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

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Supplementary material

Boolean layer data

The data search focused on ArcGIS-compatible datasets however, for some layers (table 1), pre-existing maps of the North Sea were used for visualisation and then during analysis spatial areas deemed as unsuitable for a seaweed farm were made into an ArcGIS overlay using longitude and latitude values. This enabled the layering together of both GIS and non-GIS variables, which included every criterion that was found to be a limitation or conflicting use of the North Sea for the development of an *S. latissima* cultivation site. The results of this report have relied on both categories of datasets (ArcGIS and non-ArcGIS based) thus, its accuracy will be dependent on the producers of the original layers, and some layers contained more information on their origin than others. However, further detail regarding some of the non-GIS-based layers can be found in table 1.

Table 1: Supplementary information on the quality of non-geodatabase layer source selection data. The term “layer” corresponds to an established variable for macroalga cultivation.

Layer	Description	Data source
Mean peak current speed	• Data across the top half of the water column was used to form the peak current speed model. • This was based on daily predictions throughout 2007. • The model accuracy is less robust in areas closer than 1km to land.	ABPmer, 2008
Mean significant wave height	• This was based on 7 years (2000 – 2007) of data that was used to make a wave height model. • Modelled wave data is less precise in shallow waters (<20m) and zones of complex bathymetry.	ABPmer, 2008
Bathymetry	• A standard description of long-term North Sea (a shelf sea) bathymetry. The data that composes the bathymetry model was derived from three sources: • High resolution bathymetric surveys from, echo sounders. • Data sets of merged individual surveys. • Areas absent of data were covered by coarse resolution altimetry satellite-derived measurements.	EMODnet (2016) and North Sea Observation and Assessment of Habitats (2014).

Result layers

This section is here to illustrate the information within individual layers that formed the Boolean model and to provide further detail of each variable's contribution towards the report's results.

Soft planning constraints

Generally, areas within the territorial sea limit, below 53°N and a few other distinctly utilised areas have the highest density of vessels for shipping, fishing, and underwater operations (e.g., dredging and trawling) (figure 1). Whereas outside of these zones (e.g., non-territorial regions in the northeast of the exclusive economic zone (EEZ)) areas can be found that are suitable for seaweed cultivation, where there are <20.1 vessels crossing per week and more dispersed fishing activity (Thomas *et al.,* 2019). Therefore, these areas were considered as suitable spaces for developing a seaweed farm.

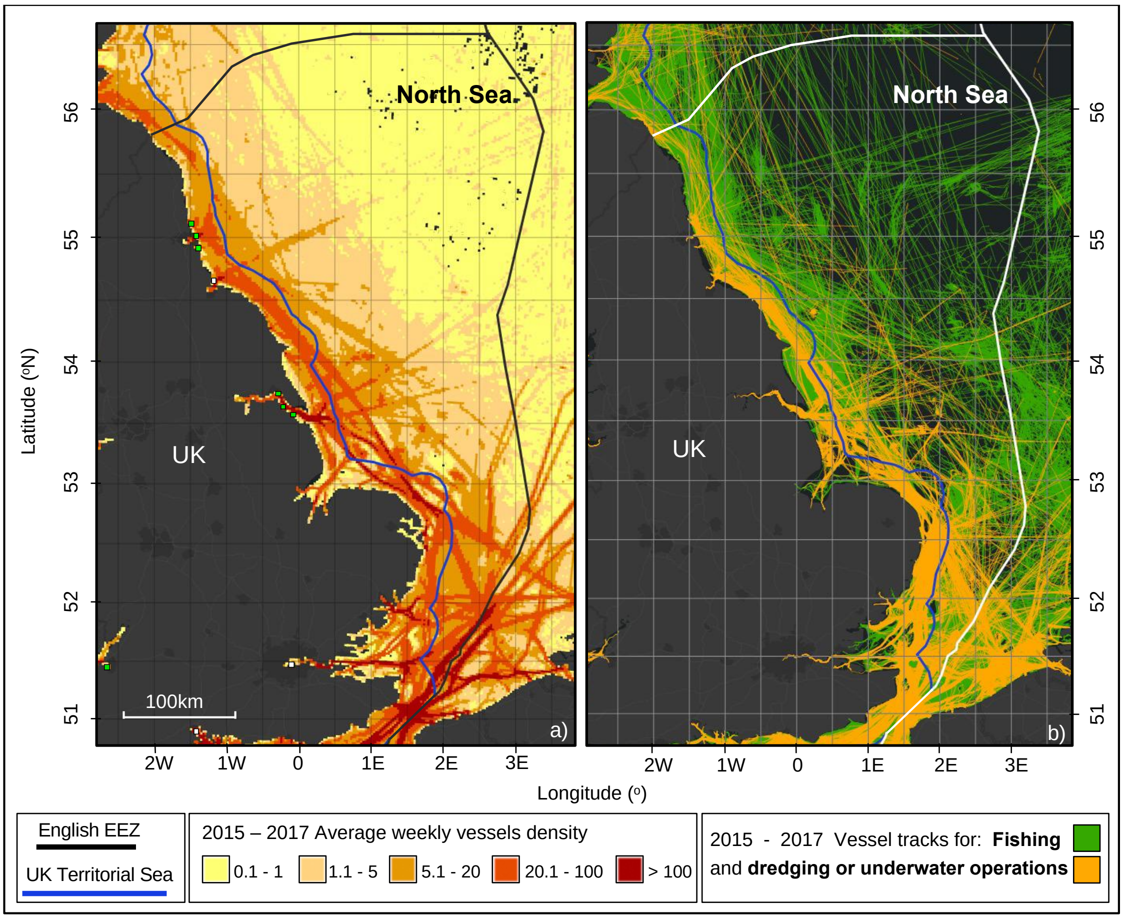

Figure 1: A) The UK's mean weekly vessel density from 2015 – 2017.
B) Transect lines from fishing vessels and underwater operations, from 2015 – 2017. Underwater operations have been added to include fishing practices such as trawling. The identification of England's North Sea exclusive economic zone and territorial seas have also been plotted to include legislative and / or political boundaries.
Made in ArcGIS online using the layer selection data sources: Seafish, 2021; The Maritime and Coastguard Agency (2020); UK Hydrographic Office, 2018.

Figure 2 shows categories of marine protected areas (MPA's), with different legislative requirements such as seasonal fluctuations, that cover a large extent of the North Sea. Though, as the seaweed farming industry is relatively new to the UK the regulatory context is still unclear (Wood *et al*., 2017; Capuzzo *et al*., 2016). However, the multi-criteria decision analysis (MCDA) for the Boolean suitability model identified that every MPA (figure 2) is an unsuitable region for the development of a seaweed farm.

Background context to the criteria decision for aquaculture within MPA's: Along with a lease and marine licence an MPA assessment is also obligatory if the Marine Management Organisation supposes a proposed farm may threaten the conservation intentions of an MPA, and if a recognised risk cannot be avoided the planning request is rejected (Wood *et al*., 2017). Therefore, as permission to cultivate macroalgae in an MPA is not guaranteed and the assessment process is carried out at a site-specific level all MPA's (figure 2) for the Boolean suitability analysis were considered as areas not appropriate for the development of a seaweed farm. Additionally, regarding the soft constraint habitat variable, a site-specific habitats regulation assessment will be required if the proposed farm could potentially impact a habitat (Wood *et al*., 2017). However, as the UK currently designates MPA's using a feature-based approach, all sites with protected habitats will be enclosed within an MPA. Suggesting that, protected habitats can be avoided during the site selection process by regarding all MPA's as unsatiable for the placement of an aquaculture site (Wood *et al*., 2017).

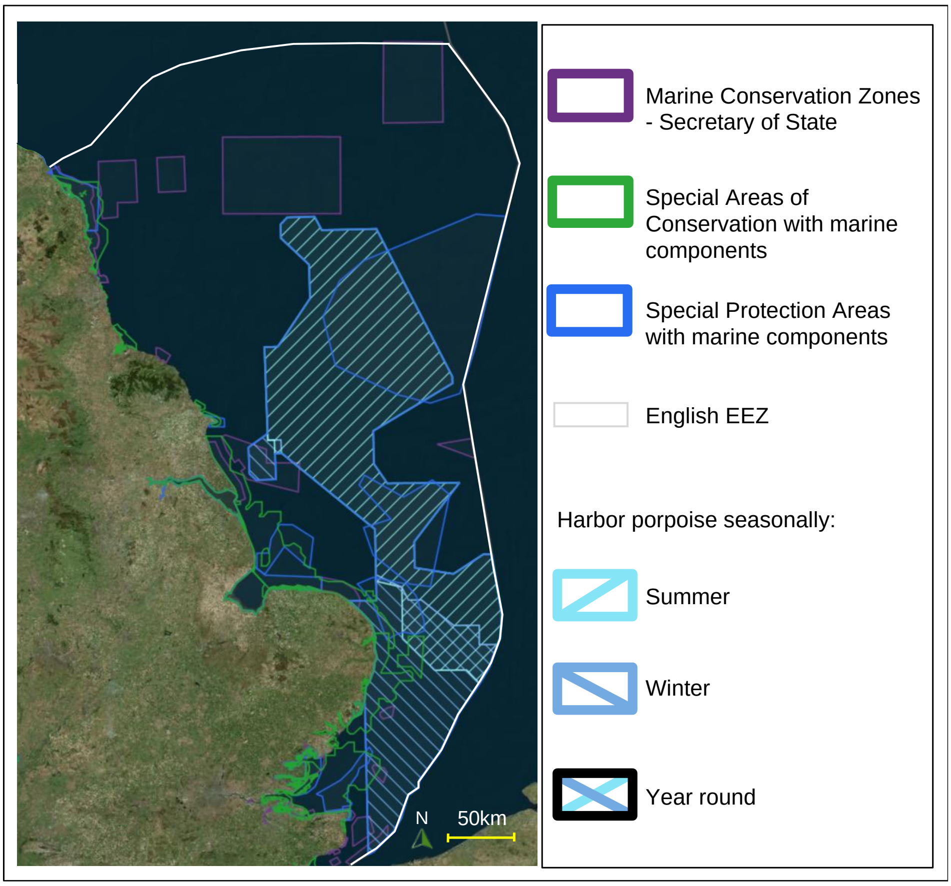

Figure 2: Current (2022) site-specific protected areas at sea in the English North Sea exclusive economic zone (EEZ). Data source: JNCC, 2022.

Hard planning constraints
Risks associated with hard constraints can be significantly reduced by locating a seaweed farm away from them, which is why the criteria decision analysis indicated that all hard constrain features (figures 3 and 4), should be excluded from potential cultivation sites within the Boolean modelling.

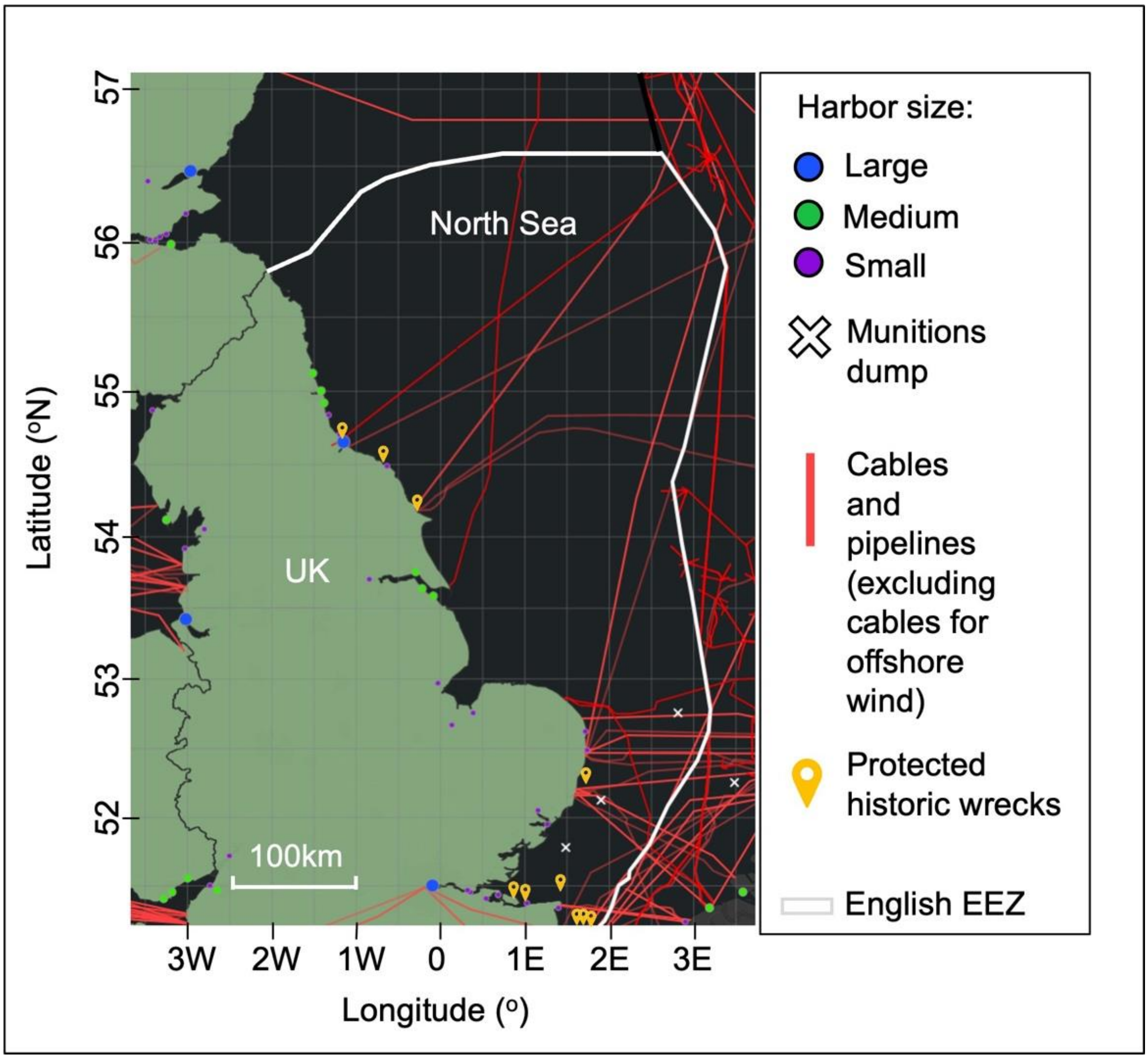

Figure 3: The location of hard constraint variables. Not to scale (figure illustrated the whereabouts of variables but not necessarily their actual size to scale). Made in ArcGIS online using the following layer selection data sources: Ports, National Geospatial Intelligence Agency (2018); Munition dumps, EMODnet (2018); Cables and pipelines, TeleGeography (2016) and Infrapedia, 2018; Protected wrecks, Maritime & Coastguard Agency (2020).

Figure 4 illustrates fully commissioned and development areas for the energy and aggregate sector. The analysis concluded that seaweed cultivation cannot occur among these hard constraint areas bar, hydrocarbon fields as currently not every oil or gas reserve is a development area, so for the Boolean model only hydrocarbon platform safety exclusion zones, were classed as unsuitable.

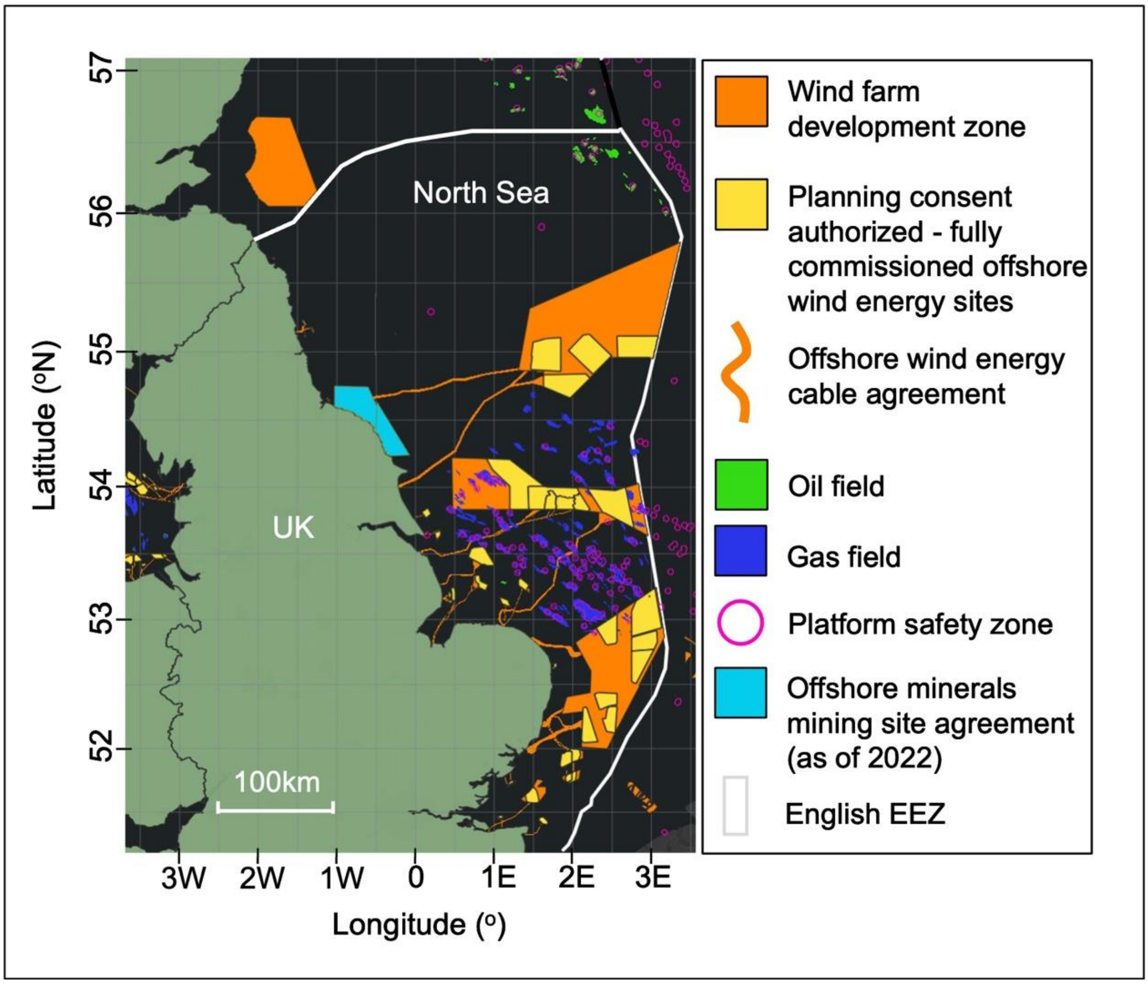

Figure 4: Positioning of current (2022) aggregate (mainly gravel and sand) extraction zones and, the offshore energy sector in the east coast English exclusive economic zone (EEZ). Made in ArcGIS online using the following layer selection data sources: Cable agreement, The Crown estate (2021); Offshore wind energy sites, Esri (2017); Oil and gas fields, Leeuwarden (2021); Offshore wind farm development zones, Global Offshore Wind Farm Database (2019) and OSPAR (2016); Authorised seabed aggregate extraction sites, The Crown Estate (2022).

Culture specific technical suitability
Figure 5 illustrates that tidal current velocities are stronger during the spring tidal phase and weaker during the neap tidal phase. Figure 5 shows that the strongest currents are usually found in straits during both neap and spring tides. Currents can be significant in transporting nutrient supplies, and findings show that the neap tidal velocity across the North Sea study area still meets the minimum current speed requirement (0.1 m/s) needed to support *S. latissima* growth (MMO, 2019). Opposingly, peak spring tidal velocities off large Southeast headlands exceeds 1.5m/s, making these areas unsuitable for the Boolean suitability map.

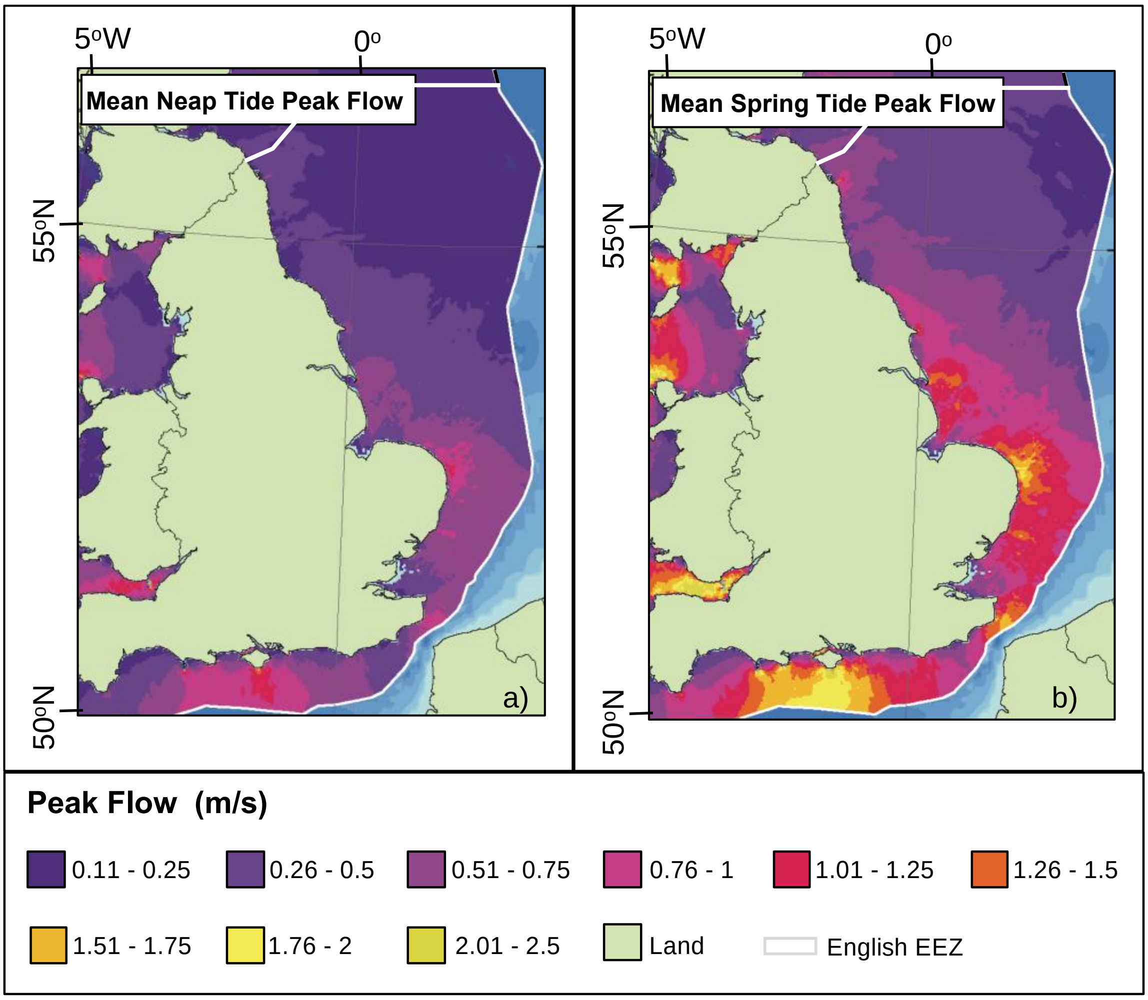

Figure 5: a) Average neap tide peak flow, during the year 2008. **b)** Average maximum current velocity for spring tides in 2008. Tidal model formed through daily forecasts over one year. Model precision is reduced in locations <1km to land. Tidal power has been analysed for the top half of the water column. This figure (modified from ABPmer, 2008) has been used to illustrate current speed: Reproduced from http://www.renewables-atlas.info /© Crown Copyright.

General North Sea bathymetry (figure 6) trends show a depth increase from south to north, and in a west to east cross-section the depth is the shallowest over Dogger Bank and between 53ºN – 54ºN. Furthermore, the water depth within the English EEZ does not reach > -150m. This concludes that the entire area, bar small coastal strips that are < 5m deep, will be suitable to facilitate infostructure for macroalgae cultivation.

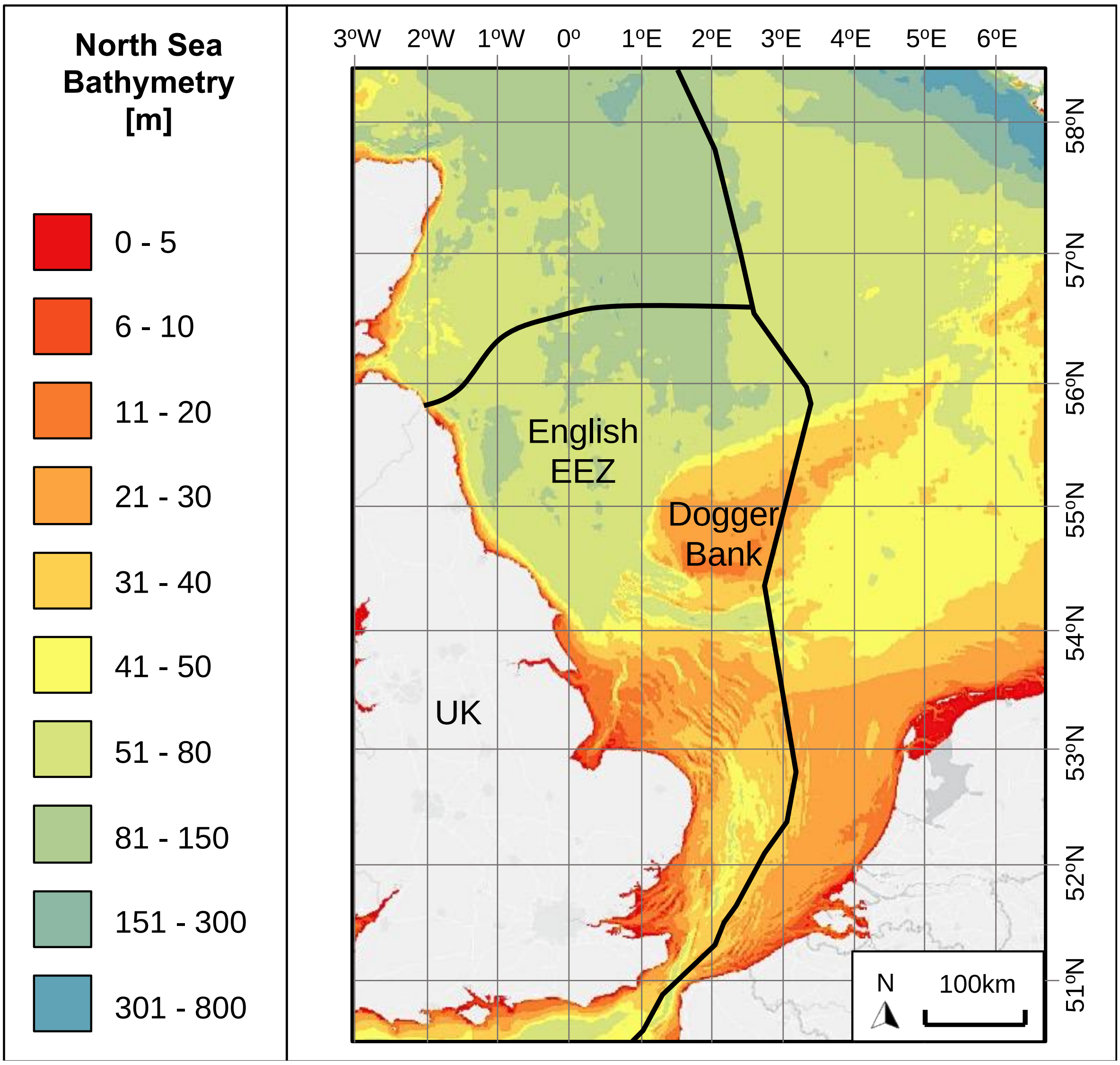

Figure 6: A standard description of long-term North Sea bathymetry. Data source: EMODnet (2016) and General Bathymetric Chart of the Oceans from the North Sea Observation and Assessment of Habitats (2014).

Figure 7 displays that in areas there is a 2m range between the annual extremes of seasonal mean significant wave heights (SWH). Additionally, the further offshore the larger the SWH. All areas bar the northeast corner of the English EEZ are year-round suitable for the Boolean suitability map. However, figure 7 shows there is increased scope for seasonal cultivation.

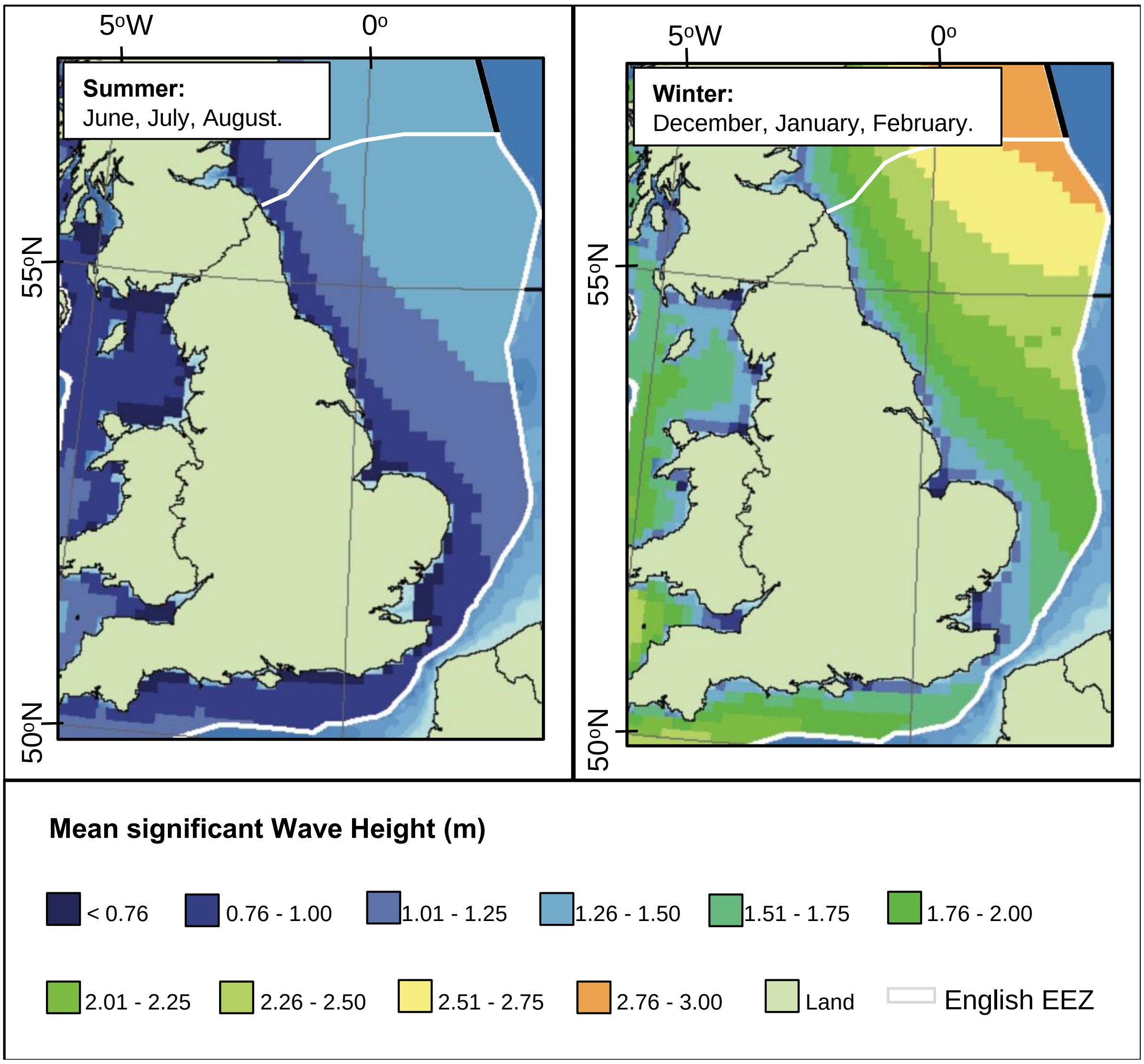

Figure 7: Annual extremes in the seasonal mean significant wave height across the UK's exclusive economic zone. Modelled wave data is less robust in shallow waters (<20m) and zones of complex bathymetry. Wave data is based on hourly values from 2000 – 2007. This figure (modified from ABPmer, 2008) has been used to illustrate wave heights: Reproduced from http://www.renewables-atlas.info /© Crown Copyright.

Saccharina latissima's **biological suitability**

Figure 8 illustrates that there is a considerable geographical expanse within the North Sea that meets the requirements to support the natural growth of *S. latissima*. This environmental suitability index includes data for photosynthetically active radiation (PAR), salinity, temperature, and total oxidised nitrogen (nutrient), variables. However, *S. latissima's* biological suitability for current speed tolerance has been included within the culture specific technical suitability analysis (figure 5). As the MCDA concluded that current speed environmental limits for farmed kelp are predominantly due to cultivation design rather than the seaweed's current tolerance in their natural environment. For the Boolean model, all areas identified as inadequate or absent of data will be classed as inappropriate for the placement of a seaweed farm.

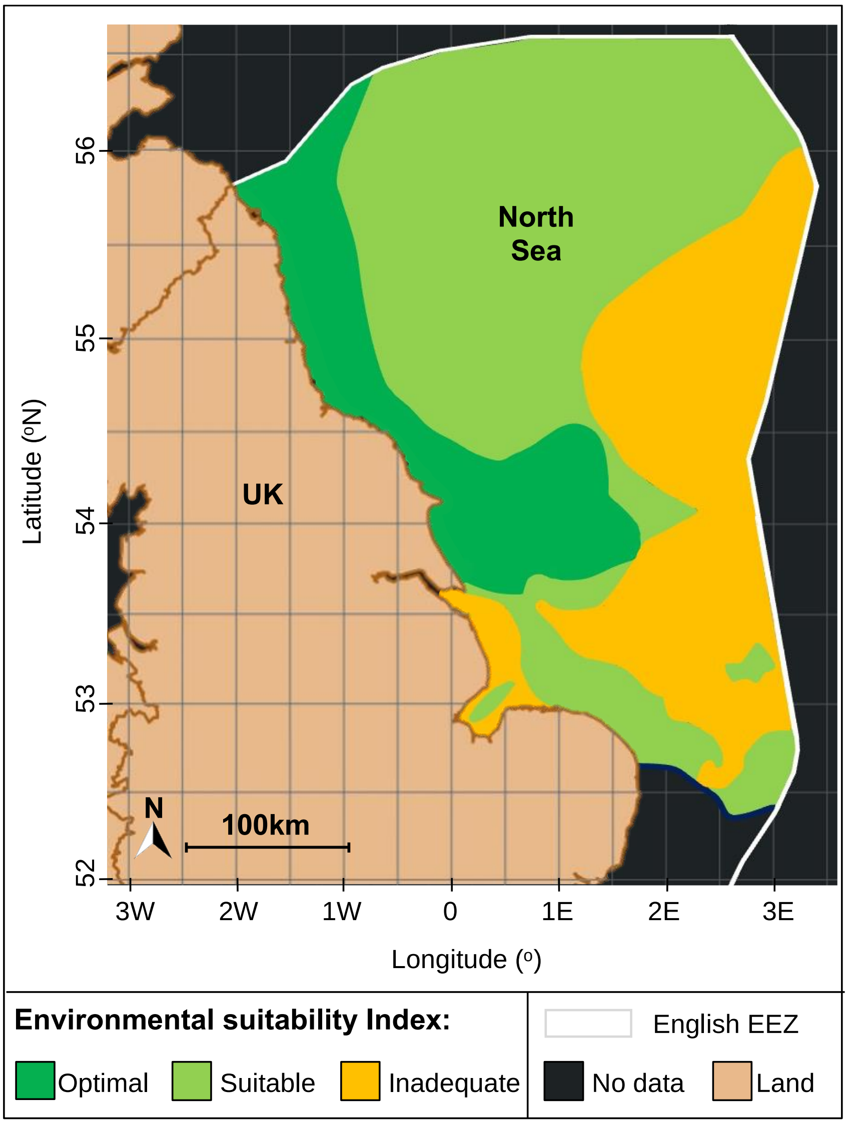

Figure 8: Areas suitable to support the year-round growth of *Saccharina latissima*. This index includes light climate, salinity, temperature and nutrient variables. Data accounts for annual extreme ranges rather than a mean value. Data source MMO (2019).

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