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# Assessing the potential for seaweed cultivation in EU seas through an integrated modelling approach

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ABSTRACT

The potential of large-scale seaweed cultivation to contribute to achieving ambitious EU-wide objectives, such as food security, energy independence, carbon neutrality and ecosystems restoration, is widely recognized. However, there is a lack of information on the suitability of EU marine regions for the installation of floating macroalgae cultivation infrastructures. In this study, we utilize the World Offshore Macro Algae Production Potential (WOMAPP) model in conjunction with state-of-the-art coupled hydrodynamic-biogeochemical models, to assess the environmental suitability of EU marine regions for seaweed cultivation. Our analysis reveals that the EU Atlantic regions are the most suitable areas for seaweed cultivation, particularly for cold-water and intermediate-water species. The potential cultivation area is extensive, spanning over 1 million km$^2$, and even taking a precautionary approach by occupying only 1% of that area could yield a yearly production of over 30 million tonnes dry weight. Adding logistical constraints (water depth and distance to coast) further limit the potential production to 5 million tonnes per year, only considering EU member states' waters. Furthermore, we discuss the opportunity to use integrated multi-trophic aquaculture (IMTA), to increase the potential for seaweed cultivation.

## 1. Introduction

As the global population continues to grow and the demand for natural resources increases, it becomes essential to use these resources sustainably and efficiently. This includes providing food, feed, energy, and other materials without exceeding planetary boundaries and respecting sustainable resource exploitation.

Seaweed (marine macroalgae) aquaculture is seen as a promising approach to meet these objectives. Seaweeds are expected to be used in a range of fields such as food production (Nayar and Bott, 2014; Roleda et al., 2010), feed (MacMonagail et al., 2018), feedstock for the bio based economy (Stévant et al., 2017; Helmes et al., 2018), pharmaceutical applications (Kang et al., 2016), cosmetics (Couteau and Coiffard, 2016) and bioremediation (i.e., removing pollutants from the aquatic environment; Elizondo-González et al., 2018). Due to their rapid growth, seaweeds have the potential to absorb large amounts of carbon, nitrogen, and phosphorous from seawater, offering natural solutions for $CO_2$ sequestration (Zhang et al., 2012; Alevizos and Barille, 2023; Wu et al., 2023) and eutrophication problems (Kotta et al., 2022).

Currently, seaweed cultivation is primarily concentrated in Asian countries, with minimal activity elsewhere (Araújo et al., 2019, 2021; Buschmann et al., 2017; Hughes et al., 2012). Cultivating seaweed in European Union (EU) waters could help the EU to achieve its ambitious environmental targets, as outlined in overarching policy initiatives, such as the Green Deal (COM(2019) 640 final), Carbon Neutrality (EC, 2019), Farm to Fork (COM(2020) 381 final), and the upcoming Nature Restoration Law (COM(2022) 304 final). Currently 99% of seaweed production in the EU depend on wild-stock harvesting while at global scale there is an opposite trend, with 99% of the production coming from cultivation (Vazquez-Calderon et al., 2022).

Given these considerations, the European Commission (EC) is promoting seaweed cultivation in its marine regions (COM(2021) 236 final). However, fundamental knowledge about the potential of this activity in European waters is still lacking. In November 2022, the EC highlighted several challenges and recommended actions to foster the growth of the algae industry into a resilient, sustainable and regenerative sector capable of meeting the increasing EU demand (EU Algae Initiative COM (2022) 592 final). Among the key issues identified were

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the high production costs and low-scale production, which are hindered by the lack of scientific understanding of the potential for growth in EU marine regions (Araújo et al., 2019; COM(2021) 236 final, van den Burg et al., 2016).

The capacity for seaweed cultivation depends on environmental factors that regulate the growth rates of the different species. To quantify the potential for cultivation, a detailed investigation of the environmental characteristics of EU marine regions is necessary. To date, studies on seaweed cultivation potential in EU waters are limited. For example, Thomas et al. (2019) assessed the potential for seaweed farming on the western coast of Sweden, in an area within Skagerrak expanding 150 km of coast. Kotta et al. (2022) further explored the potential for seaweed cultivation in the Baltic Sea using modelled environmental data to calculate potential growth rates and nutrient removal capabilities. A similar model-based approach was previously used by van der Molen et al. (2018) to identify potential environmental

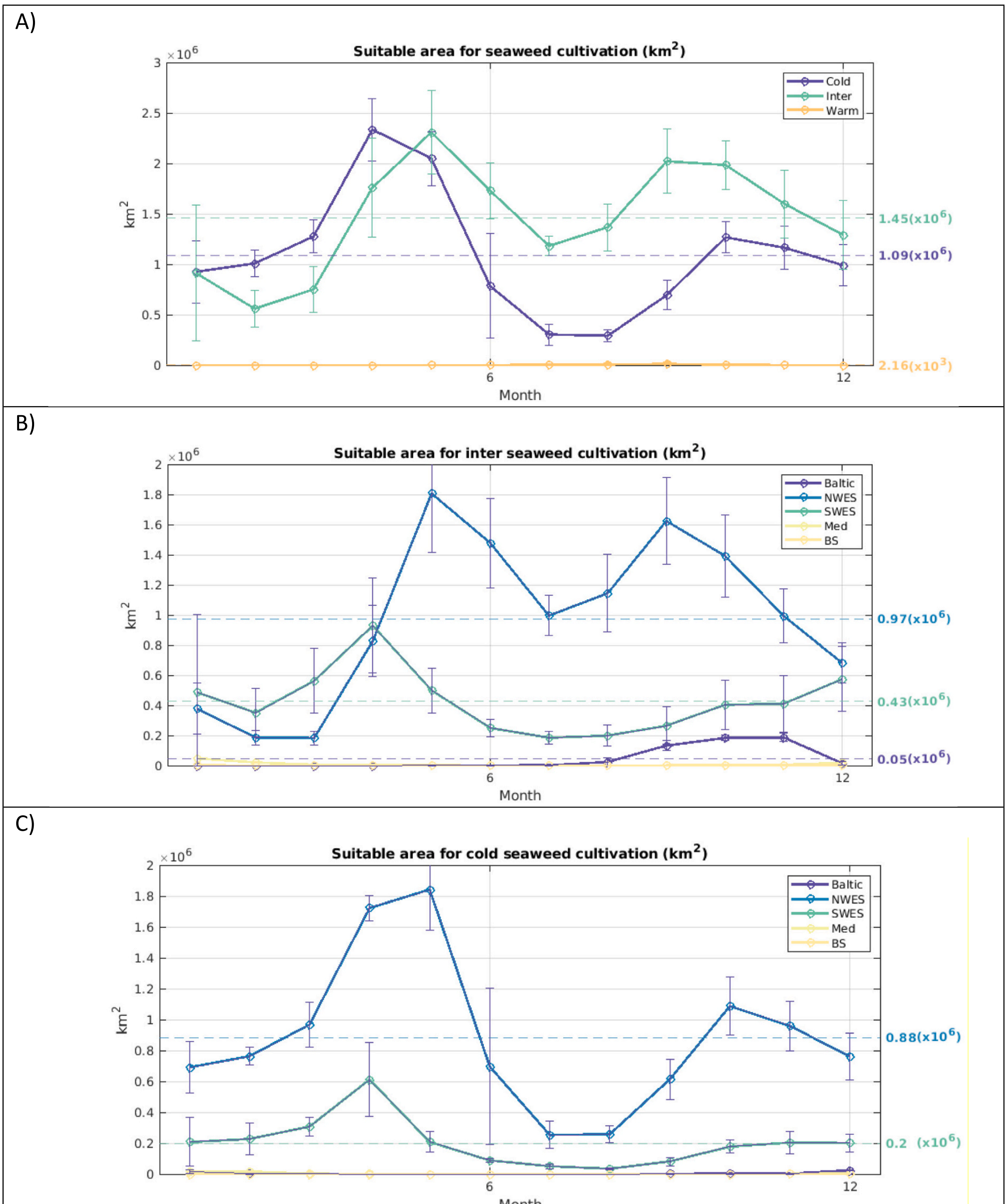


**Fig. 1.** A) Total suitable area (SSSmean>0.5) for the cold (blue line), intermediate (green line) and warm (orange line) seaweed species. B) Suitable area for intermediate seaweed species cultivation (SSS>0.5) for the five EU marine regions. C) Suitable area for cold seaweed species cultivation (SSS>0.5) for the five EU marine regions.

impacts of existing seaweed facilities in Dutch and UK waters.

However, full EU-wide evaluations of the potential for seaweed cultivation are still missing. The EU has largely invested in monitoring and research to increase the understanding of environmental conditions and their variability in its marine regions. However, available data is still insufficient to provide a comprehensive picture (including spatial and temporal variability) of marine environmental variables. In addition to these monitoring efforts, the EU has made progress in developing numerical models that could provide a broad description of environmental variables in EU waters.

The EU is, indeed, working towards developing the *EU Digital Twin of the Ocean* in the coming years. Examples of this are the numerical simulations provided by the Copernicus Marine Environmental Data service (https://marine.copernicus.eu/) or the Blue2 modelling framework (Blue2MF) developed by the Joint Research Centre (JRC) of the EC. The Blue2MF is a tool designed to evaluate the impacts of policy options on the environmental status of all EU marine regions (Macias et al., 2022) and can provide key environmental variables determining the potential growth of seaweed in marine waters.

In this article, we combine the environmental data provided by Blue2MF and Copernicus models with the World Offshore Macro Algae Production Potential model (WOMAPP, van Oort et al., 2023) to estimate the potential for seaweed growth in floating infrastructures for the five EU marine regions: Baltic Sea, North Western European Shelf (NWES), South Western European Shelf (SWES), Mediterranean Sea, and Black Sea.

Together with the bio-physical identification of cultivation capacity, it is necessary to consider other factors such as the increasing sustainability issues with wild harvesting, the high production costs in aquaculture and a limited market demand, that are hampering the development of the macroalgae sector.

The outcomes of this study, particularly the estimated spatial-temporal pattern of suitable areas for seaweed cultivation, can be a fundamental tool for investors to better locate farming sites aiming to maximize production and economic performance; while for public authorities it can help to ensure the proper allocation of aquaculture activities in integrated maritime spatial planning.

## 2. Methods

### 2.1. Environmental information for EU marine regions, the Blue2 modelling framework

The EC's JRC has developed an integrated modelling tool known as the Blue2MF, which provides numerical simulations of environmental variables at high spatial and temporal resolution in the five EU marine regions (Fig. 1). It includes either atmospheric forcing from reanalysis or from Global Circulation Models, land-use models, hydrological models for freshwater quantity and quality, hydrodynamic-biogeochemical coupled modes specific to each marine region, high trophic level marine models, and Lagrangian models (Macias et al., 2022).

This tool has been specifically designed to assess the status of EU marine ecosystems under various management scenarios, primarily related to policy implementation. Furthermore, it offers a comprehensive description of the historical and current conditions of these ecosystems when employed in hindcast mode (e.g., Macias et al., 2014; Miladinova et al., 2017).

Within Blue2MF, each of the EU marine regions has its dedicated hydrodynamic-biogeochemical setups (Table 1), as the unique characteristics of the ecosystems require specific, tailored biogeochemical models. The hydrodynamic model utilized in all cases is the General Estuarine Transport Model (GETM) (Burchard and Bolding, 2002), with varying spatial resolutions to balance computational time and numerical accuracy needs (Table 1). All regional implementations share the same atmospheric forcing from the European Centre for Medium Weather Forecast (ECMWF) ERA5 reanalysis. Additionally, riverine conditions, including freshwater quantity and quality (nutrients), are consistent for all EU marine regions and are provided by the combined hydrological models LISFLOOD (water quantity) and GREEN (water quality) included in the Blue2MF (Burek et al., 2013; Grizzetti et al., 2012).

The hydrodynamic-biogeochemical models within the Blue2MF were integrated for the period spanning January 2015 to December 2018, providing monthly values of the environmental variables required for the Seaweed Site Suitability (SSS) calculation (see next subsection).

### 2.2. Seaweed site suitability computed by the WOMAPP model

The WOMAPP model calculates SSS based on six environmental factors: sea surface temperature (SST), sea surface salinity (SSsal), surface nitrate concentration (N), and surface phosphate concentration (P), provided by the Blue2MF described above and significant wave height (SWH) and solar irradiance (Irr) provided by ERA5 reanalysis. Previous studies (e.g., Breeman and Pakker, 1994; Field et al., 1998; Hauxwell et al., 2003; Binzer et al., 2006) have also shown the significance of these factors in seaweed growth. The SSS is computed as follows:

$$SSS_{i,x} = min(f(SST), f(SSsal), f(N), f(P), f(SWH), f(Irr)) \tag{1}$$

Where *'i'* stands for month and *'x'* for the position within the model grid. The SSS provides a value between 0 (not suitable) and 1 (perfectly suitable) for seaweed cultivation for each evaluated site. The shape of the limiting functions is shown in Fig. S1.

In the original study by van Oort et al. (2023), WOMAPP was utilized to assess the suitability for three distinct types of seaweed: cold-water species (representing *'brown'* macroalgae), intermediate-water species (representing *'green'* macroalgae), and warm-water species (representing *'red'* macroalgae). In alignment with this approach, our study evaluates the suitability of EU marine regions for the cultivation of these three major seaweed groups. Table 2 provides a list of the main species within each group currently being cultivated in the EU.

The SSS can be multiplied by a potential growth rate (PGR, in tonnes dry weight $ha^{-1}$ $month^{-1}$) to obtain an Absolute Annual Growth Rate (AAGR) that is specific for each evaluated time and position:

$$AAGR_{i,x} = SSS_{i,x} * PGR \left(t\, DW\, ha^{-1} month^{-1}\right) \tag{2}$$

Although conceptually straightforward, the WOMAPP approach is somewhat limited by the availability of consistent and reliable environmental data required to calculate the SSS index. While certain data, such as sea surface temperature (*SST*) or significant wave height (*SWH*), can be obtained through remote sensing, others are more difficult to acquire and are only measured sporadically in both time and space. The original implementation of the WOMAPP model utilized global environmental data at relatively low spatial resolution ($1^{o}$) and monthly

**Table 1**
Regional model setup descriptions and references for Blue2MF data.

| Marine region | Spatial resolution (km) | Hydrodynamic model | Biogeochemical model | References |
|---|---|---|---|---|
| Baltic Sea | 7.4 × 3.7 | GETM | ERGOM | Parn et al., 2020, 2021 |
| NWES | 8.8 × 5.5 | GETM | ERSEM | Duteil et al., 2023; Friedland et al., 2021 |
| SWES | 8.8 × 5.5 | GETM | L-ERSEM | Ferreira Cordeiro et al., 2022 |
| Mediterranean | 9.2 × 9.2 | GETM | MedERGOM | Macias et al., 2014, 2018a, 2018b, 2019 |
| Black Sea | 2.8 × 3.6 | GETM | BSEM | Miladinova et al., 2020; |

**Table 2**
Main seaweed species cultivated in the EU. Sources: Kotta et al., 2022; van der Burg et al., 2013; van der Molen et al., 2018; Vazquez Calderon et al., 2022.

| Class | Species | Intermediate/cold |
|---|---|---|
| Brown | *Alaria esculenta* | Cold |
| Brown | *Alaria marginata* | Cold |
| Brown | *Alaria* sp. | Cold |
| Brown | *Ascophyllum nodosum* | Cold |
| Brown | *Fucus serratus* | Cold |
| Brown | *Fucus vesiculosus* | Cold |
| Brown | *Himanthalia elongata* | Cold |
| Brown | *Himanthalia* sp. | Cold |
| Brown | *Laminaria digitata* | Cold |
| Brown | *Laminaria hyperborea* | Cold |
| Brown | *Laminaria* sp. | Cold |
| Brown | *Saccharina latissima* | Cold |
| Brown | *Undaria pinnatifida* | Cold |
| Brown | *Undaria* sp. | Cold |
| Green | *Codium tomentosum* | Intermediate |
| Green | *Ulva intestinalis* | Intermediate |
| Green | *Ulva lactuca* | Intermediate |
| Green | *Ulva* sp. | Intermediate |
| Green | *Ulvella lens* | Intermediate |
| Red | *Falkenbergia* sp. | Intermediate |
| Red | *Asparagopsis* sp. | Intermediate |
| Red | *Calliblepharis jubata* | Intermediate |
| Red | *Chondrus crispus* | Intermediate |
| Red | *Chondrus* sp. | Intermediate |
| Red | *Gracilaria* sp. | Intermediate |
| Red | *Palmaria palmata* | Intermediate |
| Red | *Porphyra umbilicalis* | Intermediate |
| Red | *Vertebrata lanosa* | Intermediate |

climatological values. However, such data is too coarse in both space and time to conduct the SSS analysis in regional seas. This limitation prompted our use of Blue2MF data in this study.

### 2.3. Location of seaweed cultivation facilities

The location of existing seaweed cultivation facilities in EU waters were obtained from the EMODnet Human Activities portal (https://emodnet.ec.europa.eu/en/human-activities) accessed in October 2023. The positions of these cultivation sites were utilized to validate the results from the WOMAPP model as further outlined in the results section.

### 2.4. Alternative sources of environmental information, the Copernicus Marine Environmental Service

To complement and, in certain respects, validate the results obtained from the SSS calculations using the environmental data from Blue2MF, information from the Copernicus Marine Service models was utilized. Specifically, ten different datasets were retrieved from the Copernicus Marine Data Storage (https://data.marine.copernicus.eu/products) in October 2023 (see Table 3). These datasets offer physical and biogeochemical conditions for the five EU marine regions, covering the same period of January 2015 to December 2018 used in the Blue2MF integration. The Copernicus model data was projected onto the Blue2MF grid to generate fully comparable spatial maps, and the same environmental variables were employed to calculate the Seaweed Site Suitability using the WOMAPP model (SSS-Copernicus).

The SSS derived from the Blue2MF data and the SSS-Copernicus were compared to evaluate the uncertainty in the predictions, focusing on spatial patterns and seasonal dynamics. Detailed findings from this comparison are presented in the results section.

## 3. Results

### 3.1. SSS calculations

To determine which type of seaweed has the highest potential for cultivation in EU marine regions, we evaluated the total area in which mean SSS is higher than 0.5, following the criteria defined by van Oort et al. (2023). Integrated values (Fig. 1A) clearly indicate that both intermediate and cold species (mean area of 1.45 and 1.1 million km$^2$, respectively) are more suitable for cultivation, while warm species do not appear to be of potential interest (mean suitable area of 2160 km$^2$). For this reason, warm species are excluded from subsequent analyses, focusing solely on intermediate and cold species.

By marine region, it is evident that the most suitable basins for intermediate species cultivation are the NWES and SWES domains (970,000 and 430,000 km$^2$, respectively), with only 50,000 km$^2$ being suitable in the Baltic Sea (Fig. 1B). A similar situation is found for cold seaweed species (Fig. 1C), with 880,000 km$^2$ in the NWES domain and 200,000 km$^2$ in the SWES domain, being the only suitable regions.

For both types of species (intermediate and cold), specific seasonal cycles of suitability are apparent in the NWES and SWES domains (Fig. 1B and C). In the NWES domain, SSS for both types of seaweed presents two peaks, one in spring and another in fall. The main difference is that for intermediate species, the peaks are closer together with a less acute summer dip, while for cold water species, the peaks occur further apart (i.e., during colder months), and the minimum in summer is larger. In the SWES domain, SSS cycles are somewhat different, with the main peaks for both types of species occurring during spring, a moderate decrease in summer, and a gradual increase towards the end of the year.

To better understand the spatial distribution of SSS levels and the factors limiting their value for intermediate and cold water species, we present the maps in Figs. 2 and 3. Mean SSS for the 4-year analysed period for intermediate species (Fig. 2A) confirms the concentration of suitable areas in the NWES and SWES domains, with some areas in the southern Baltic Sea showing moderate SSS values. The North Sea, Irish Sea and coastal regions of the Celtic Sea are the regions within the NWES domain showing higher SSS values. In the SWES domain, SSS for intermediate water species is high in the coastal fringe and particularly in the northern coast of the Bay of Biscay. Fig. 2A also shows that the positions of the seaweed cultivation sites correspond to regions for which the model calculates relatively high SSS values.

The main limiting factors for intermediate seaweed species growth are spatial heterogeneity (Fig. 2B). In the Baltic Sea, this type of seaweed is mostly limited by temperature, as well as in the North Sea. In the Irish Sea and British Channel regions, the most limiting factor is salinity, while waves are limiting suitability in the north-western part of the NWES domain. In most of the SWES domain, the main limiting factor is nitrogen, although in coastal areas (especially in the northern area of the domain), salinity and phosphate availability can be the most limiting factors. In the Mediterranean Sea, nutrients are the main limiting factor,

**Table 3**
Regional models from the Copernicus Marine Service used in the analysis.

| Marine region | Spatial resolution (km) | Hydrodynamic dataset | Biogeochemical dataset |
|---|---|---|---|
| Baltic Sea | 2 × 2 | BALTICSEA_MULTIYEAR_PHY_003_011 | BALTICSEA_MULTIYEAR_BGC_003_012 |
| NWES | 12.3 × 7.4 | NWSHELF_MULTIYEAR_PHY_004_009 | NWSHELF_MULTIYEAR_BGC_004_011 |
| SWES | 9.2 × 9.2 | IBI_MULTIYEAR_PHY_005_002 | IBI_MULTIYEAR_PHY_005_002 |
| Mediterranean | 4.7 × 4.7 | MEDSEA_MULTIYEAR_PHY_006_004 | MEDSEA_MULTIYEAR_BGC_006_008 |
| Black Sea | 4.1 × 3.1 | BLKSEA_MULTIYEAR_PHY_007_004 | BLKSEA_REANALYSIS_BIO_007_005 |

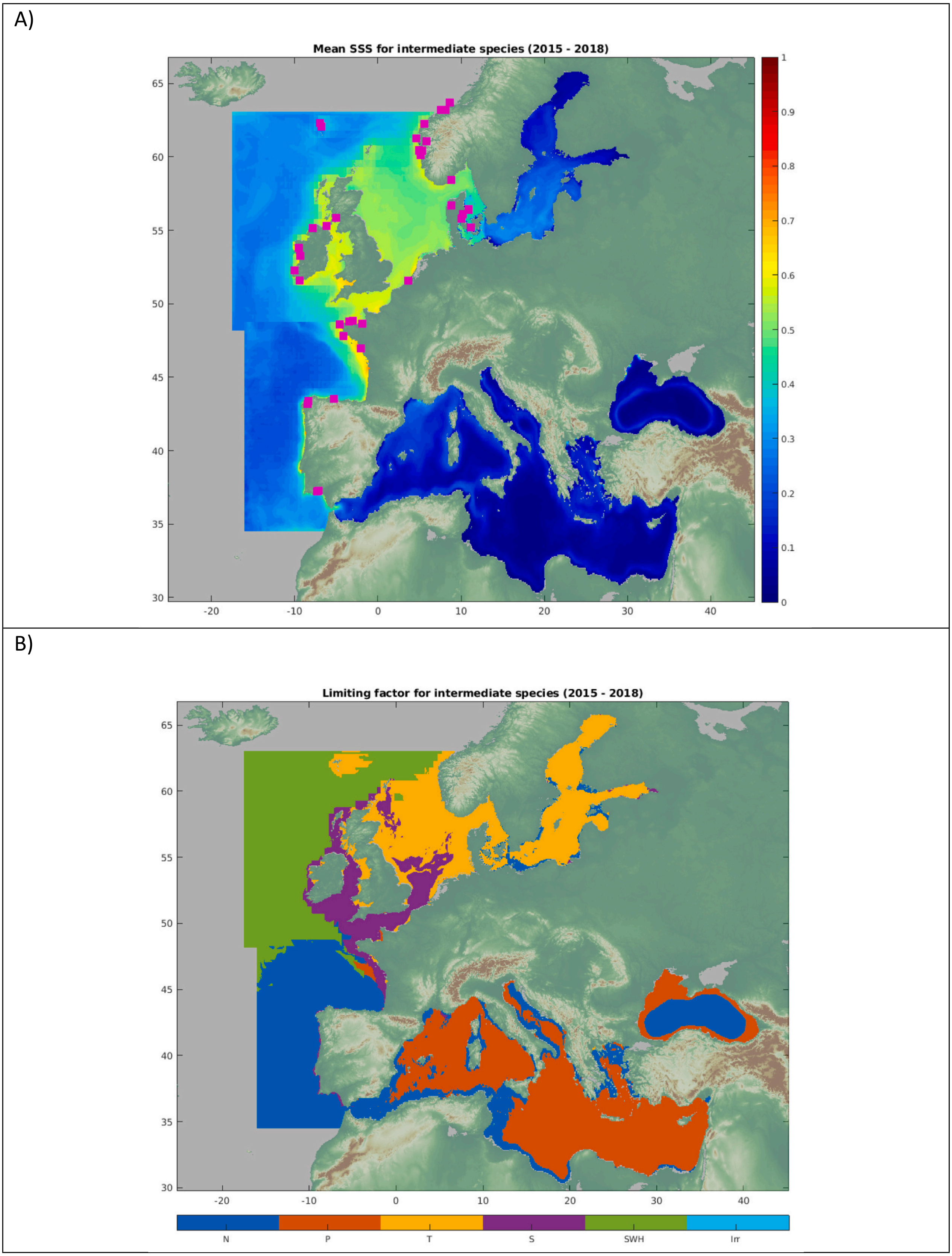


**Fig. 2.** A) Mean SSS over the 48-month study period for intermediate species in the five EU marine regions. Magenta squares mark the position of known seaweed cultivation sites. B) Main limiting factor for intermediate seaweed species growth for the entire study period. N: nitrate, P: phosphate, T: temperature, S: salinity, SWH: waves, Irr: irradiance.

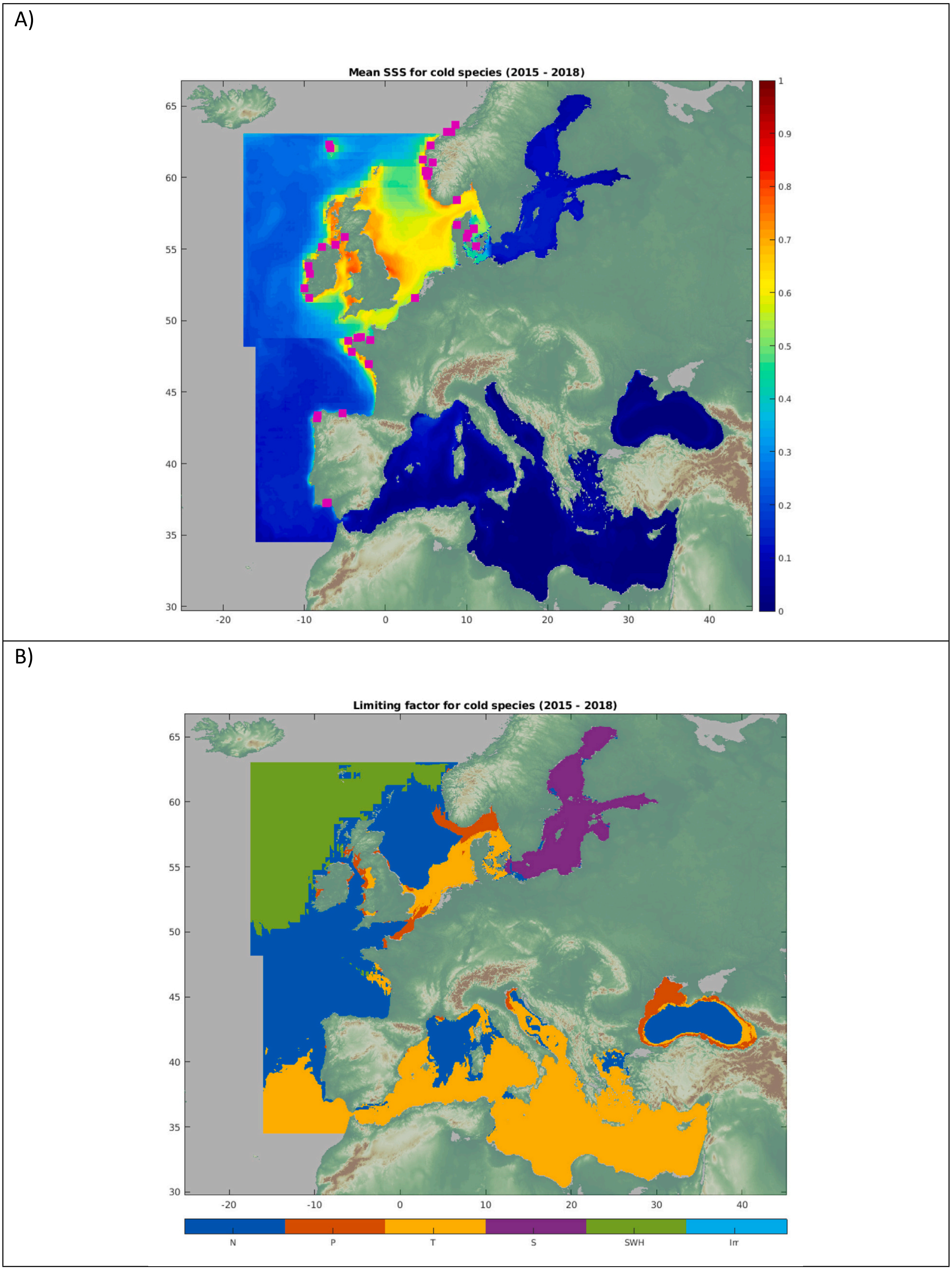


**Fig. 3.** A) Mean SSS over the 48-month study period for cold species in the five EU marine regions. Magenta squares mark the position of known seaweed cultivation sites. B) Main limiting factor for cold seaweed species growth for the entire study period. N: nitrate, P: phosphate, T: temperature, S: salinity, SWH: waves, Irr: irradiance.

with a transition from nitrogen-limited conditions in the west to phosphate-limited in the east. The same is true for the Black Sea, where coastal regions are mostly limited by phosphate, while in the open sea nitrate is a limiting factor.

The spatial distribution of SSS for cold water species (Fig. 3A) shows an even higher concentration of suitable areas within the NWES domain and the northernmost regions of the SWES domain. In the NWES, high SSS values are calculated for most of the coastal areas with decreasing values moving offshore. In the SWES domain, high SSS values are only calculated at the very coastal fringe, as with intermediate species, particularly in the northern coasts of the Bay of Biscay. Again, the location of cultivation sites coincides with suitable areas according to our modelling approach.

The limiting factors for cold water species (Fig. 3B) are somewhat different. In the Baltic Sea, the growth is mostly limited by salinity, in the southern coasts of the NWES domain, temperature and phosphate are co-limiting, while in the open sea regions of the North Sea and the SWES domain, nitrate is the limiting factor. As for intermediate water species (Fig. 2B), the growth of cold species in the north-western part of the NWES domain is limited by waves' height. For the southern part of the SWES domain and for the Mediterranean Sea, temperature is the most impacting factor for cold water species while for the Black Sea nutrient availability is, once again, the limiting parameter, phosphate in the coastal regions and nitrate in the open waters.

A more detailed look at the seasonal maps of SSS values (Fig. S2) shows that variability is larger for intermediate water species than for cold water species. Intermediate seaweed can potentially grow in southern regions (Mediterranean Sea and southern SWES) during cold months (winter/fall). During the warmest period of the year (spring/summer) SSS for intermediate species is only high in the northern part of the SWES domain and within the NWES, in a similar pattern shown in Fig. 2A. Seasonal variability in SSS distribution for cold water species (Fig. S2) is lower as it remains high only in the northernmost regions of the Atlantic domains. Only during winter, some regions in the north-western Mediterranean and southern SWES shows slightly higher SSS values.

From the maps shown in Figs. 2 and 3, it became quite clear that suitable areas for intermediate and cold water species are quite coincident in general. Obviously, simultaneous cultivation of both type of species is not possible for the same space and time so additional useful information for a potential stakeholder is shown in Fig. S3, where the percentage of time during the investigated period (2015 to 2018) that SSS values are above the 0.5 threshold for each type of seaweed is shown. From this figure, it seems clear that conditions within the North Sea proper are more appropriate for cold water species cultivation while further south it seems better to concentrate on the cultivation of intermediate species.

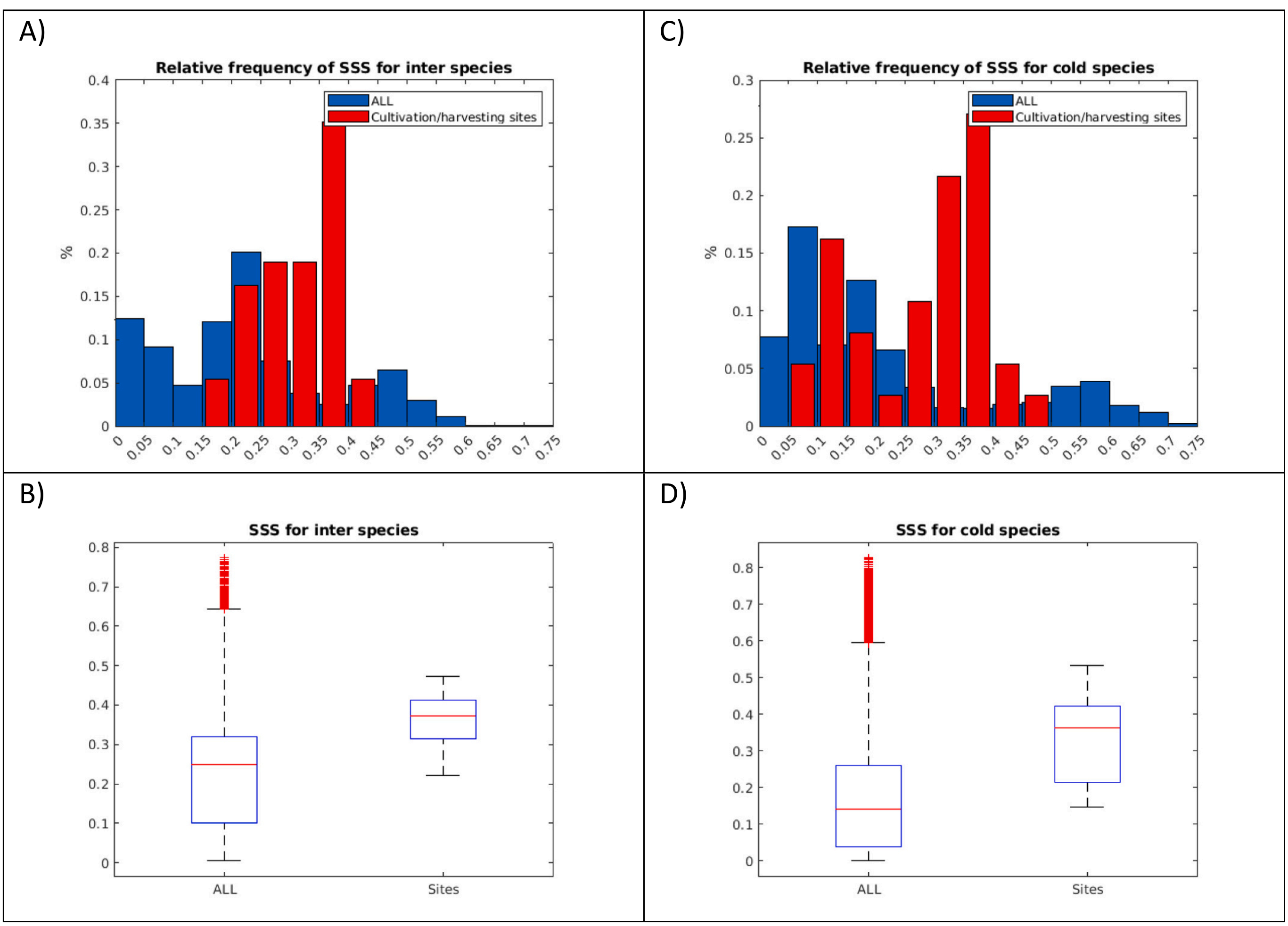


**Fig. 4.** A) Probability distribution function of SSS values for intermediate species in the entire Blue2 domain (blue bars) and at the cultivation sites (red bars). B) Box-plot for SSS values for intermediate seaweed species in the entire Blue2 domain and at cultivation sites. C) Probability distribution function of SSS values for cold species in the entire Blue2 domain (blue bars) and at the cultivation sites (red bars). D) Box-plot for SSS values for cold seaweed species in the entire Blue2 domain and at cultivation sites.

### 3.2. SSS validation

Validating the SSS values provided by the WOMAPP model presents a considerable challenge. While the underlying hydrodynamic and biogeochemical conditions have been previously validated for the different marine regions, as stated in Table 1, there are no monitoring data available to directly test the reliability of the SSS calculation. However, an indirect validation method involves checking if the observed locations of seaweed cultivation facilities (magenta squares in Figs. 2A and 3A) correspond to modelled suitable areas.

The probability distributions of SSS for the entire modelled region (blue bars) and the corresponding SSS extracted at the specific observed geo-located cultivation sites (red bars) are shown in Figs. 4A (intermediate-water species) and 4C (cold-water species). It is qualitatively evident that, for both species types, cultivation sites are concentrated around relatively high SSS values, with no cultivation sites coinciding with low SSS. The differences are further highlighted in the box-plots shown in Fig. 4B and D. For both types of species, the mean SSS is higher in the observed cultivation sites than in the entire modelled domain, with these differences being significant under both normal (i.e., t-student, $p < 0.01$) and non-normal (i.e., Mann Whitney $U$ test, $p < 0.01$) statistical tests. It is important to note, however, that the spatial resolution of the Blue2 models (Table 1) is not high enough to properly resolve coastal topography and associated oceanographic patterns. Additionally, cultivation sites are typically located in coastal bays, for which our models cannot provide accurate estimates of environmental variables (and hence SSS), making the comparison quite challenging.

Another approach to validate the SSS derived using the Blue2 models is to apply the WOMAPP model to the environmental conditions provided by the Copernicus Marine models detailed in Table 2. We then compare both the spatial patterns of SSS and the temporal distribution of suitable areas (SSS $>$ 0.5) calculated with both sets of biophysical models (Fig. 5).

For both types of species, there are high correlations between Blue2MF and Copernicus spatial and temporal SSS patterns, with correlation coefficients around 0.8 for intermediate species and around 0.9 for cold-water species, and very similar root mean square deviation values in both datasets. To exemplify these high correlation values and the very similar absolute figures, the time-series of suitable areas for both types of species, using both biophysical models (Blue2 and Copernicus), are shown in Fig. S4. It is important to bear in mind that the Blue2 and Copernicus models are independent and only share the atmospheric forcing (from ECMWF) and some boundary conditions in the open North Atlantic Ocean.

### 3.3. Potential yield calculations

Given the good agreement between the two modelling approaches shown above, we can assume that the depicted SSS distributions (both spatial and temporal) are a reliable approximation of the observed suitability for seaweed cultivation in EU marine regions. Consequently, we can go a step further and apply the WOMAPP approach to calculate the AAGR (Eq. (2)) by assuming a Potential Growth Rate (PGR) of 4.4 t dry weight (DW) per hectare and per month (van Oort et al., 2023).

To compute the AAGR, we impose a more stringent limitation than in the original WOMAPP application (van Oort et al., 2023): i.e., the SSS should be above 0.5 for at least six months in a year to consider the location as *'adequate'* for seaweed cultivation. The application of this limiting threshold generates the maps shown in Fig. 6 for the mean AAGR for both types of species. Integrating the spatial data in Fig. 6 allows us to calculate the overall potential production of seaweed in the different EU marine regions (Fig. 7). As previously indicated, most potential production occurs in the NWES (80%) and SWES (20%) domains, with a possible overall growth for seaweed of approximately 3 billion tonnes per year.

These figures of suitable areas serve as upper bound values, as utilizing the entire North Sea for seaweed cultivation, as shown in Fig. 6, would be unrealistic. Previous assessments, such as those by van Oort et al. (2023), have suggested that only 1% of the suitable area should realistically be allocated to seaweed cultivation to prevent severe alteration of marine ecosystems and allow for other anthropogenic activities. Adhering to these precautionary principles, this would imply the potential occupation of approximately 10,000 km$^2$ with an annual seaweed productivity of around 30 million tonnes DW.

We can further refine this approach by taking into consideration some logistical constrains for the cultivation activity such as the water depth (limiting the anchoring of structures) and the distance to coast (determining the travelling time to the installations). As a proof of concept, we applied a water depth limit of 100 m and a maximum distance to coast of 10 nautical miles and excluded non-EU Member States (i.e., UK and Norway shorelines). The potential seaweed harvest occupying 1% of the suitable area amounts to 5.5 to 4.3 Mt. y$^{-1}$ using between 1900 and 1400 km$^2$ (Table 4).

The biomass production by cultivating seaweed (i.e., the AARG) has

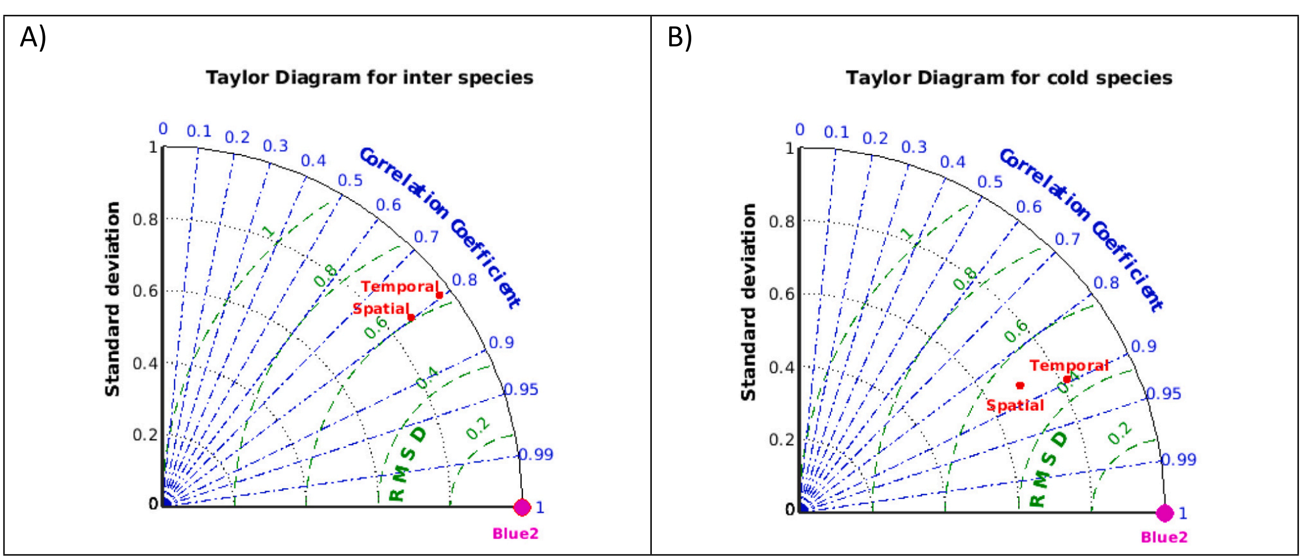


**Fig. 5.** Taylor diagrams for the comparison of SSS calculated with Blue2MF data and with Copernicus models for spatial and temporal patterns. A) For Intermediate seaweed species. B) For cold seaweed species.

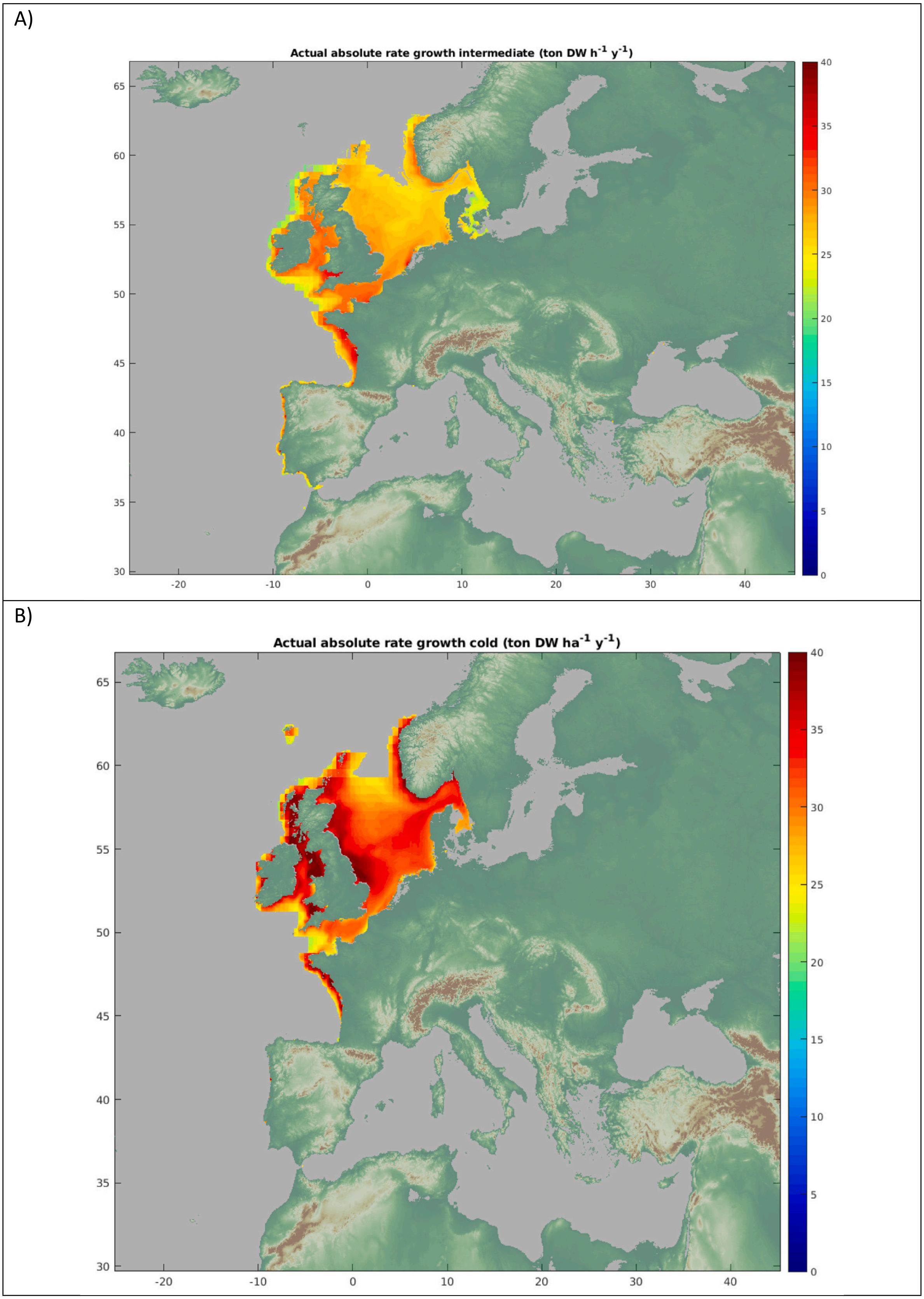


**Fig. 6.** Actual absolute rate of growth (AARG) for intermediate (A) and cold (B) species in the regions where SSS is above 0.5 during at least 6 months per year.

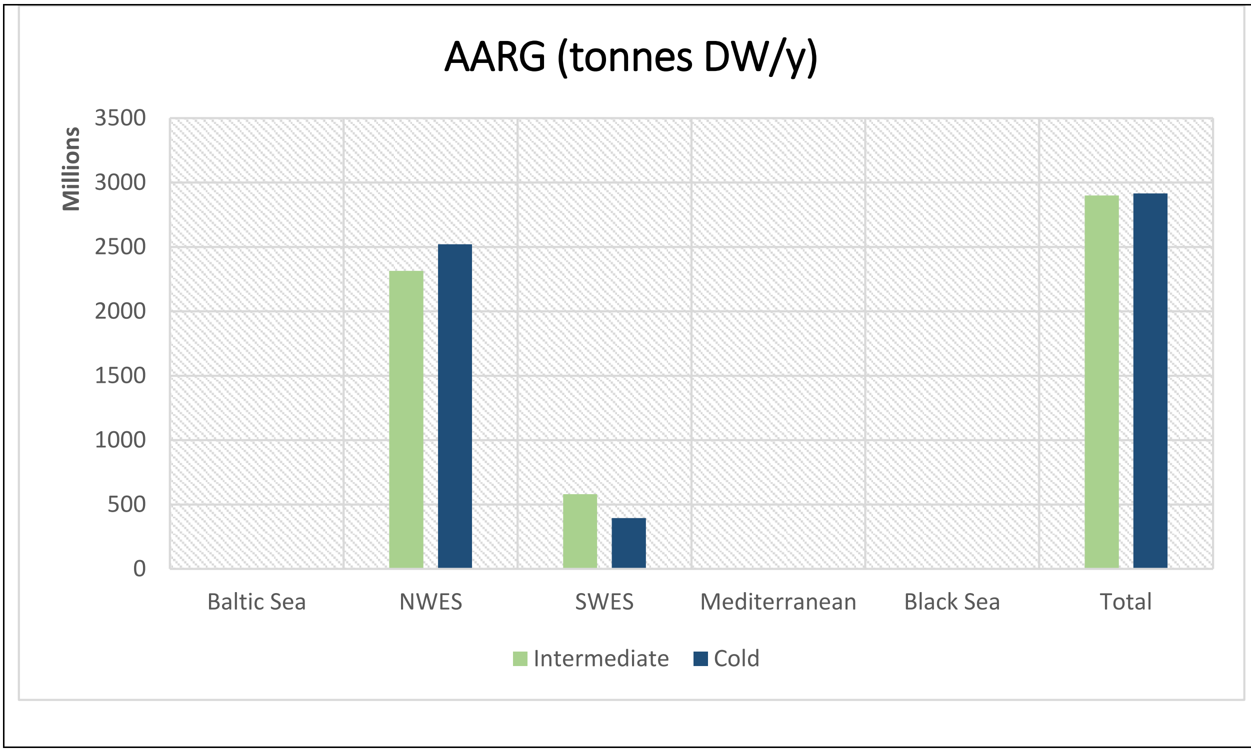


**Fig. 7.** Integrated Actual absolute rate of growth (AAGR) for each marine region (million tonnes of dry weight per year) for intermediate (green bars) and cold (blue bars) seaweed species.

**Table 4**
Integrated values of seaweed biomass potential production, used area and production per unit area when considering using 1% of the suitable area (e.g., > 6 months per year with SSS > 0.5) with <100 m depth and within 10 nm of the shoreline, excluding non-EU countries.

| | Type of species | Baltic Sea | NWES | SWES | Mediterranean | Black Sea | Total |
|---|---|---|---|---|---|---|---|
| Seaweed biomass (tonnes DW/y) | Intermediate | 0 | 3,238,203.0 | 2,267,564.6 | 5194.6 | 10,246.8 | 5,521,209.1 |
| | Cold | 0 | 2,622,100.7 | 1,692,075.0 | 0 | 0 | 4,314,175.8 |
| Assimilated C (tonnes/y) | Intermediate | 0 | 1126,247.0 | 788,658.9 | 1806.7 | 3563.8 | 1,920,276.5 |
| | Cold | 0 | 911,966.64 | 588,503.71 | 0 | 0 | 1,500,470.3 |
| Assimilated N (tonnes/y) | Intermediate | 0 | 133,090.1 | 93,196.9 | 213.5 | 421.1 | 226,921.7 |
| | Cold | 0 | 107,768.3 | 69,544.2 | 0 | 0 | 177,312.6 |
| Assimilated P (tonnes/y) | Intermediate | 0 | 14,248.0 | 9977.2 | 22.86 | 45.09 | 24,293.32 |
| | Cold | 0 | 11,537.2 | 7445.1 | 0 | 0 | 18,982.37 |
| Used area ($km^2$) | Intermediate | 0 | 1185.2 | 744.12 | 2.03 | 3.64 | 1935.03 |
| | Cold | 0 | 868.9 | 523.29 | 0 | 0 | 1392.24 |
| Production per area (tonnes /ha y) | Intermediate | – | 27.32 | 30.47 | 25.60 | 28.18 | 28.53 |
| | Cold | – | 30.18 | 32.34 | 0 | 0 | 30.99 |

significant biogeochemical implications, as it involves individual nutrients (nitrogen (N) and phosphorus (P)) and carbon (C) (e.g., Howard et al., 2017; Smale et al., 2018; Kotta et al., 2022; Wu et al., 2023). Values of biomass in Table 4 (upper rows) could be transformed to elementary composition in terms of C, N and P using the partition values reported by Gao et al. (2022) (C:34.7%, N: 4.11% and P: 0.44%) computed from a mean of 98 species of seaweed (Table 4).

### 3.4. Economic analysis (social benefits)

The EU's seaweed industry is currently facing economic challenges. To be able to compete in the global market and meet the EU's goal of increasing seaweed production, the industry must improve its economic performance. High production costs and limited market demand raise concerns about the competitiveness of European producers based solely on prices (van den Burg et al., 2016; Bak, 2018; STECF, 2023).

Consequently, the EU seaweed sector has several options for achieving viability: 1) receiving financial support from the government, which could be justified by its bio-remediation capabilities (e.g., carbon, nitrogen, and phosphorus sequestration); 2) increasing production in an effort to achieve economies of scale at various levels of the market chain; 3) focusing on high-value products and segments (Gereffi and Lee, 2016; Gereffi and Fernandez-Stark, 2016; van den Burg et al., 2021).

An increase in production, as estimated in the AARG (Table 4), would generate economies of scale not only in production but also in other levels of the market chain, such as processing, allowing bio refineries to operate at full capacity. This would help reduce production costs and ensure a consistent supply of seaweed products at competitive prices.

The AARG and the biomass elementary composition (Table 4) can also provide insight into the potential economic benefits of using seaweed cultivation for bio-remediation purposes. However, there is considerable uncertainty and controversy surrounding the estimation of the social costs of carbon, nitrogen, phosphorous emissions, and the economic benefits of sequestering them. These social costs, which quantify the economic costs associated with additional emissions to the environment, vary widely in the literature due to different assumptions and methodologies used (e.g., for the social costs of carbon, van den Bergh and Botzen, 2015; Nordhaus, 2017; Ricke et al., 2018; Pindyck, 2019).

The US Environmental Protection Agency (EPA, 2022) recently estimated the social cost of carbon (SCC) at USD 190 per tonne of $CO_2$. However, this estimate has been met with controversy, as different values are assigned to human lives based on each country's willingness or ability to pay. Carleton et al. (2022) estimated that the EPA's SCC would approximately double if all lives were valued equally (approximately USD 380 or €360 per tonne of $CO_2$). Van Grinsven et al. (2013) estimated an average social cost of €18 per kg of nitrogen, in line with Birch et al. (2011), while Gourevitch et al. (2021) estimated an average social cost of $934 or €823 per kg of phosphorus for the period 2016–19.

Obviously, the total amount of C, N, and P removed from the environment, as well as the associated social benefits, will vary depending on the final use of the seaweed. For instance, if the seaweed is harvested and buried or permanently stored, all assimilated elements will be effectively removed from the environment, maximizing the social benefit in terms of bio-remediation. This maximum social benefit would amount to 21–26 billion €/y or approximately 5000 €/t (Table 5 and Fig. 8), depending on the cultivated species.

On the other hand, if the biomass is used as food or feed, the assimilated N and P will return to the environment, and the only sequestered C will be the one naturally stored during the growth of the seaweed. In this scenario, the social benefit is much lower at around 1.2 billion €/y or 260 €/t (Table 5 and Fig. 8). If the biomass is used for biofuel production, the assimilated N and P will also return to the environment (no bio-remediation), but the assimilated C will prevent fossil C from being emitted into the atmosphere. In this case, the social benefit is over 2 billion €/y or 460 €/t (Table 5 and Fig. 8).

This suggests that the ecosystems benefits vary from €0.26 to €4.82 per kg depending on the final use. This could justify financial support for seaweed production up to these amounts, which is significant, considering the average farmed seaweed price ranges between €2 and €5 per kg (STECF, 2023; FAO, 2024).

## 4. Discussion

Despite large areas of EU marine regions being unsuitable for seaweed cultivation, such as the Mediterranean and Black Seas, the potentially suitable area remains extensive, totalling over 1.5 million $km^2$ for intermediate species and over 1 million $km^2$ for cold water species (Fig. 1A), is located mostly in the NWES and SWES domains. Identifying the Atlantic areas as the only suitable marine EU regions for seaweed cultivation aligns with previous global reports (e.g., Halpern et al., 2019; Lehahn et al., 2016; van Oort et al., 2023). Also, the average value of AAGR in those suitable places is 27 t DW $ha^{-1}$ $y^{-1}$ for intermediate species and 31 t DW $ha^{-1}$ $y^{-1}$ for cold species, which fall within the range of previously published values (e.g., Lehahn et al., 2016; Chynoweth, 2002; Bruhn et al., 2011; Gao et al., 2022).

When considering the precautionary approach by Van Oort et al. (2023), i.e. using only 1% of suitable area and the logistic restrictions indicated above (e.g., 6 months per year of SSS > 0.5, shallow and coastal regions and excluding non-EU MS), the yearly production potential for seaweed is close to 5 Mt. $y^{-1}$ (Table 4). This figure significantly exceeds the actual EU seaweed production, which stands at 0.3 Mt. $y^{-1}$ (Cai et al., 2021) but it is lower than the 8 Mt. $y^{-1}$ demand predicted for the EU by 2030 (European Commission, COM(2022) 592 final).

The assimilation of nutrients by the cultivated seaweed is quite significant (Table 4), and could alter biogeochemical conditions and cycles in the areas where the installations are located, potentially alleviating eutrophication issues (Kotta et al., 2022). However, the large assimilation of elemental nutrients may also have possible deleterious consequences for the marine ecosystems, such as altering natural N:P ratios, obstructing phytoplankton growth, and disturbing marine food webs from the bottom to the top (Bach et al., 2021; Sheppard et al., 2023; van der Burg et al., 2013). These considerations and a proper environmental impact assessment should be fully considered before deciding on the locations of large cultivation sites.

Similarly, the assimilation of organic carbon into seaweed biomass has been proposed to represent a meaningful sink for atmospheric $CO_2$ if managed properly (e.g., Duarte et al., 2013; Trevathan-Tackett et al., 2015). During seaweed growth, a significant amount of assimilated carbon is effectively sequestered into the sediments, the deep ocean or in refractory organic matter (Gao et al., 2022). Therefore, the potential for carbon sequestration could, in principle, be derived from the AARG values provided by the WOMAPP approach.

As indicated above, the mean carbon content of seaweed biomass is reported as 34.7% (Gao et al., 2022), with 56.8% of this carbon being potentially naturally sequestered (Wada et al., 2008; Zhang et al., 2012; Krause-Jensen and Duarte, 2016; Watanabe et al., 2020). This indicates the potential for carbon sequestration by seaweed cultivation in EU waters, estimated to be between 0.85 Mt. C $y^{-1}$ and 1.1 Mt. C $y^{-1}$ (3.1 Mt. $CO_2$ $y^{-1}$ and 4 Mt. $CO_2$ $y^{-1}$). Translating to approximately 600 t of C per $km^2$ $y^{-1}$, this range aligns with previously published estimates (Arzeno-Soltero et al., 2023; Wu et al., 2023) and represents a significantly higher value than any other blue carbon ecosystem (11–44 t C $km^{-2}$ $y^{-1}$) (Krause-Jensen and Duarte, 2016). Notably, recent estimates (Bertram et al., 2021) indicate that the overall natural blue carbon sequestration potential in EU countries was 1.2 Mt. C y-1 in 2019, highlighting the substantial potential to enhance this fundamental ecosystem service through seaweed cultivation.

Moreover, the carbon assimilated in the seaweed biomass is substantially larger, estimated to be between 1.5 and 1.9 Mt. C $y^{-1}$ (5.5 to 7 Mt. $CO_2$ $y^{-1}$) for cold and intermediate species (Table 4). Therefore, contingent on the final destination of the produced biomass (e.g., Arzeno-Soltero et al., 2023), the potential to sequester atmospheric carbon through this activity could be significantly larger (Arzeno-

**Table 5**

Integrated values of seaweed biomass potential C, N and P assimilation, sequestration and its economic benefits when considering using 1% of the suitable area (e.g., > 6 months per year with SSS > 0.5) with <100 m depth and within 10 nm of the shoreline, excluding non-EU countries. Assimilated refers to the amount of individual elements in the seaweed biomass, sequestered refers to the amount of carbon that is naturally sequestered (as Dissolved Organic Carbon or in the sediments) during the seaweed normal growth.

| Type of species | Element | Assimilated (t/y) | Sequestered (t/y) | Social cost (€ /t) | Benefits assimilate (M € / y) | Benefits sequestered (M €/ y) | Benefits (bio-remediation) (€/t) | Benefits (sequestration) (€/t) |
|---|---|---|---|---|---|---|---|---|
| Cold | C | 1,500,470 | 852,267 | 1321 | 1982 | 1126 | 459.5 | 261.0 |
| | N | 177,313 | | 18,000 | 3192 | | 739.8 | |
| | P | 18,982 | | 823,000 | 15,622 | | 3621.2 | |
| | Total | 1,696,765 | 852,267 | | 20,796 | 1126 | 4820.5 | 261.0 |
| Intermediate | C | 1,920,277 | 1,090,717 | 1321 | 2537 | 1441 | 459.5 | 261.0 |
| | N | 226,922 | | 18,000 | 4085 | | 739.8 | 0.0 |
| | P | 24,293 | | 823,000 | 19,993 | | 3621.2 | 0.0 |
| | Total | 2,171,492 | 1,090,717 | | 26,615 | 1441 | 4820.5 | 261.0 |

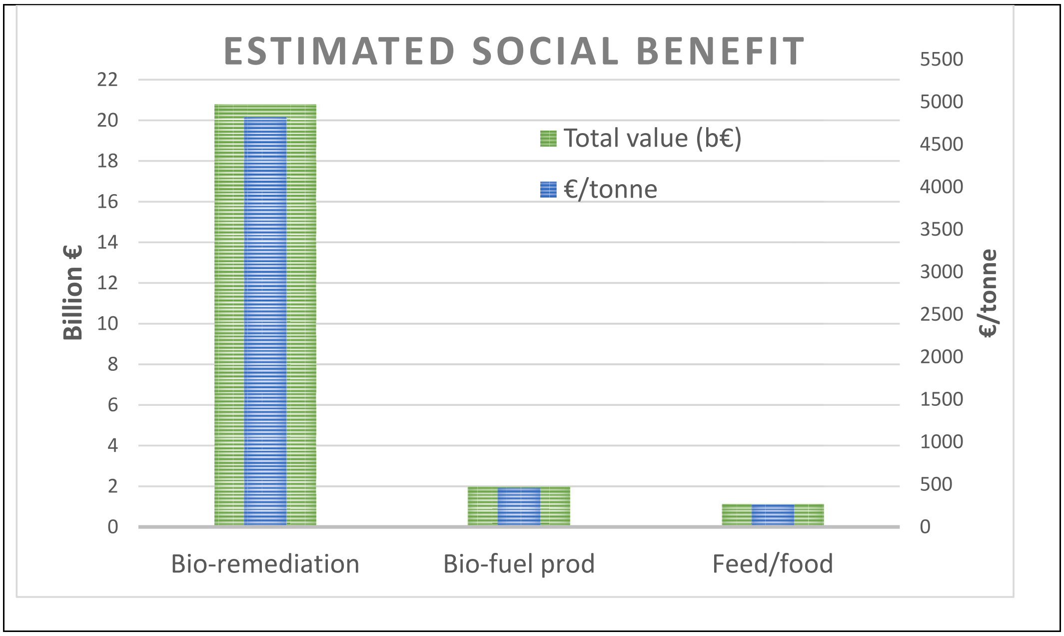


**Fig. 8.** Economic estimation of the total value (in billion €, green bars) and per tonne (blue bars) of the seaweed production depending on the use of the biomass. '*Bio-remediation*' indicates that the produced biomass will be removed and buried, in this case all elements in the biomass will be isolated from the environment (so effectively sequestered). '*Bio-fuel prod*' indicates that the biomass will be used for fuel production, in this case N and P will be recirculated to the environment (no associated social cost) but all the C in the biomass is accounted for as it will prevent using fossil C. '*Feed/food*' indicate that the biomass will be used as food and all elements will be recirculated into the environment, in this case the social cost is only the one associated to the naturally sequestered C (Table 4).

Soltero et al., 2023).

The economic analysis presented above could be, potentially, enhanced by applying production models and analyses, considering elements such as selling price and operational costs to assist interested stakeholders with the planning of potential future installations. Hence, coupling the biophysical analyses presented here with an appropriate socio-economic model is a future endeavour worth considering.

### *4.1. Uncertainty considerations*

Despite the large potential productivity for seaweed cultivation in EU marine regions calculated by our model approach, careful consideration of the sources of uncertainty is essential. The WOMAPP model is based on a series of functional relationships between seaweed growth and environmental conditions that are averaged for large groups of species (van Oort et al., 2023). To provide more robust and precise estimates of potential production, it would be necessary to obtain the limitation functions for the specific species to be cultivated.

In this selection of species, various considerations should be taken into account, such as the ease of cultivation, potential for sales, and ecological risks. Another important aspect that was not tackled in this study, is the potential risk that a '*large-scale*' seaweed cultivation might pose on the environment. Most notably the increase in competition (e.g., cultivated algae vs phytoplankton), noise (vessel traffic), sedimentary anoxia and hypoxia in bottom waters, seaweed pathogens (diseases), gene flow from cultivated seaweed species (e.g., altering natural population fitness) (Cottier-Cook et al., 2016; Grebe et al., 2019). There are however few studies targeting the potential impacts of floating seaweed cultivation installations. More specifically, the entanglement of marine mammals on longlines and mooring system and the seafloor shading at shallow farm sites (reducing benthic primary production) are the main potential impacts. The FAO does not list potential positive impacts to habitat resulting from aquaculture, however situ-specific positive impacts on benthic species has been recorded (Visch et al., 2020) and on biodiversity (Radulovich et al., 2015). Moreover, kelp farming activities may positively impact marine ecosystem when used as a bio extraction (carbon dioxide in shallow waters) (Chung et al., 2011), or bioremediation strategy (remove excess of nutrient), e.g. within integrated multitrophic aquaculture system (Chopin et al., 2004). Further investigations (both monitoring and modelling) and a comprehensive impact assessment should be conducted to ensure a proper balance between the above-mentioned environmental risks and benefits associated with seaweed cultivation implementation.

However, once a species is selected as a suitable candidate and given that its functional response to environmental factors is understood, the Blue2MF data could be readily used to calculate suitability for that particular seaweed species.

Indeed, the biophysical model data present a second source of uncertainty in the SSS estimations. Despite the extensive validation of the used models (Blue2 and Copernicus) in various contexts, these tools have inherent limitations affecting their accuracy. Mechanistic models, such as those used here, rely on the description of physiological processes and relationships through functional equations. These equations are based on theoretical knowledge and evidence from laboratory and field studies to constrain their parameters.

However, the complexity of these models is limited by factors such as current knowledge and computational power, meaning that even the most sophisticated models are but approximations of real ecosystems (e.g., Skogen et al., 2021). These limitations introduce uncertainty in the derived ecological parameters, which influences the calculations, such as those carried out by the WOMAPP model. Therefore, computed SSS values should not be interpreted as precise point values, but rather as estimations that are useful for comparing the suitability of large spatial domains, as demonstrated in our present work.

Another crucial factor to consider is the spatial resolution of the applied biophysical models (Tables 1 and 2). In general, they do not resolve fine scales, below a few kilometres, and therefore may not adequately replicate very coastal conditions. The choice of model resolution is the result of balancing computational demands and spatial coverage. Seaweed cultivation sites are more likely to be located close to the coast, among other reasons for easier logistics (e.g., Kapetsky et al., 2013). As shown in Fig. S5, the native resolution of the SSS calculations may not allow for differentiation of conditions in individual wind-farming places, and current cultivation sites may be located outside the model domain. This limitation underscores the need for a higher resolution-modelling framework in the future to provide more precise assessments, especially given the local characteristics of activities such as seaweed cultivation and wind-farming.

However, the observation that SSS in observed cultivation sites is typically high, and the very significant correlation between the SSS calculated with two entirely independent modelling frameworks (Blue2 and Copernicus), suggest that the presented SSS patterns might not be far from reality. Furthermore, the limiting factor calculated for the different basins reflects the known conditions for those marine regions, providing further indication of the suitability of the approach.

For instance, the Black Sea typically experiences phosphate deficiency in coastal regions, while nitrogen is more limiting in open sea regions (Miladinova et al., 2020; Friedland et al., 2021). This exact limitation pattern is mirrored by the WOMAPP approach for both types of seaweed (Figs. 2B and 3B). Similarly, in the Mediterranean Sea, there is a clear, well-described west-to-east progression from nitrogen-limited to phosphate-limited conditions (Tanaka et al., 2011; Huertas et al., 2012). This same pattern is computed by WOMAPP for intermediate water species (Fig. 2B), while for cold water species, water temperature is the most limiting factor, as expected (Fig. 3B).

Another revealing pattern is the significant limitation that wave height imposes on the potential growth of both types of seaweed in the north-western side of the Atlantic domains (Figs. 2B and 3B). This aligns with the typical path for North Atlantic storms (e.g., Cardone et al., 2015), so it is unsurprising that wave conditions prevent the cultivation of seaweed in this region.

The Baltic Sea is typically a cold and brackish basin (Leppäranta and Myrberg, 2009; Snoeijs-Leijonmalm et al., 2017). Therefore, the main limiting factors are temperature for intermediate seaweed species and low salinity for cold-water species, as also described in previous works (Bonsdorff and Pearson, 1999; Kaiser et al., 2011; Kotta et al., 2022). According to the WOMAPP model, cold-water seaweed species do not thrive in low salinity (van Oort et al., 2023), while low temperatures will naturally hinder the growth of intermediate species.

### 4.2. Options for fostering seaweed cultivation

Results of our analysis (Table 4) show a significant potential for seaweed cultivation in EU waters. About 5.5 to 4.3 million tonnes per year when occupying 1% of the suitable area. However, these computed numbers are still lower than predicted demand in the coming decades showing the need for alternative solutions to enhance the potential for this activity.

One option is enhancing production by applying seaweed breeding techniques. Breeding seaweed encompasses a series of interconnected stages, including the selection of parental plants, seedling production, open sea cultivation, harvesting and processing. These stages influence each other significantly and collectively determine the quality and quantity of the final products (Hwang et al., 2019). To optimize seaweed breeding, it is crucial to identify the most suitable species for cultivation, advance innovative nursery techniques for producing high-quality seeding material, and refine harvesting methods. Additionally, identifying and controlling seaweed pathogens and associated diseases are essential aspects of this optimization process (Campbell et al., 2019). Effective management policies are also necessary to sustainably regulate the industry (Cottier-Cook et al., 2016).

Another possibility is the integration of seaweed cultivation with other aquaculture activities, following the concept of Integrated Multi-Trophic Aquaculture (IMTA, Neori et al., 2004), where extractive species (such as seaweed) are grown together with fish cultures. In IMTA sites, the nutrients released by the finfish cages (through excess of feeds and/or excretion) are used by the seaweed for growth, which is typically regarded as an effective way to avoid eutrophication issues near the farming sites (van der Burg et al., 2013). However, this type of integrated cultivation technique could also represent an opportunity for the seaweed itself, in sites which limiting nutrient concentrations prevented seaweed growth. Growing seaweed within an IMTA would mean that the limitation by nutrients (N and P) is removed (or strongly reduced). From our investigations (see Figs. 2 and 3), vast areas of EU seas are mostly limited by nutrient availability (e.g., Mediterranean and Black Seas), so we repeated the WOMAPP calculations, removing the nutrient limitation from the equations (assuming the nutrients will be provided by the fish cultures).

When taking this IMTA approach, the total suitable area for seaweed cultivation (shown in Fig. 1) increases almost 3 times for cold-water species, two times for intermediate-water species, and it multiplies by 500 in the case of warm-water species (Fig. S6A). For intermediate species (Fig. S6B), the main cultivation areas are still the NWES and SWES domains (around 1.3 million km$^2$ in each), but there appear to be suitable regions (about 0.3 million km$^2$) in the Baltic, Mediterranean, and Black Seas. For cold species (Fig. S6C), there is a large increase in the suitable cultivation area in the Mediterranean (up to 0.6 million km$^2$) mostly during winter-time. Warm water species can be also cultivated in almost 1 million km$^2$ in the Mediterranean using the IMTA approach (Fig. S6D) during summer and fall periods.

Spatially, the suitability map for intermediate species under the IMTA assumption (Fig. S7A) shows newly suitable regions in the southern part of the Baltic and SWES domains, in the western and northern Mediterranean, and in most of the Black Sea. Of course, nutrients are no longer limiting factors (Fig. S7B) but rather salinity, temperature and waves. Suitable areas for cold-water species in IMTA installations (Fig. S8A) are still mostly concentrated around the North Sea and Ireland, but there is an increase in suitability levels in the north-western Mediterranean and central Black Sea. In this case, temperature, waves, and salinity (in the Baltic) are the main limiting factors (Fig. S8B). Finally, for warm-water species, suitable areas are located mostly in the eastern Mediterranean Sea and the southernmost region of the SWES domain (Fig. S9A). For these species, temperature is the most limiting factor, except for the Baltic and Black Seas, where low salinity is limiting (Fig. S9B).

Despite the necessary caution regarding model limitations, as described above, the analysis and data provided in this manuscript could be extremely useful for different strategic sectors within the EU Blue Economy. The SSS spatial classification should enable interested stakeholders to select suitable places and to discard unsuitable areas for the installation of cultivation infrastructures. However, there are many other considerations, such as technological and legislative factors, that make the deployment of seaweed cultivation systems very complex (Kapetsky et al., 2013; Lehahn et al., 2016), which are not included in our analysis.

The integration of other spatial information layers such as wind intensity, waves, tides, or currents could further enhance the utility of the spatial maps generated by the modelling framework. This integration could support the development of multi-purpose platforms (MPPs, Abhinav et al., 2023) that considers various factors to optimize the use of maritime space (Menicou and Vassiliou, 2010; Griffin et al., 2015; van den Burg et al., 2017).

Furthermore, given the potential for Blue2 models to forecast several decades into the future (e.g., Macias et al., 2018a, 2018b; Miladinova et al., 2024), it would be possible to use this system to aid in long-term plans for cultivation activities, anticipating the impacts of climate change on marine ecosystems and their suitability for seaweed cultivation in the coming decades. This is a subject worth of further investigations by applying the methodology and modelling chain presented in this contribution.

## 5. Conclusions

In conclusion, our modelling assessment has identified that cold and intermediate water seaweed species have the potential to be extensively cultivated in European seas. Most of the suitable areas are located in Atlantic regions, with a potential cultivation extent exceeding 1 million km$^2$. Even utilizing 1% of the available area and restricting the activity to the coastal fringe, this could yield over 9 million tonnes of seaweed biomass per year, enough to fulfil the expected demand from the EU in the coming years.

However, further research is needed to address gaps in the resolution of the models as this is, currently, not high enough to resolve localized patterns or gradients in environmental conditions. In the future, higher resolution models should be implemented to assess seaweed cultivation potential at a spatial scale relevant for individual farming sites. Also, more accurate production estimations could be derived by applying environmental control functions for specific seaweed species of interest in EU waters.

Another important venue for future investigations is the generation of forecast analyses for suitability in the coming decades. As environmental conditions evolve in response to global change, species-specific suitability will also be altered. This information is crucial for any stakeholder with interest in investing in the sector.

The large-scale production of seaweed has, thus, the potential to yield numerous benefits, including economic gains, job creation, and the absorption of atmospheric carbon. However, it is important to acknowledge that such an undertaking could also result in unintended ecosystem impacts, such as alterations to biogeochemical cycles. These impacts have the potential to be locally significant, and as such, it is imperative to perform further investigations focusing on long-term sustainability aspects of this activity. In doing so, the proper implementation of seaweed cultivation sites can be pursued in a responsible and sustainable manner.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used GPT@JRC to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

## CRediT authorship contribution statement

**D. Macias:** Writing – original draft, Investigation, Conceptualization. **J. Guillen:** Writing – review & editing, Formal analysis. **O. Duteil:** Writing – review & editing, Investigation. **E. Garcia-Gorriz:** Writing – review & editing, Investigation. **N. Ferreira-Cordeiro:** Writing – review & editing, Investigation. **S. Miladinova:** Writing – review & editing, Investigation. **O. Parn:** Writing – review & editing, Investigation. **C. Piroddi:** Writing – review & editing, Investigation. **L. Polimene:** Writing – review & editing, Investigation. **N. Serpetti:** Writing – review & editing, Investigation. **A. Stips:** Writing – review & editing, Investigation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2024.741353.

## References


Alevizos, E., Barille, L., 2023. Global Ocean spatial suitability for macroalgae offshore cultivation and sinking. Front. Mar. Sci. 10, 1320642. https://doi.org/10.3389/fmars.2023.1320642.

Araújo, R., Lusser, M., Sanchez Lopez, J., Avraamides, M., 2019. Brief on Algae Biomass Production. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/665775.

Araújo, R., Vázquez Calderón, F., Sánchez López, J., Azevedo, I.C., Bruhn, A., Fluch, S., Garcia Tasende, M., Ghaderiardakani, F., Ilmjärv, T., Laurans, M., Mac Monagail, M., Mangini, S., Peteiro, C., Rebours, C., Stefansson, T., Ullmann, J., 2021. Current status of the algae production industry in Europe: an emerging sector of the blue bioeconomy. Front. Mar. Sci. 7, 626389 https://doi.org/10.3389/fmars.2020.626389.

Arzeno-Soltero, I.B., Saenz, B.T., Frieder, C.A., Long, M.C., DeAngelo, J., Davis, S.J., et al., 2023. Large global variations in the carbon dioxide removal potential of seaweed farming due to biophysical constraints. Commun. Earth Environ. 4, 1–12. https://doi.org/10.1038/s43247-023-00833-2.

Bach, L.T., Tamsitt, V., Gower, J., Hurd, C.L., Raven, J.A., Boyd, P.W., 2021. Testing the climate intervention potential of ocean afforestation using the Great Atlantic *Sargassum* Belt. Nat. Commun. 12, 2556. https://doi.org/10.1038/s41467-021-22837-2.

Bak, U.G., 2018. Production method and cost of commercial-scale offshore cultivation of kelp in the Faroe Islands using multiple partial harvesting. Algal Res. 33, 36–47.

Bertram, C., Quaas, M., Reusch, T.B.H., Vafeidis, A.T., Wolff, C., Rickels, W., 2021. The blue carbon wealth of nations. Nat. Clim. Chang. 11, 704–709. https://doi.org/10.1038/s41558-021-01089-4.

Binzer, T., Sand-Jensen, K., Middelboe, A.L., 2006. Community photosynthesis of aquatic macrophytes. Limnol. Oceanogr. 51, 2722–2733. https://doi.org/10.4319/lo.2006.51.6.2722.

Birch, M.B., Gramig, B.M., Moomaw, W.R., Doering III, O.C., Reeling, C.J., 2011. Why metrics matter: evaluating policy choices for reactive nitrogen in the Chesapeake Bay Watershed. Environ. Sci. Technol. 45, 168–174.

Bonsdorff, E., Pearson, T.H., 1999. Variation in the sublittoral macrozoobenthos of the Baltic Sea along environmental gradients: a functional-group approach. Aust. J. Ecol. 24, 312–326. https://doi.org/10.1046/j.1442-9993.1999.00986.x.

Breeman, A.M., Pakker, H., 1994. Temperature ecotypes in seaweed – adaptive significance and biogeographic implications. Bot. Mar. 37, 171–180. https://doi.org/10.1515/botm.1994.37.3.171.

Bruhn, A., Dahl, J., Nielsen, H.B., Nikolaisen, L., Rasmussen, M.B., Markager, S., Olesen, B., Arias, C., Jensen, P.D., 2011. Bioenergy potential of *Ulva lactuca*: biomass yield, methane production and combustion Bioresour. Technol. 102, 2595–2604. https://doi.org/10.1016/j.biortech.2010.10.010.

Burchard, H., Bolding, K., 2002. GETM, a General Estuarine Transport Model. EUR 20253 EN. European Commission, JRC23237.

Burek, P., de Roo, A., van der Knijff, J.M., 2013. LISFLOOD—Distributed Water Balance and Flood Simulation Model—Revised User Manual. OPOCE, Luxembourg.

Buschmann, A.H., Camus, C., Infante, J., Neori, A., Israel, Á., Hernández-González, M.C., Pereda, S.V., Gomez-Pinchetti, J.L., Golberg, A., Tadmor-Shalev, N., Critchley, A.T., 2017. Seaweed production: overview of the global state of exploitation, farming and emerging research activity. Eur. J. Phycol. 52, 391–406.

Cai, J., Lovatelli, A., Aguilar-Manjarrez, J., Cornish, L., Dabbadie, L., Desrochers, A., Diffey, S., Garrido Gamarro, E., Geehan, J., Hurtado, A., Lucente, D., Mair, G., Miao, W., Potin, P., Przybyla, C., Reantaso, M., Roubach, R., Tauati, M., Yuan, X., 2021. Seaweeds and microalgae: an overview for unlocking their potential in global aquaculture development. In: FAO Fisheries and Aquaculture Circular No. 1229. FAO, Rome.

Campbell, I., Kambey, C.S.B., Mateo, J.P., Rusekwa, S.B., Hurtado, A.Q., Msuya, F.E., Stentiford, G.D., Cottier-Cook, E.J., 2019. Biosecurity policy and legislation for the global seaweed aquaculture industry. J. Appl. Phycol. 32, 2133–2146. https://doi.org/10.1007/s10811-019-02010-5.

Cardone, V.J., Callahan, B.T., Chen, H., Cox, A.T., Morrone, M.A., Swail, V.R., 2015. Global distribution and risk to shipping of very extreme sea states (VESS). Int. J. Climatol. 35 (1), 69–84.

Carleton, T., Jina, A., Delgado, M., Greenstone, M., Houser, T., Hsiang, S., Zhang, A.T., 2022. Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. The Quart. J. Econ. 137 (4), 2037–2105.

Chopin, T., Cooper, J.A., Reid, G., Cross, S., Moore, C., 2004. Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. Rev. Aquac. 4, 209–220. https://doi.org/10.1111/j.1753-5131.2012.01074.x.

Chung, I.K., Beardall, J., Mehta, S., Sahoo, D., Stojkovic, S., 2011. Using marine macroalgae for carbon sequestration: a critical appraisal. J. Appl. Phycol. 23, 877–886. https://doi.org/10.1007/s10811-010-9604-9.

Chynoweth, D.P., 2002. Review of biomethane from marine biomass History, Results and Conclusions of the "US Marine Biomass Energy Program" (1968–1990). Department of Agricultural and Biological Engineering, University of Florida, Gainsville, p. 194.

Cottier-Cook, E.J., Nagabhatla, N., Badis, Y., Campbell, M., Chopin, T., Dai, W., Fang, J., He, P., Hewitt, C., Kim, G.H., Huo, Y., Jiang, Z., Kema, G., Li, X., Liu, F., Liu, H., Liu, Y., Lu, Q., Luo, Q., Mao, Y., Msuya, F.E., Rebours, C., Shen, H., Stentiford, G.D., Yarish, C., Wu, H., Yang, X., Zhang, J., Zhou, Y., Gachon, C.M.M., 2016. Safeguarding the Future of the Global Seaweed Aquaculture Industry. United Nations University (INWEH) and Scottish Association for Marine Science Policy Brief, ISBN 978-92-808-6080-1, 12pp. https://www.sams.ac.uk/t4-media/sams/pdf/globalseaweed-policy-brief.pdf.

Couteau, C., Coiffard, L., 2016. Seaweed applications in cosmetics. In: Fleurence, J., Levine, I. (Eds.), Seaweed in Health and Disease Prevention. Elsevier, Amsterdam, pp. 423–441.
Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I., Marbà, N., 2013. The role of coastal plant communities for climate change mitigation and adaptation. Nat. Clim. Change 3 nature.com/articles/nclimate1970.
Duteil, O., Macias Moy, D., Stips, A., 2023. Sensitivity of the North Sea Ecosystem to a Combined Reduction of Phosphorus and Nitrogen Loads: A Model Study, EUR 31495 EN. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/039666. ISBN 978-92-68-03120-9. JRC132207.
Elizondo-González, R., Quiroz-Guzmán, E., Escobedo-Fregoso, C., Magallón-Servín, P., Peña-Rodríguez, A., 2018. Use of seaweed *Ulva lactuca* for water bioremediation and as feed additive for white shrimp *Litopenaeus vannamei*. PeerJ 6, e4459.
Environmental Protection Agency (EPA), 2022. Report on the social cost of greenhouse gases: Estimates incorporating recent scientific advances. Available at: https://www.epa.gov/system/files/documents/2022-11/epa_scghg_report_draft_0.pdf.
European Commission, 2019. Directorate-General for Climate Action, Going Climate-Neutral by 2050 – A Strategic Long-Term Vision for a Prosperous, Modern. Competitive and Climate-Neutral EU Economy Publications Office. https://data.europa.eu/doi/10.2834/02074.
FAO (Food and Agriculture Organization of the United Nations), 2024. FAO Fisheries and Aquaculture - FishStatJ - Software for Fishery and Aquaculture Statistical Time Series. Rome, Italy. Available: https://www.fao.org/fishery/en/topic/166235?lang=en.
Ferreira Cordeiro, N., Polimene, L., Stips, A., Macias Moy, D., 2022. Modelling the biogeochemistry of the Bay of Biscay and the Iberian coast: model description and validation, EUR 31217 EN. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/953750, JRC130407. ISBN 978-92-76-56885-8.
Field, C.B., Behrenfeld, M.J., Randerson, J.T., Falkowski, P., 1998. Primary production of the biosphere: integrating terrestrial and oceanic components. Science 281, 237–240.
Friedland, R., Macias, D., Cossarini, G., Daewel, U., Estournel, C., Garcia-Gorriz, E., Grizzetti, B., Grégoire, M., Gustafson, B., Kalaroni, S., Kerimoglu, O., Lazzari, P., Lenhart, H., Lessin, G., Maljutenko, I., Miladinova, S., Müller, 2021. Effects of Nutrient Management Scenarios on Marine Eutrophication Indicators: A Pan-European, Multi-Model Assessment in Support of the Marine Strategy Framework Directive. In Frontiers in Marine Science, vol. 8. Frontiers Media SA. https://doi.org/10.3389/fmars.2021.596126.
Gao, G., Gao, L., Jiang, M., Jian, A., He, L., 2022. The potential of seaweed cultivation to achieve carbon neutrality and mitigate deoxygenation and eutrophication. Environ. Res. Lett. 17, 014018 https://doi.org/10.1088/1748-9326/ac3fd9.
Gereffi, G., Fernandez-Stark, K., 2016. Global Value Chains Analysis: A Primer, 2nd edn. Center on Globalization, Governance & Competitiveness, Duke University, Durham, NC.
Gereffi, G., Lee, J., 2016. Economic and social upgrading in global value chains and industrial clusters: why governance matters. J. Bus. Ethics 133, 25–38.
Gourevitch, J.D., Koliba, C., Rizzo, D.M., Zia, A., Ricketts, T.H., 2021. Quantifying the social benefits and costs of reducing phosphorus pollution under climate change. J. Environ. Manage. 293, 112838.
Grebe, G.S., Byron, C.J., St. Gelais, A., Kotowicz, D.M., Olson, T.K., 2019. An ecosystem approach to kelp aquaculture in the Americas and Europe. Aquac. Rep. 15, 100215 https://doi.org/10.1016/j.aqrep.2019.100215.
Griffin, R., Buck, B., Krause, G., 2015. Private incentives for the emergence of co-production of offshore wind energy and mussel aquaculture. Aquaculture 436, 80–89.
Grizzetti, B., Bouraoui, F., Aloe, A., 2012. Changes of nitrogen and phosphorus loads to European seas. Glob. Chang. Biol. 18, 769–782. https://doi.org/10.1111/j.1365-2486.2011.02576.x.
Halpern, B.S., Frazier, M., Afflerbach, J., Lowndes, J.S., Micheli, F., O'Hara, C., et al., 2019. Recent pace of change in human impact on the World's oceans. Sci. Rep. 9, 11609. https://doi.org/10.1038/s41598-019-47201-9.
Hauxwell, J., Cebrián, J., Valiela, I., 2003. Eelgrass *Zostera marina* loss in temperate estuaries: relationship to land-derived nitrogen loads and effect of light limitation imposed by algae. Mar. Ecol. Prog. Ser. 247, 59–73. https://doi.org/10.3354/meps247059.
Helmes, R.J., López-Contreras, A.M., Benoit, M., Abreu, H., Maguire, J., Moejes, F., van den Burg, S.W., 2018. Environmental impacts of experimental production of lactic acid for bioplastics from *Ulva spp*. Sustainability 10, 1–15.
Howard, J., Sutton-Grier, A., Herr, D., Kleypas, J., Landis, E., Mcleod, E., Pidgeon, E., Simpson, S., 2017. Clarifying the role of coastal and marine systems in climate mitigation. Front. Ecol. Environ. 15, 42–50. https://doi.org/10.1002/fee.1451.
Huertas, I.E., Ríos, A.F., García-Lafuente, J., Navarro, G., Makaoui, A., Sánchez-Román, A., Rodriguez-Galvez, S., Orbi, A., Ruíz, J., Pérez, F.F., 2012. Atlantic forcing of the Mediterranean oligotrophy. Glob. Biogeochem. Cycles 26, GB2022.
Hughes, A.D., Kelly, M.S., Black, K.D., Stanley, M.S., 2012. Biogas from macroalgae: is it time to revisit the idea? Biotechnol. Biofuels 5, 86.
Hwang, E.K., Yotsukura, N., Pang, S.J., Su, L., Shan, T.F., 2019. Seaweed breeding programs and progress in eastern Asian countries. Phycologia 58 (5), 484–495. https://doi.org/10.1080/00318884.2019.1639436.
Kaiser, M.J., Attrill, M.J., Jennings, S., Thomas, D.N., Barnes, D.K.A., Brierley, A.S., Hiddink, J.G., Kaartokallio, H., Polunin, N.V.C., Raffaelli, D.G., 2011. Marine Ecology: Processes, Systems, and Impacts, second ed. Oxford University Press, Oxford.
Kang, J.Y., Chun, B.S., Lee, M.C., Choi, J.S., Choi, I.S., Hong, Y.K., 2016. Anti-inflammatory activity and chemical composition of essential oil extracted with supercritical CO2 from the brown seaweed *Undaria pinnatifida*. J. Essent Oil Bear. Pl. 19, 46–51.
Kapetsky, J.M., Aguilar-Manjarrez, J., Jenness, J., 2013. A Global Assessment of Offshore Mariculture Potential From a Spatial Perspective. FAO Fisheries and Aquaculture Technical Paper, 549.
Kotta, J., Raudsepp, U., Szava-Kovats, R., Aps, R., Armoskaite, A., Barda, I., Bergströme, P., Futter, M., Gröndahl, F., Hargrave, M., Jakubowska, M., Jänes, H., Kaasik, A., Kraufvelin, P., Kovaltchouk, N., Krost, P., Kulikowski, T., Kõivupuu, A., Kotta, I., Lees, L., Loite, S., Maljutenko, I., Nylund, G., Paalme, T., Pavia, H., Purina, I., Rahikainen, M., Sandowk, V., Visch, W., Yang, B., Barboza, F.R., 2022. Assessing the potential for sea-based macroalgae cultivation and its application for nutrient removal in the Baltic Sea. Sci. Tot. Environ. 839, 156230 https://doi.org/10.1016/j.scitotenv.2022.156230.
Krause-Jensen, D., Duarte, C.M., 2016. Substantial role of macroalgae in marine carbon sequestration. Nat. Geosci. 9, 737–742.
Lehahn, Y., Ingle, K.N., Golberg, A., 2016. Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: feasibility and sustainability. Algal Res. 17, 150–160. https://doi.org/10.1016/j.algal.2016.03.031.
Leppäranta, M., Myrberg, K., 2009. Physical Oceanography of the Baltic Sea. Springer Science & Business Media.
Macias, D., García-Gorriz, E., Piroddi, C., Stips, A., 2014. Biogeochemical control of marine productivity in the Mediterranean Sea during the last 50 years. Glob. Biochem. Cycl. 28 (8), 897–907. https://doi.org/10.1002/2014GB004846.
Macias, D., Garcia-Gorriz, E., Stips, A., 2018a. Major fertilization sources and mechanisms for Mediterranean Sea coastal ecosystems. Limnol. Oceanogr. 63, 897–914. https://doi.org/10.1002/lno.10677.
Macias, D., Garcia-Gorriz, E., Stips., 2018b. Deep winter convection and phytoplankton dynamics in the NW Mediterranean Sea under present climate and future (horizon 2030) scenarios. Nat. Sci. Rep. 8 (1), 6626. https://doi.org/10.1038/s41598-018-24965-0.
Macias, D., Huertas, I.E., Garcia-Gorriz, E., Stips, A., 2019. A non Redfieldian stoichiometry driven by phytoplankton phosphate frugality explains nutrients and chlorophyll patterns in the Mediterranean Sea. Prog. Oceanogr. 173, 37–50. https://doi.org/10.1016/j.pocean.2019.02.005.
Macias, D., Stips, A., Grizzetti, B., Aloe, A., Bisselink, B., de Meij, A., De Roo, A., Duteil, O., Ferreira-Cordeiro, N., Garcia-Gorriz, E., González-Fernández, D., Hristov, J., Miladinova, S., Parn, O., Piroddi, C., Pisoni, E., Pistocchi, A., Polimene, L., Serpetti, N., Thoma, C., Udias, A., Vigiak, O., Weiss, F., Wilson, J., Zanni, M., 2022. Water/marine Zero Pollution Outlook. A Forward-Looking, Model-Based Analysis of Water Pollution in the EU. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/681817, JRC131197.
MacMonagail, M., Cummins, E., Bermejo, R., Daly, E., Costello, D., Morrison, L., 2018. Quantification and feed to food transfer of total and inorganic arsenic from a commercial seaweed feed. Environ. Int. 118, 314–324.
Menicou, M., Vassiliou, V., 2010. Prospective energy needs in Mediterranean offshore aquaculture: renewable and sustainable energy solutions. Renew. Sust. Energ. Rev. 14 (9), 3084–3091. https://doi.org/10.1016/j.rser.2010.06.013.
Miladinova, S., Stips, A., Garcia-Gorriz, E., Macias, D., 2017. Black Sea thermohaline properties: Long-term trends and variations. J. Geophys. Res. Oceans 122 (7), 5624–5644.
Miladinova, S., Stips, A., Macias Moy, D., Garcia-Gorriz, E., 2020. Seasonal and inter-annual variability of the phytoplankton dynamics in the Black Sea Inner Basin. Oceans 1 (4), 251–273. https://doi.org/10.3390/oceans1040018.
Miladinova, S., Garcia-Gorriz, E., Moy, D.M., Stips, A., 2024 Jan 2. Transport and dispersion of PFOA and PFOS in the Black Sea. Environ. Res., 118100 https://doi.org/10.1016/j.envres.2024.118100 (Epub ahead of print. PMID: 38176628).
Nayar, S., Bott, K., 2014. Current status of global cultivated seaweed production and markets. World Aquac. 45, 32–37.
Neori, A., Chopin, T., Troell, M., Buschmann, A.H., Kraemer, G.P., Halling, C., Shpigel, M., Yarish, C., 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. Aquaculture 231, 361–391.
Nordhaus, W.D., 2017. Revisiting the social cost of carbon. PNAS 114 (7), 1518–1523. https://doi.org/10.1073/pnas.1609244114.
Parn, O., Friedland, R., Garcia, G.E., Stips, A., 2020. Report on the biogeochemical model setup for the Baltic Sea and its applications. EUR 30252 EN, Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/672255. ISBN 978-92-76-19448-4. JRC120378.
Parn, O., Lessin, G., Stips, A., 2021. Effects of sea ice and wind speed on phytoplankton spring bloom in central and southern Baltic Sea. PLoS One 16 (3), e0242637.
Pindyck, R.S., 2019. The social cost of carbon revisited. J. Environ. Econ. Manage. 94 (2019), 140–160. https://doi.org/10.1016/j.jeem.2019.02.003.
Radulovich, R., Umanzor, S., Cabrera, R., Mata, R., 2015. Tropical seaweeds for human food, their cultivation and its effect on biodiversity enrichment. Aquaculture 436, 40–46. https://doi.org/10.1016/j.aquaculture.2014.10.032.
Ricke, K., Drouet, L., Caldeira, K., Tavoni, M., 2018. Country-level social cost of carbon. Nature Clim Change 8, 895–900. https://doi.org/10.1038/s41558-018-0282-y.
Roleda, M.Y., Marfaing, H., Desnica, N., Jónsdóttir, R., Skjermo, J., Rebours, C., Nitschke, U., 2010. Variations in polyphenol and heavy metal contents of wild-harvested and cultivated seaweed bulk biomass: health risk assessment and implication for food applications. Food Control 95, 121–134.
Sheppard, E.J., Hurd, C.L., Britton, D.D., Reed, D.C., Bach, L.T., 2023. Seaweed biogeochemistry: global assessment of C:N and C:P ratios and implications for ocean afforestation. J. Phycol. 59, 879–892. https://doi.org/10.1111/jpy.13381.

Skogen, M.D., Ji, R., Akimova, A., Daewel, U., Hansen, C., Hjøllo, S., van Leeuwen, S.M., Maar, M., Macias, D., Mousing, E.A., Almroth-Rosell, E., Sailley, S.F., Spence, M., Troost, T.A., Wolfshaar, K., 2021. Disclosing the truth: are models better than observations? Mar. Ecol. Prog. Ser. https://doi.org/10.3354/meps13574.

Smale, D.A., Moore, P.J., Queiros, A.M., Higgs, N.D., Burrows, M.T., 2018. Appreciating interconnectivity between habitats is key to blue carbon management. Front. Ecol. Environ. 16, 71–73. https://doi.org/10.1002/fee.1765.

Snoeijs-Leijonmalm, P., Schubert, H., Radziejewska, T. (Eds.), 2017. Biological Oceanography of the Baltic Sea. Springer Science & Business Media.

STECF (Scientific, Technical and Economic Committee for Fisheries), 2023. Economic Report on the EU aquaculture (STECF-22-17). Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/51391.

Stévant, P., Rebours, C., Chapman, A., 2017. Seaweed aquaculture in Norway: recent industrial developments and future perspectives. Aquac. Int. 25, 1373–1390.

Tanaka, T., Thingstad, T.F., Christaki, U., Colombet, J., Cornet-Barthaux, V., Courties, C., Grattepanche, J.-D., Lagaria, A., Nedoma, J., Oriol, L., Psarra, S., Pujo-Pay, M., Van Wambeke, F., 2011. Lack of P-limitation of phytoplankton and heterotrophic prokaryotes in surface waters of three anticyclonic eddies in the stratified Mediterranean Sea. Biogeosciences 8, 525–538.

Thomas, J.B.E., Ramos, F.S., Gröndahl, F., 2019. Identifying suitable sites for macroalgae cultivation on the swedish west coast. Coast. Manag. 47, 88–106. https://doi.org/10.1080/08920753.2019.1540906.

van den Burg, S.W.K., van Duijn, A.P., Bartelings, H., van Krimpen, M.M., Poelman, M., 2016. The economic feasibility of seaweed production in the North Sea. Aquacult. Ecol. Manag. 20, 235–252.

Trevathan-Tackett, S.M., Kelleway, J., Macreadie, P.I., Beardall, J., Ralph, P., Bellgrove, A., 2015. Comparison of marine macrophytes for their contributions to blue carbon sequestration. Ecology 96, 3043–3057. https://doi.org/10.1890/15-0149.1.

van den Bergh, J.C.J.M., Botzen, W.J.W., 2015. Monetary valuation of the social cost of CO2 emissions: A critical survey. Ecol. Econ. 114, 33–46. https://doi.org/10.1016/j.ecolecon.2015.03.015.

van den Burg, S.W., Kamermans, P., Blanch, M., Pletsas, D., Poelman, M., Soma, K., Dalton, G., 2017. Business case for mussel aquaculture in offshore wind farms in the North Sea. Mar. Policy 85, 1–7.

van den Burg, S.W.K., Selnes, T., Alves, L., Giesbers, E., Daniel, A., 2021. Prospects for upgrading by the European kelp sector. J. Appl. Phycol. 33 (1), 557–566.

van der Burg, S.W.K., Stuiver, M., Veenstra, F.A., Bikker, P., López-Contreras, A., Palstra, A.P., Broeze, J., Jansen, H., Jak, R., Gerritsen, A., Harmsen, P., Kals, J., Garcia, A., Brandenburg, W., Van Krimpen, M., van Duijn, A.P., Mulder, W.J., van Raamsdonk, L., 2013. A Triple P Review of the Feasibility of Sustainable Offshore Seaweed Production in the North Sea. LEI Report 13-077. Wageningen University & Research, Wageningen. https://www.wur.nl/upload_mm/8/a/d/d69d82b9-904f-4bf1-9844-c24bd5d39346_Rapport%2013-077%20vdBurg_DEF_WEB.pdf (Accessed 5 December 2023).

van der Molen, J., Ruardij, P., Mooney, K., Kerrison, P., O'Connor, N.E., Gorman, E., Timmermans, K., Wright, S., Kelly, M., Hughes, A.D., Capuzzo, E., 2018. Modelling potential production of macroalgae farms in UK and Dutch coastal waters. Biogeosciences 15, 1123–1147. https://doi.org/10.5194/bg-15-1123-2018.

Van Grinsven, H.J., Holland, M., Jacobsen, B.H., Klimont, Z., Sutton, M.A., Jaap Willems, W., 2013. Costs and benefits of nitrogen for Europe and implications for mitigation. Environ. Sci. Technol. 47 (8), 3571–3579.

van Oort, P.A.J., Verhagen, A., van der Werf, A.K., 2023. Can seaweeds feed the world? Modelling world offshore seaweed production potential. Ecol. Model. 484, 110486 https://doi.org/10.1016/j.ecolmodel.2023.110486.

An overview of the algae industry in Europe. In: Vazquez-Calderon, F., Sanchez-Lopez, J., Guillen, J., Avraamides, M. (Eds.), 2022. Producers, Production Systems, Species, Biomass Uses, other Steps in the Value Chain and Socio-Economic Data. Publications Office of the European Union, Luxembourg. ISBN 978-92-76-54516.

Visch, W., Kononets, M., Hall, P.O.J., Nylund, G.M., Pavia, H., 2020. Environmental impact of kelp (*Saccharina latissima*) aquaculture. Mar. Pollut. Bull. 155, 110962 https://doi.org/10.1016/j.marpolbul.2020.110962.

Wada, S., Aoki, M.N., Mikami, A., Komatsu, T., Tsuchiya, Y., Sato, T., Shinagawa, H., Hama, T., 2008. Bioavailability of macroalgal dissolved organic matter in seawater mar. Ecol. Prog. Ser. 370, 33–44.

Watanabe, K., Yoshida, G., Hori, M., Umezawa, Y., Moki, H., Kuwae, T., 2020. Macroalgal metabolism and lateral carbon flows can create significant carbon sinks. Biogeosciences 17, 2425–2440.

Wu, J., Keller, D.P., Oschlies, A., 2023. Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: an earth system modeling study. Earth Syst. Dynam. 14, 185–221. https://doi.org/10.5194/esd-14-185-2023.

Zhang, J., Fang, J., Wang, W., Du, M., Gao, Y., Zhang, M., 2012. Growth and loss of mariculture kelp *Saccharina japonica* in Sungo Bay, China. J. Appl. Phycol. 24, 1209–1216.