this would imply that a 1ha and 1km^2 *S. latissima* farm in the North Sea could annually (every cultivation cycle) produce 2.1t and 210t of DW protein, respectively. For comparison purposes, when related to the UK's most cultivated arable crop, wheat, which is ~13% protein, *S. latissima's* protein content is 3% lower. However, per hectare *S. latissima* cultivation would produce almost double the volume of protein (2.1t DW protein ha^{-1}) than wheat (1.1t DW protein ha^{-1}) due to its high biomass yield (table 3, figure 5). Although, in comparison to the protein yielded from higher trophic levels, on the basis that in the UK there is capacity for 2500 free-range chickens per ha^{-1} (DEFRA, 2019), ~5.5 tonnes of protein per ha^{-1} per year can be produced from chicken eggs (6g protein per egg) (USDA, 2019). This value is ~2.6* (times) higher than potential *S. latissima* yields. However, food production from higher trophic levels requires more resources and is usually a bigger burden on the environment (Notarnicola *et al*., 2017; Smil, 2014; Reijnders *et al*., 2003; Smil, 2002).

To put *S. latissima's* yield predictions (table 3) into perspective, roughly every 12,000ha (120km^2) (figure 6) would supply 1% of the UK's population (670,000 people) (Office for National Statistics, 2021) with their yearly protein demand

(~25,400t of protein) when using the most recent (2017) daily per capita protein consumption prediction of 104g (figure 1) (FAO, 2018). However, using the highest hypothetical *S. latissima* DW yield (57.5t ha^{-1}) (table 3) and protein content (26%) predictions (Pereira, 2016) that are based on growth under optimum conditions (equivalent to a protein yield of ~15t per ha), this would reduce the 12,000ha area required to ~1690ha (16.9km^2).

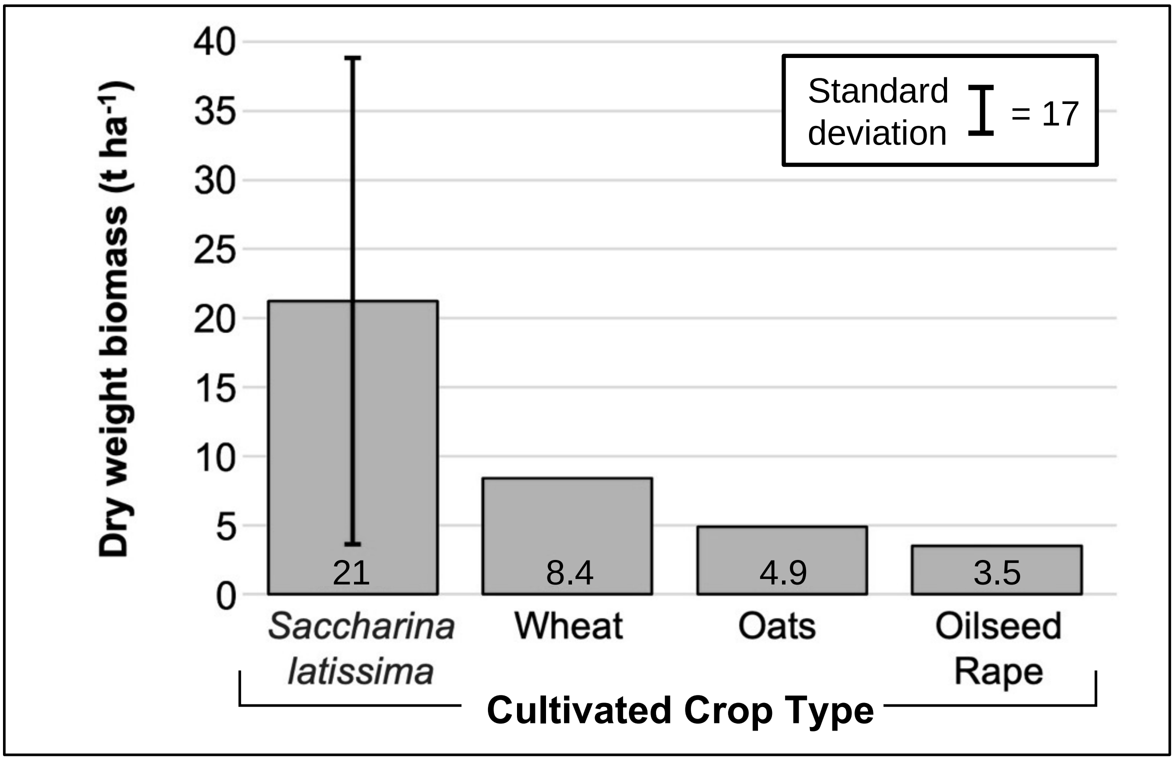


Figure 5: The mean dry weight yield in tonnes per hectare (0.01Km^2) per year for *Saccharina latissima* grown across different geographical regions (using findings from table 3), in comparison to some of the UK's most cultivated arable crops. The error bar is at a 99.9% confidence level. Values for wheat, oats and oilseed rape are a five-year (2015 – 2020) average of UK yield data. Data source (DEFRA, 2020).

From a different evaluation viewpoint, if the protein yielded by North Sea *S. latissima* cultivation were to supply 5% of the UK's population (3.35 million people) (Office for National Statistics, 2021) with their current protein demand (104g per day (figure 1), 10,452t per month) (FAO, 2018) for one month (30 days), then using the average protein yield (2.1t ha^{-1}) and content (10%) predictions, approximately 5000ha (50km^2) would have to be utilised. Figure 6 illustrates the area required if the monthly protein demand from 5% of the population were to be met by *S. latissima* farming. Marine Scotland (2017) has defined a small-medium farm as ≤ 0-50 x 200m seaweed cultivation lines, and with 1.5m line spacing 50 lines would cover 1.5ha (0.015km^2). This means that if the demand were to be met by a series of small-medium size *S. latissima* farms (illustrated in figure 6) 3333 cultivation sites would be required.

It is important to know that this study does not suggest the implication of 3333* 1.5ha macroalgae farms. Rather, these statistics and figure 6 have been used to demonstrate the scale of cultivation in relation to the significance of potential yields.

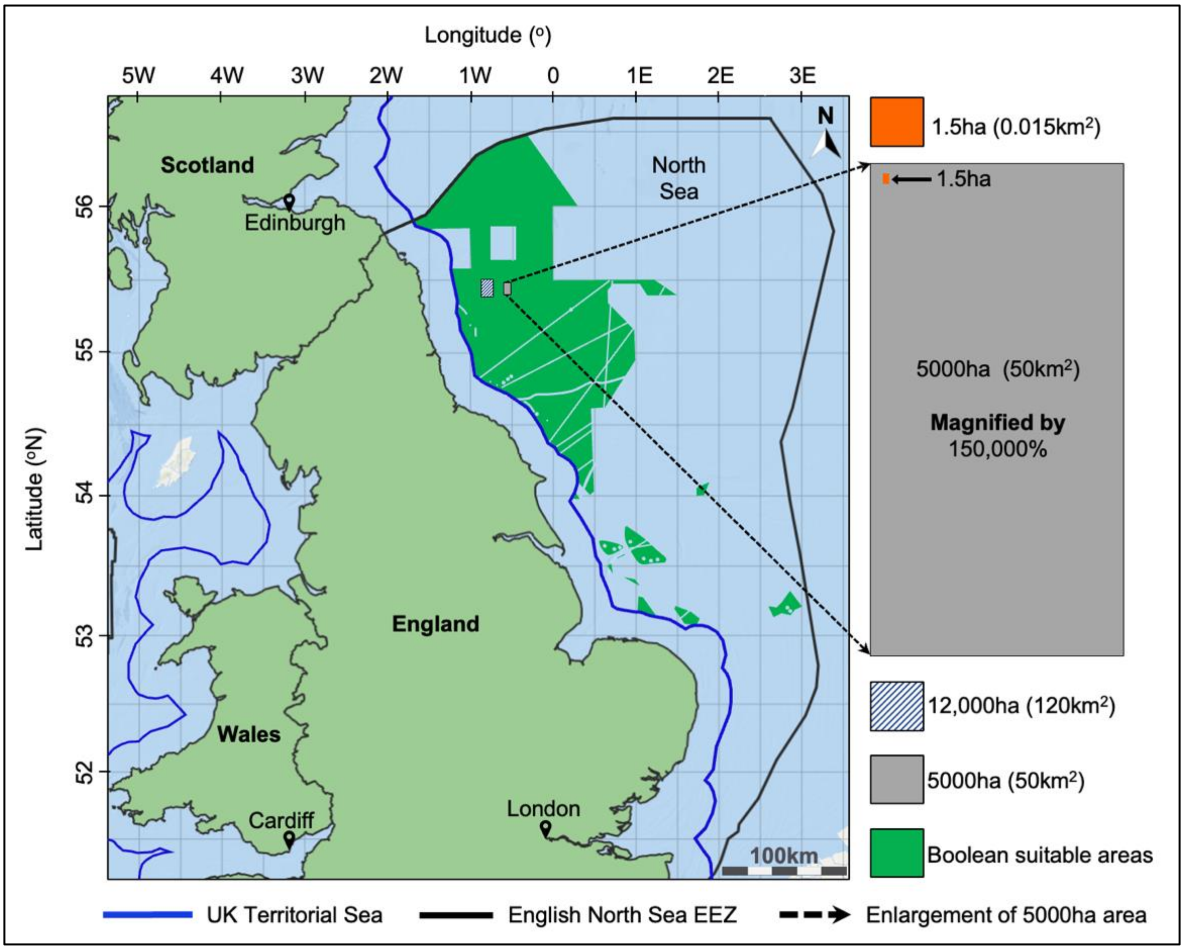


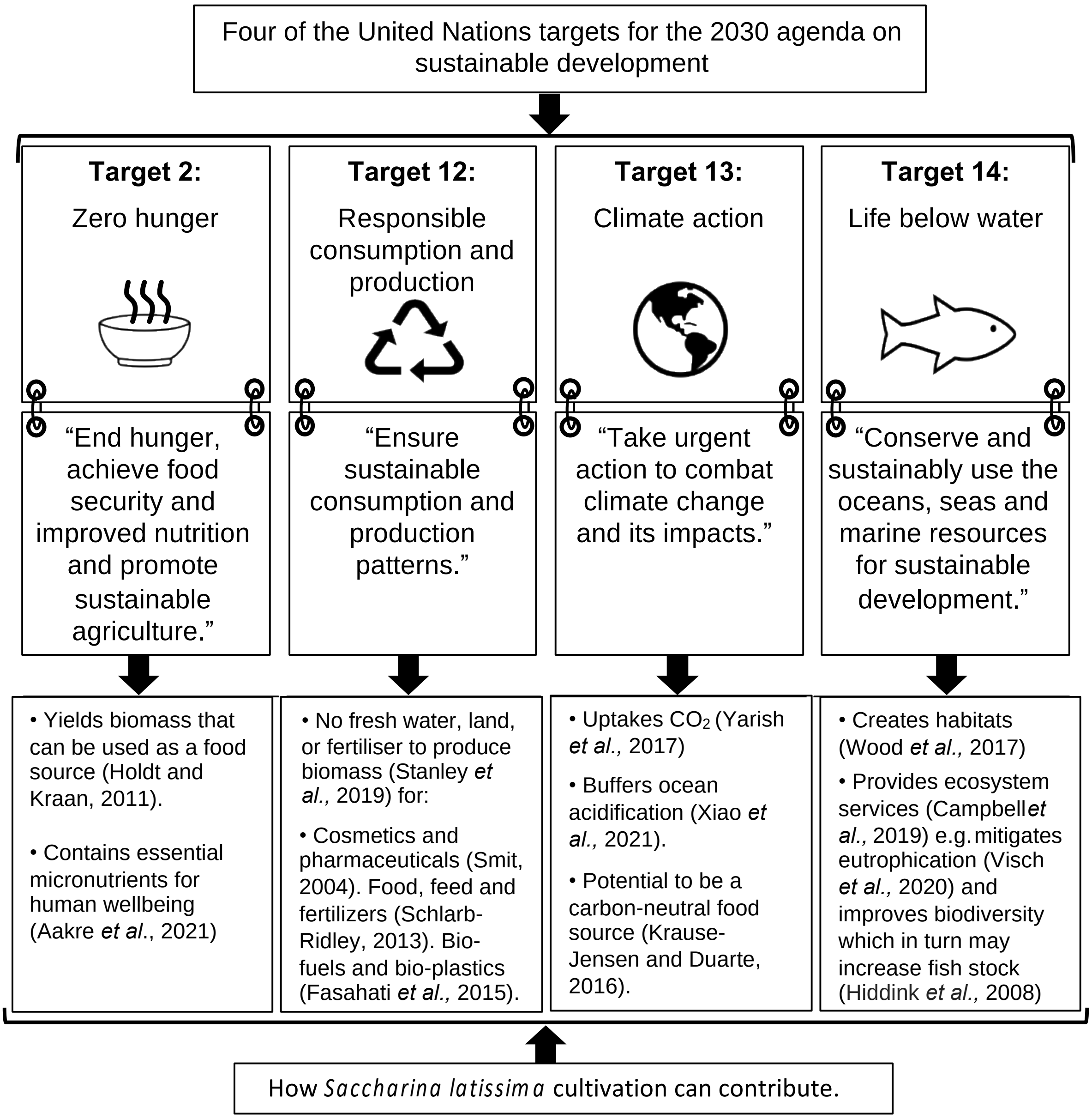
Figure 6: Illustration of areas that would have to be utilised to produce enough protein to supply 1% of the UK's population with their yearly protein demand (~12,000ha) and 5% of the UK's population with their monthly protein demand (~5000ha). This figure also demonstrates the scale of a small-medium size farm (1.5ha) within a ~5000ha area. It would take 3333 of these small-medium size farms to cover a total area of 5000ha. Areas to demonstrate scale have been placed at random within the Boolean suitability map. Made using ArcGIS, ha refers to hectare.

Amino acid profile and quality

The essential amino acids to total amino acid (EAA/TAA) ratio is used to assess the quality of protein within food for human consumption (Bleakley *et al*., 2017; Černá, 2011). A study in the Faroe Islands found that essential amino acids that humans cannot self-synthesise for example, lysine which is a valuable EAA within the protein economy (Leinonen *et al.,* 2019), have been found to make up >50% of the amino acids in *S. latissima* when harvested in March (Bak *et al*., 2019). A food with an EAA score of >100% means that the quantity of EAA's exceeds ratio requirements (mg EAA/g protein) for 3 –10-year-olds (WHO, 2007), and findings from Bak *et al*., (2019) show that *S. latissima* had a score of 106% (when harvested in March), indicating that that the protein content in *S. latissima* is high quality (WHO, 2007). Furthermore, Bak *et al.,* (2019) found that regardless of total protein percentage the ratio of different amino acids in *S. latissima* does not significantly deviate between cultivation depth and exposed or sheltered cultivation sites.

Environmental interactions

The rationale behind this project was the unprecedented need for the sustainable production of resources. Both positive and negative environmental modifications can be correlated to macroalgae cultivation (Xiao *et al*., 2021; Seghetta *et al*., 2016). However, if appropriate measures are put in place *S. latissima* can be sustainably cultivated (Campbell *et al*., 2019). Furthermore, sustainable *S. latissima* aquaculture and the ecosystem services that it yields could have socio-economic benefits (Visch *et al.,* 2020; Wood *et al.,* 2017), which would help the UK to reach 2030 goals such as those set by the United Nations (UN, 2020) (figure 7).



Four of the United Nations targets for the 2030 agenda on sustainable development

Target 2: Zero hunger

"End hunger, achieve food security and improved nutrition and promote sustainable agriculture."

- Yields biomass that can be used as a food source (Holdt and Kraan, 2011).
- Contains essential micronutrients for human wellbeing (Aakre *et al*., 2021)

Target 12: Responsible consumption and production

"Ensure sustainable consumption and production patterns."

- No fresh water, land, or fertiliser to produce biomass (Stanley *et al.,* 2019) for:
- Cosmetics and pharmaceuticals (Smit, 2004). Food, feed and fertilizers (Schlarb-Ridley, 2013). Bio-fuels and bio-plastics (Fasahati *et al.,* 2015).

Target 13: Climate action

"Take urgent action to combat climate change and its impacts."

- Uptakes CO_2 (Yarish *et al.,* 2017)
- Buffers ocean acidification (Xiao *et al.,* 2021).
- Potential to be a carbon-neutral food source (Krause-Jensen and Duarte, 2016).

Target 14: Life below water

"Conserve and sustainably use the oceans, seas and marine resources for sustainable development."

- Creates habitats (Wood *et al.,* 2017)
- Provides ecosystem services (Campbell *et al.,* 2019) e.g. mitigates eutrophication (Visch *et al.,* 2020) and improves biodiversity which in turn may increase fish stock (Hiddink *et al.,* 2008)

How *Saccharina latissima* cultivation can contribute.

Figure 7: The United Nations sustainable development goals and how seaweed farming could help to reach these targets. Target quotations are credit of the United Nations (2020).

This may contribute towards an assortment of different solutions that together might help ease the rate of climate change whilst still allowing humanity to develop (Yarish *et al.*, 2017; Duarte *et al*., 2017).

Conclusion

Decision-makers will have an essential role in tackling challenges related to the growing human population and the subsequent snowballing increase in food supply demands, which present complicated sustainability challenges. However, this study's Boolean modelling has identified the whereabouts of ~2.05 million hectares (~20,500km^2) suitable for *S. latissima* cultivation absent of environmental, technical, and planning constraints, within the highly utilised English North Sea area. This is significant as sections of this identified area could be used to produce a currently underexploited alternative food source. Furthermore, if properly controlled this production would efficiently and sustainably utilise the ocean's resources to contribute towards meeting the unprecedented rise in resource demands.

Upon analysis, the Boolean feasible areas have capacity to produce large quantities of *S. latissima* biomass that could make a meaningful contribution to the UK's protein supply. However, there are many predictions for *S. latissima's* protein content at the lower end of values when compared to other UK farmed foods, and the protein percentage of *S. latissima* within the identified Boolean areas remains uncertain. Therefore, at present, prospects for *S. latissima* solely as a source of protein remain very limited. Consequently, the cultivation of North Sea *S. latissima* currently should not be regarded as a potential viable protein supply but, rather as an alternative food source which has a high-quality amino acid profile, contains bioactive compounds and essential minerals that can contribute towards overall human wellbeing.

Future work

Boolean approach

As the Boolean model values each criterion with equivalent importance, outcomes presume that all Boolean areas are equally suitable for farm site selection. Therefore, it is recommended that future work investigates this report's Boolean areas using a suitability index weighted overlay, as this more detailed approach will be able to distinguish between adequate and highly optimum sites, which will help strengthen site selection decision-making.

Quantifying yield expectation

Examining existing literature indicated that *S. latissima*'s potential protein yield is subject to surrounding environmental conditions thus, predictions have large variability. Therefore, future work within trial sites is required to evaluate the site-specific feasibility of an *S. latissima* farm to facilitate high protein yields. This could be achieved through water quality surveys. For example, by examining nitrogen concentrations the growth rate and protein percentage of *S. latissima* will have an increased confidence level.

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