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Assessing the potential for sea-based macroalgae cultivation and its application for nutrient removal in the Baltic Sea

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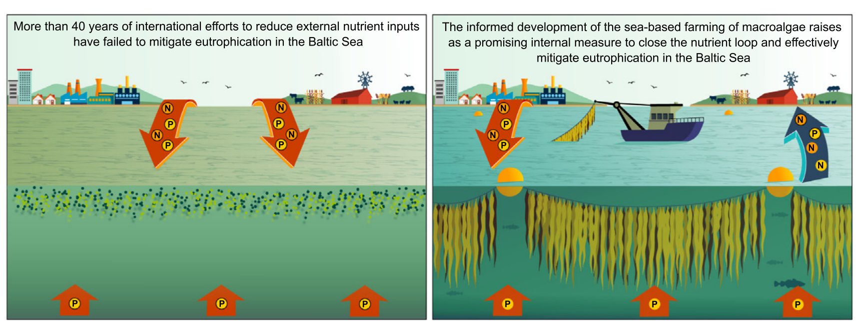
HIGHLIGHTS

- Production potential of macroalgal farms is high in the Baltic Sea.
- Potential farm locations are widespread across the Baltic Sea.
- Different farmed species have different production hotspots.
- Macroalgal farms, when established, reduce eutrophication symptoms in the Baltic Sea.

GRAPHICAL ABSTRACT



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ABSTRACT

Marine eutrophication is a pervasive and growing threat to global sustainability. Macroalgal cultivation is a promising circular economy solution to achieve nutrient reduction and food security. However, the location of production hotspots is not well known. In this paper the production potential of macroalgae of high commercial value was predicted across the Baltic Sea region. In addition, the nutrient limitation within and adjacent to macroalgal farms was investigated to suggest optimal site-specific configuration of farms. The production potential of *Saccharina latissima* was largely driven by salinity and the highest production yields are expected in the westernmost Baltic Sea areas where salinity is >23. The direct and interactive effects of light availability, temperature, salinity and nutrient

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concentrations regulated the predicted changes in the production of *Ulva intestinalis* and *Fucus vesiculosus*. The western and southern Baltic Sea exhibited the highest farming potential for these species, with promising areas also in the eastern Baltic Sea. Macroalgal farming did not induce significant nutrient limitation. The expected spatial propagation of nutrient limitation caused by macroalgal farming was less than 100–250 m. Higher propagation distances were found in areas of low nutrient and low water exchange (e.g. offshore areas in the Baltic Proper) and smaller distances in areas of high nutrient and high water exchange (e.g. western Baltic Sea and Gulf of Riga). The generated maps provide the most sought-after input to support blue growth initiatives that foster the sustainable development of macroalgal cultivation and reduction of in situ nutrient loads in the Baltic Sea.

1. Introduction

The development of alternative methods to produce commodities such as food, feed, fuel, and pharmaceuticals is crucial to sustain the increasing human demand for natural resources. In this regard, marine ecosystems are often seen as a treasure trove to satisfy human needs (Hasselström et al., 2020; Rotter et al., 2021). Today more than 40% of the human population live near coastal areas and an increasing proportion relies on their services (Martínez et al., 2007; Neumann et al., 2015). As a result, these environments are subjected to an increasing diversity of impacts, thereby jeopardizing their sustainability (e.g. Dailianis et al., 2018; Gerovasileiou et al., 2019).

“Blue Growth” is a long-term initiative to support productive growth and the sustainable use of aquatic resources (FAO, 2018; World Commission on Environment and Development, 1987). Within the Blue Growth initiative, the cultivation of marine macroalgae is a promising enterprise in that it competes for neither arable land nor freshwater resources. Importantly, as macroalgae assimilate nutrients that are then removed from the marine environment upon harvest, macroalgal farming provides low-impact eutrophication remediation in coastal waterbodies currently degraded by excessive accumulation of nutrients (Campbell et al., 2019; Jiang et al., 2020).

The contribution by Europe to the global production of algal biomass is scant (0.57% in 2016) and relies almost exclusively on the harvesting of wild stocks (98% of the European production in 2016), while aquaculture-based technologies supplies most of the global supply (97% of the global production in 2016, Araújo et al., 2019, 2021). Due to concerns over potential in situ environmental impacts of the harvesting of wild stocks (Camia et al., 2018; Thomas et al., 2019), the number of companies engaged in aquaculture-based initiatives and algal-derived products has increased rapidly throughout Europe (Camia et al., 2018; Araújo et al., 2021). Nevertheless, seaweed aquaculture in Europe is in an early stage of development (FAO et al., 2019). Securing space for macroalgae cultivation in Europe (and elsewhere) requires an identification of areas with the highest production potentials. To date, most studies have been case-specific and developed at small scales (e.g. Thomas et al., 2019; but see van der Molen et al., 2018 for a modelling exercise at a regional scale). However, the modelling frame should cover wider geographic ranges to provide meaningful evidence at the scales (i.e. national, regional) at which maritime spatial plans (MSP) are developed.

The Baltic Sea has a long and well-documented history of scientific research, high data density and multiple on-going cross-border collaborations supporting the effective management of marine resources (Reusch et al., 2018). Nevertheless, more than 97% of the marine area in the Baltic Sea is currently considered degraded by eutrophication (Helin, 2013; Fleming-Lehtinen et al., 2015; Andersen et al., 2017; Breitburg et al., 2018), primarily due to the legacy nitrogen and phosphorus (HELCOM, 2018). Nevertheless, the excessive eutrophication in the Baltic Sea can be regarded as a rich and cost-free source of nutrients for macroalgal cultivation. Here, aquaculture can make a positive contribution to nutrient removal; the harvesting of internally produced macroalgae offers a potential for efficient recirculation of nutrients from sea to land. Despite salinity constraints, several characteristics of the Baltic Sea favour macroalgal farming for eutrophication control. First, nutrient limitation is less likely than in many other marginal seas (Kotta et al., 2017). Second, external nutrient control is inadequate to solve the eutrophication problem in the Baltic Sea (Savchuk, 2018; Murray et al., 2019; Kotta et al., 2020). Third, and most importantly, developed economies around the Baltic Sea support a healthy and waste-free macroalgal production industry; responsibly produced macroalgae are attractive for regional consumers concerned about food traceability and content (Barbier et al., 2019). The first macroalgal farms are limited to the westernmost parts of the Baltic Sea where robust technical solutions have recently been developed (Thomas et al., 2019).

This paper presents an analysis of a large collection of recent measurements of macroalgal growth in the Baltic Sea region which forms the basis for a new model chain to predict the production potential of seaweed species of high farming potential in the Baltic Sea region (*Saccharina latissima*, *Ulva intestinalis* and *Fucus vesiculosus*). This production potential was modelled as the statistical relationships between environmental variables and macroalgal growth yield over the entire Baltic Sea region. An analysis of the potential nutrient removal by cultivated macroalgae in hypothetical farms and surrounding areas subsequently determined the optimal spatial configuration of farms with no significant effects of nutrient limitation on macroalgal biomass yields. Nutrient availability was modelled as a function of hydrodynamics, nutrient concentrations in seawater and the rate of nutrient assimilation of the farmed macroalgae. The modelling results provide a factual large-scale assessment of the feasibility of macroalgal farming and the potential of macroalgal farms to reduce nutrient loads in the Baltic Sea.

2. Material and methods

2.1. Environmental control of macroalgal growth

Seaweed growth in natural assemblages is controlled by both abiotic and biotic factors (Field et al., 1998; Hauxwell et al., 2003). However, abiotic constraints are often dominant in macroalgal farms, owing to the effective internal control of fouling by nuisance algae and grazing (Titlyanov and Titlyanova, 2010). Light, nutrient availability, temperature and salinity are thus key factors that drive growth patterns of macroalgae (Breeman and Pakker, 1994; Field et al., 1998; Hauxwell et al., 2003; Binzer et al., 2006).

Light availability is defined by the amount of irradiance arriving at the sea surface, the optical characteristics of the water and the self-shading within algal assemblages. The first two variables define the light field above underwater canopies and the maximum photosynthetic rates of macroalgae (Kirk, 1994; Anthony et al., 2004). Self-shading is a critical biological limitation in natural macroalgal assemblages, because it establishes the actual threshold for realized photosynthesis (Binzer et al., 2006; Tait and Schiel, 2010). In macroalgal farms, however, this limitation is less severe, because algae are suspended in the water, thereby enabling maximum use of the natural resources (e.g. light, and nutrients) and the highest possible algal yield (Titlyanov and Titlyanova, 2010).

Nutrient availability strongly affects the production of macroalgae (Raven and Hurd, 2012). Importantly, some macroalgal species can store nutrients in their tissues in order to circumvent temporal lack of nutrients (Lüning, 1990). Nevertheless, cultivated seaweeds grow better in areas with high nitrogen and phosphorous levels. Harvests in farms are inhibited, however, if macroalgae are cultivated too densely and/or the water exchange is insufficient to replenish the nutrient supply (Titlyanov and Titlyanova, 2010).

Temperature affects macroalgal production less than light and nutrients, unless the temperature is beyond the thermal tolerance of the species.

Within these limits, macroalgae exhibit relative uniform responses to temperature changes (Wiencke and tom Dieck, 1990). Even at extreme temperatures, a long-term acclimation of macroalgae is expected to significantly ease the constraints imposed by temperature (Nejrup et al., 2013).

Salinity is recognized as an important stressor that affects macroalgal habitats (Kaiser et al., 2011). The salinity gradients are most prominent in estuaries and/or semi-enclosed seas, such as the Baltic Sea, and are often characterized by a significant loss of marine taxa and a decrease of diversity towards low salinity conditions (e.g. Bonsdorff and Pearson, 1999). In such ecosystems, the salinity has a strong structuring role which may supersede the effect of other environmental variables, including nutrient availability, and this is especially true in areas where salinity conditions approach the species' tolerance limits (Krause-Jensen et al., 2007).

2.2. Standard macroalgal farms

Three seaweed species have high farming potential in the Baltic Sea region. The growth of *Saccharina latissima* is limited by overly high (>20 °C) or low temperatures (<5 °C) and by overly low salinity (<10−13) (Gerard et al., 1987; Spurkland and Iken, 2011; Nepper-Davidsen et al., 2019). Moreover, exposure to waves, turbidity and nutrient availability significantly affect the growth of *S. latissima*, although the exact responses to these variables are less known (Chapman et al., 1978; Mols-Mortensen et al., 2017). *Ulva intestinalis* is an opportunistic green alga that is widely distributed in littoral zones across the Baltic Sea. Due to its high production potential, *U. intestinalis* may form drifting algal mats in eutrophic embayments (Bäck et al., 2000). *U. intestinalis* tolerates a wide range of environmental conditions (e.g., salinity, temperature, light, pH, inorganic carbon) and, importantly, high nutrient availability enhances its resistance to environmental extremes. These properties have led to *U. intestinalis* being cultivated experimentally in the central (Gulf of Gdansk) and western parts (Hjarnø in Kattegat) of the Baltic Sea (Brzeska-Roszczyk et al., 2017; Christiansen, 2018). Salinity dictates the potential growth of the perennial brown alga *Fucus vesiculosus*, which in contrast to *S. latissima*, can inhabit almost the entire Baltic Sea region except for areas with salinity <4 (Barboza et al., 2019). In contrast to *U. intestinalis*, *F. vesiculosus* grows better under moderate nutrient enrichment. However, low performance at high nutrient levels is likely an indirect effect of biofouling (Wallentinus, 1984; Torn et al., 2006), which can be mitigated somewhat in algal farms (Meichssner et al., 2020). To date, a few small-scale experimental trials to farm *F. vesiculosus* in the Baltic Sea region have been initiated (Balina et al., 2018; Mikkelsen, 2019; Meichssner et al., 2020), but unlike *S. latissima* and *U. intestinalis*, robust technical solutions to cultivate *F. vesiculosus* remain lacking.

2.2.1. Saccharina latissima farm

The cultivation of *S. latissima* has expanded along the European Atlantic coast in recent years to meet the increasing demands for fresh algal biomass by many quickly developing industries. The size of existing farms ranges from fully commercial scale (ca. 100 ha) to experimental scale (a few ha). The raft systems employed in the cultivation can be constructed using either horizontal (long-line) or hanging ropes (garland and vertical types), but in general horizontal ropes are preferred for kelp mariculture in environments with moderate to high degrees of water motion (Peteiro et al., 2016). In our model, a standard *S. latissima* farm consists of a horizontal long-line cultivation system at 1 m depth covering 5 ha (200 × 250 m). The system consists of a series of 65 long-lines running parallel to one another and separated by 4-m access corridors. This provides a total of 12 km of long-line upon which kelp can grow. A typical deployment season for *S. latissima* in the Baltic Sea region would be from November to May. The initial biomass of *S. latissima* in the farm is 6 g ww per 1 m long-line. This farm is harvested once at the end of the deployment in May.

2.2.2. Ulva intestinalis farm

There are currently no commercial *Ulva intestinalis* farms in Europe (Burg et al., 2013), but floating nets are used to cultivate this species in Asia (Ohno and Critchley, 1993). Experimental farms in the Baltic Sea have used either horizontal ropes (long-line) at Hjarnø (Kattegat) or nets in the Gulf of Gdansk and ropes and nets in the St. Petersburg region (Gulf of Finland) (Kovaltchouk, 1996; Kruk-Dowgiałło and Dubrawski, 1998; Brzeska-Roszczyk et al., 2017; Christiansen, 2018). In this model, a standard *U. intestinalis* cultivation farm covers 5 ha of sea area (200 × 250 m). The farm contains 65 horizontal parallel ropes, each 200 m long, placed within 1 m depth. The average distance between ropes is 4 m. This provides a total of 12 km of long-line upon which *U. intestinalis* can grow. A typical deployment season for *U. intestinalis* in the Baltic Sea region would be from May to September. One harvest cycle is 1 month and the species can be harvested 5 times in a growing season. The initial biomass of *U. intestinalis* in the farm is 20 g ww per 1 m long-line.

2.2.3. Fucus vesiculosus farm

No commercial *Fucus vesiculosus* farm operates at present. In the model, a standard *F. vesiculosus* cultivation system covers 5 ha sea area (200 × 250 m). The farm contains 65 lines of adjacently placed 1 m^3 cages at 1 m depth. The cages are placed parallel to one another and separated by 4 m access corridors. This provides a total of 13,000 cages within which *F. vesiculosus* can grow. A typical deployment period for *F. vesiculosus* in the Baltic Sea region would be from May to September. The initial biomass of *F. vesiculosus* in the farm is 900 g ww per 1 m^3 cage (Fucosan, 2020). This farm is harvested once at the end of the deployment period in September.

2.3. Environmental data and species growth data

A compilation of all available experimental data relevant to macroalgal cultivation for the Baltic Sea region into a harmonized geo-referenced database ($n_{total} = 3334$; $n_{Saccharina\ latissima} = 219$; $n_{Ulva\ intestinalis} = 200$, $n_{Fucus\ vesiculosus} = 2915$; see supplement data) was used to model the growth of the selected species along the key environmental gradients. This diverse database included measurements from the existing macroalgal farms as well as data obtained from experimental studies of macroalgal growth under controlled conditions.

The most relevant ecological variables were selected to attain the most robust predictions of the role of the environment on macroalgal growth. Ill-suited variable selection may cause a model to include irrelevant variables and lower its predictive power (Mac Nally, 2000). Earlier studies have shown that macroalgal cultivation depends mostly on temperature, salinity, wave exposure, light and nutrient availability in the water (Titlyanov and Titlyanova, 2010).

The utilization of dissolved organic nutrients is common in the microbial community, whereas seaweeds primarily acquire dissolved inorganic nutrients. Nevertheless, dissolved organic nutrients can be an important source of nutrients for some macroalgal species in some ecosystems, often associated with low inorganic nutrient concentrations (Van Engeland et al., 2011; Li et al., 2016; Alexandre and Santos, 2020). In the nutrient rich Baltic Sea ecosystem, however, it is likely that this mode of nutrient acquisition is not prevailing. The organic nutrients are often first assimilated by bacteria and then transformed by bacteria into inorganic nitrogen or phosphorus forms, which are subsequently taken up by the macroalgae. As there are too many unknowns on seaweed-bacteria interactions and considering large spatial scale of our models, in the current paper only dissolved inorganic nutrients was used to predict large-scale patterns of macroalgal production potential in the Baltic Sea region.

Model inputs for the physical and biogeochemical conditions in the Baltic Sea were obtained from BALTICSEA_ANALYSIS_FORECAST_PHY_003_006, BALTICSEA_ANALYSIS_FORECAST_BIO_003_007 and BALTICSEA_ANALYSIS_FORECAST_WAV_003_010 within the Copernicus open access data portal (http://marine.copernicus.eu/services-portfolio/access-to-products/). These physical products covering the entire Baltic Sea area contain data with hourly resolution and 25 vertical levels. The biogeochemical data are provided with 6-hour resolution and 25 vertical levels. The horizontal grid in both products is regular in latitude and longitude and is approximately 1 nautical mile. The physical product is based on simulations with the HBM ocean model HIROMB-BOOS-Model. The biogeochemical product is based on simulations performed with the BALMFC-ERGOM version of the biogeochemical model ERGOM, originally developed at IOW, Germany. The BALMFC-ERGOM version has been further developed at the Danish Meteorological Institute (DMI) and Bundesamt für Seeschifffahrt und Hydrographie (BSH). The BALMFC-ERGOM model is run online coupled with the HBM ocean model code. In our analyses, daily averages of environmental variables were used. Data for the global distribution of photosynthetically available radiation at the sea surface was obtained from Pfeifroth et al. (2017). This product covers the entire Baltic Sea area, is regular in latitude and longitude at a resolution of 0.05×0.05 degrees and contains data with daily resolution.

2.4. Modelling the growth yields of macroalgal farms along environmental gradients of the Baltic Sea

Growth models were based on algal dry weight yields estimated experimentally across the Baltic Sea as opposed to length measurements. This approach allowed the calculation of negative growth estimates during periods of resource limitation. Yields were normalized with the total incubation time (to produce data for daily yield).

Boosted Regression Trees (BRT; R 3.2.2. for Windows; Elith et al., 2008) were used to model the relationship between macroalgal growth yields and surface water temperature, salinity, irradiance, wave height, nitrates (NO_3^-) and phosphates (PO_4^{3-}) values obtained from the Copernicus products (see previous subsection). The established relationships were used to predict the macroalgal production potential for the entire harvest cycle of *S. latissima*, *U. intestinalis* and *F. vesiculosus* at the Baltic Sea scale.

In contrast to traditional regression techniques, BRT avoids starting with a data model, but rather uses an algorithm to ascertain the relationship between the response variable and its predictors (Elith et al., 2008). BRT models were used first to test if and how different environmental factors (predictors) contribute to the variability of measured dependent variables (training data). Then, BRT were used to predict potential production of macroalgae at the Baltic Sea scale based on the predictive model derived from the first step (model application). BRT models were then fitted using a learning rate, number of trees, and interaction depth set at 0.001, 3000, and 5, respectively. Once the plausible effects of environmental variables on dependent variables were ascertained, monotonic constraints were applied to better represent causality in the modelled relationships. The performance of the fitted models was evaluated using cross-validation statistics (Hastie et al., 2009). Standard errors for the predictions and pointwise standard errors for the partial dependence curves, produced using the R package "pdp" (Greenwell, 2017), were estimated using bootstrap (100 replications).

Unlike *S. latissima* and *U. intestinalis*, farm-scale estimates of the production potential of *F. vesiculosus* are unavailable. The only experimental *F. vesiculosus* farm in the Baltic Sea region consists of small plastic baskets with an edge length and volume of 28 cm and 14 L, respectively (Fucosan, 2020; Meichssner et al., 2020). When describing a standard macroalgal farm (see the subsection below), a similar caging approach was used, but with larger-volume cages (1 m^3 each) to meet aquaculture requirements. However, algal self-shading in larger cages is expected to yield systematically lower algal growth than in smaller cages (Binzer et al., 2006). In order to account for light limitation in macroalgal canopies at farm scale, the predicted growth yields of *F. vesiculosus* (obtained from the previously described BRT procedure) were further corrected using an experimentally-driven function that predicts an expected reduction of *F. vesiculosus* growth along increasing biomass yield (Pärnoja et al., 2014).

2.5. Assessing nutrient removal at macroalgal farms

Farmed macroalgae can extract large quantities of dissolved inorganic nutrients from seawater. These nutrients are transformed into macroalgal biomass and then removed from the marine environment upon harvest (Sfriso et al., 2020). The rates of nutrient removal vary largely among algal species, but also within species, mainly due to differences in the prevailing environmental conditions. Algal growth is optimal given a sufficient nutrient supply. However, when the uptake of nutrients by algae exceeds the import of nutrients, algal growth may be nutrient-limited leading to suboptimal growth conditions. To describe this situation, nutrient limitation at farms should be modelled as a function of hydrodynamics, nutrient concentration in seawater and the actual capacity of nutrient uptake by algae. Such models provide the means to account for short-term dynamics of growth conditions and thereby suggest working solutions to avoid nutrient limitation within farms.

The nutrient limitation of macroalgae growth was modelled using the following linear relationship:

$$\frac{dB}{dt} = rf(N, P),$$

where B [kg] is macroalgal biomass in wet weight, r daily growth rate [kg/(day*m)] for *S. latissima* and *Ulva intestinalis*, [kg/(day*m^3)] for *Fucus vesiculosus* and $f(N,P) \in \{0,1\}$ is the nutrient limitation function [non-dimensional].

The nutrient limitation function was calculated as follows:

$$f(N, P) = \min\ (N_{lim}, P_{lim}),$$

and

$$N_{lim} = \frac{N^x}{KN^x + N^x},$$

$$P_{lim} = \frac{P^x}{(KN*rfr)^x + P^x},$$

where x is a scaling factor (x = 1 equivalent to Michaelis-Menten function), KN is the half saturation concentration of nitrogen and rfr is the Redfield ratio with $x = 0.9$, $KN = 1.2$, $rfr = 1/16$.

N and P are daily concentrations of inorganic nitrogen and phosphorus respectively at the model grid of 1 km^2. The concentrations were obtained from the coupled NEMO-ERGOM model (BALTICSEA_ANALYSISFORECAST_BIO_003_007). The N and P concentrations at the grid cell are affected by advection and diffusion due to hydrodynamics and local biogeochemical processes.

The macroalgal growth rates were obtained from the Boosted Regression Trees (BRT) models (see the subsection "Modelling the growth yields of macroalgal farms along environmental gradients of the Baltic Sea" above for further details). The daily recycling of nutrients was represented through the growth rate coefficient, r. The initial biomass of macroalgae was defined by the size of the macroalgae farm in the grid cell of 1 km^2. The modelling was performed for the realistic period of deployment defined for the different standard macroalgae farms (see the subsection "Standard macroalgal farms" above). The macroalgal wet biomass was converted to mass of removed N and P at the farm scale using the following conversion coefficients for N and P (share): *S. latissima* 0.640 and 0.120; *U. intestinalis* 0.114 and 0.017; *F. vesiculosus* 0.139 and 0.028, respectively.

The standard macroalgal farms described in this study are small and, in such settings, nutrient limitation is unlikely due to the high internal reserve of nutrients in the Baltic Sea. However, nutrient limitation may develop and farm production yields may decline, if too many small farms are located in the same area. The avoidance of this situation requires site-specific estimates of the minimum distance between standard macroalgal farms to assure optimal growth rates. This study used actual hydrodynamic data, expected site-specific growth potential of macroalgae (obtained from the BRT models above) and applied a simplified model framework to estimate the uptake of nutrients by algae and the plausible propagation of the effect of nutrient reduction in space. For this, the daily mean current velocity at each location was calculated using the NEMO model (BALTICSEA_ANALYSISFORECAST_PHY_003_006). These daily mean velocities were multiplied by time to obtain the distance of the uptake of nutrients by algae and the propagation of nutrient reduction in space within a day. The critical distance between farms was calculated as the square root of the area from which farms removed more than 5% of the available nutrient stock from the control volume (upper 10 m water layer). Then, daily means were averaged over the entire deployment period of the macroalgal farms. This was then used as the maximum between-farm distance in which two macroalgal farms can effect each other in terms of nutrient availability.

3. Results

3.1. Spatial models

3.1.1. Saccharina latissima

The fitted BRT models accounted for 98.7% of the variation in the production yield of *S. latissima*. Salinity was the most important predictor in the model explaining 98% of total variability, followed by the marginal contribution of wave height. At salinities >23 the production yields were high and stable. Algal production was significantly lower in less saline environments with virtually no production at salinity <15. The elevated local exposure to waves reduced production but this effect was orders of magnitude weaker compared to the effect of salinity (Fig. S1).

As predicted by the environment-production relationships, the highest production yields can be expected in the westernmost areas of the Baltic Sea where salinity is constantly >23. The environmental conditions suitable for the cultivation of *S. latissima* abruptly deteriorate further south with the southernmost plausible farming region predicted in southern Denmark and northern Germany (Fig. 1).

3.1.2. Ulva intestinalis

The BRT model accounted for 72.5% of the variance in the production yield of *U. intestinalis*. Solar irradiance, temperature and nitrate concentration were the most important variables accounting for 80% of the model variability (58% of total variability explained). The remaining variability was explained by water phosphate, salinity and wave height. In general, the production yield was higher at elevated values of all these environmental variables exhibiting a saturation behaviour above particular light, nutrient and salinity threshold values (Fig. S2). Moreover, salinity interacted strongly with nitrate and irradiance. At salinities >4, the response of algal production to changes in irradiance and nitrate were stronger (Fig. S3).

Due to its broad environmental tolerance, *U. intestinalis* had a wide spatial distribution of production hotspots, covering all Danish Straits, the coasts of southern Sweden, Germany, Poland, Lithuania, Latvia and Estonia (Fig. 2). The expected farm yields at these hotspots are in all cases >0.75 kg ww m^{-1}. Low production zones were limited to the northernmost parts of the Baltic Sea (e.g. Bothnian Bay) and the easternmost parts of the Gulf of Finland where the expected production yields were almost zero.

3.1.3. Fucus vesiculosus

The BRT model fitted on the production yield of *F. vesiculosus* accounted for 84.7% of the variance. Solar irradiance, water nitrate, temperature and salinity were the most important variables, accounting for more than 90% of the model variability (78% of total variability explained). The remaining 10% was attributed to water phosphate and wave height. Algal production increased monotonically in response to most of the studied environmental variables, attaining a plateau at high ranges of environmental variables. However, increasing concentrations of water phosphate resulted in an abrupt reduction in production (Fig. S4). The BRT modelling also unveiled strong interactive effects between temperature, irradiance and salinity. Specifically, at high irradiances the production yields were high regardless of temperature and salinity values. In addition, elevated nitrate values triggered stronger response of production yields to changes in temperature (Fig. S5).

Clear hotspots of *F. vesiculosus* production were identified in the western Baltic Sea. However, high production values were also predicted across the southern Baltic and along the Polish, Lithuanian and Estonian coastlines (Fig. 3). The expected production yield at these hotspots attained as much as 1.5 kg alga per m^3 cage. The production potential gradually decreased to zero in the marginal habitats of the Baltic Sea (e.g. in Bothnian Bay,

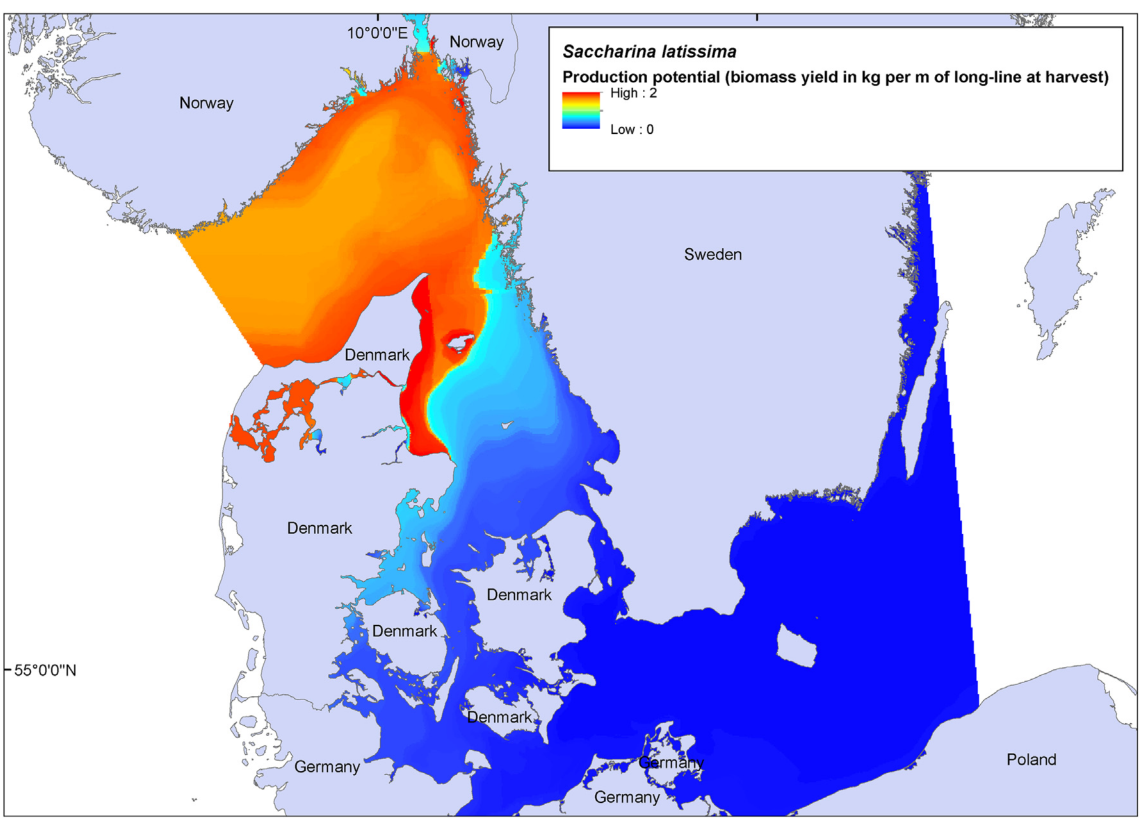

Fig. 1. The production potential of *Saccharina latissima* per harvest in the Baltic Sea area (kg algae per m of long-line at harvest).

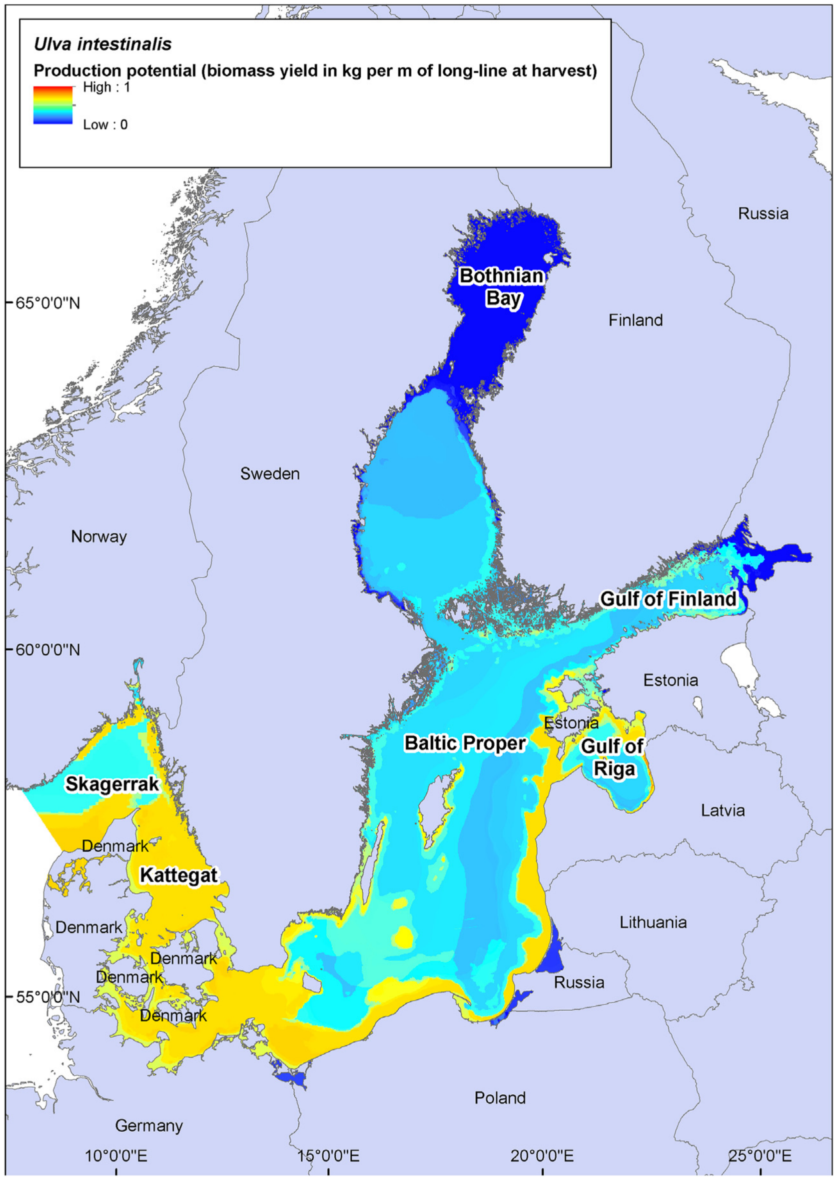

Fig. 2. The production potential of *Ulva intestinalis* per harvest in the Baltic Sea area (kg algae per m of long-line at harvest).

the Gulf of Riga and the eastern parts of the Gulf of Finland). In these regions salinity is below the lower threshold for the algal species.

3.2. Nutrient removal at farms

Saccharina latissima was most efficient in nutrient removal in the Skagerrak area (Fig. 4A, B). The amount of N and P removed at the farm scale during the deployment period was a few tens of kg. The farm efficiency to extract nutrients drops down several orders of magnitude in an abrupt transition zone between Skagerrak and Kattegat. This transition zone closely matches the location of the salinity front between the Skagerrak (salinities ca 30) and the Kattegat (salinities 18–26). The Skagerrak area is suitable for the farming of *S. latissima* owing to the high current speeds that bring nutrient-rich waters from adjacent areas to the farms, while displacing nutrient-depleted waters from the farms to the adjacent region (Fig. 5A). Over a cultivation cycle, one *S. latissima* farm can remove up to 0.07% of available nitrogen and phosphorus from a 1 km^2 sea area (Fig. 6A, B). Consequently, in terms of nitrogen the critical minimum distance between two *S. latissima* farms without inducing nutrient limitation on macroalgal production yields is 100 m. However, in terms of phosphorus this distance is often only 30 m (Fig. 7A, B).

Ulva intestinalis and *Fucus vesiculosus* showed similar nutrient removal patterns. The highest removal hotspots were located adjacent to river estuaries of the western and southern Baltic Sea and in the Gulf of Riga and in the Bothnian Sea. While *U. intestinalis* had a higher nutrient removal potential in coastal areas, the nutrient removal potential of *F. vesiculosus* was higher in offshore areas. In high productivity areas, a single farm of *U. intestinalis* can remove up to tens of kg of nutrients, and a *F. vesiculosus* farm can remove up to a few kg of nutrients. In the estuaries of large rivers of the southern Baltic Sea, the removal of nutrients can be an order of magnitude greater (Fig. 4C–F). The daily mean distance over which the influence of *U. intestinalis* and *F. vesiculosus* can potentially spread exceeds 5 km in the offshore areas of the Gulf of Bothnia, the Gulf of Finland, the Gulf of Riga and the Baltic Proper. In coastal areas of the Bothnian Sea, the Gulf of Finland and the Baltic Proper the distance is three times longer (Fig. 5B). Over a cultivation cycle, a farm of *U. intestinalis* or *F. vesiculosus* can remove up to 0.30% or 0.15% of the available nutrient stocks from a 1 km^2 sea area, respectively (Fig. 6C,D). The critical minimum distance between two farms without inducing nutrient limitation is 150 m for *U. intestinalis* and 250 m for *F. vesiculosus*. However, the critical distance can be <100 m for *U. intestinalis* and <150 m for *F. vesiculosus* in many regions (Fig. 7C–F). Importantly, the expected spatial propagation of nutrient

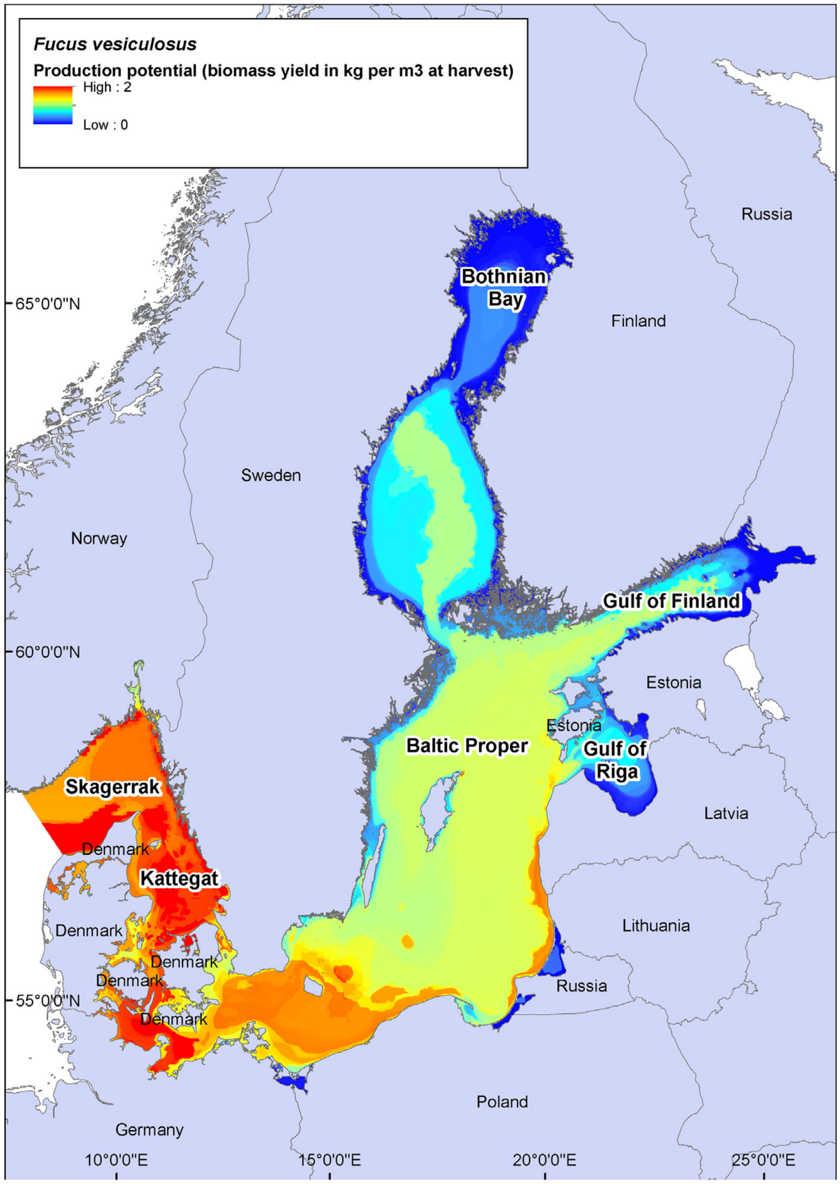

Fig. 3. The production potential of *Fucus vesiculosus* per harvest in the Baltic Sea area (kg algae per m^3 of incubation cage at harvest).

limitation due to macroalgal farming is always greater for nitrogen than for phosphorus.

4. Discussion

4.1. Species-specific production potential in the Baltic Sea

The models and derived spatially explicit predictions of production potential for *S. latissima*, *U. intestinalis* and *F. vesiculosus* presented provide the first region-wide assessment of the environmental suitability for the development of macroalgal farming in the Baltic Sea. The large-scale, empirical and integrative nature of the generated evidence revealed the opportunities the heterogeneous environmental mosaic of the Baltic Sea offers for the development of sea-based macroalgal aquaculture. Beyond the intuitive production hotspots predicted in the more saline western Baltic Sea for all analysed species, promising areas to cultivate *U. intestinalis* and *F. vesiculosus* were also identified in the less saline eastern sub-basins. Predicted biomass yields and the estimated distances required to prevent nutrient limitations in farms suggest that viable macroalgal farming initiatives relying on different species are possible across the region. This finding — along with the spatially defined estimates for nutrient removal at farms — provides the required input for an informed and coordinated consideration of sea-based macroalgal aquaculture as a viable internal measure for mitigating eutrophication at the Baltic Sea scale.

4.1.1. Saccharina latissima

The predicted changes in production yields for *S. latissima* closely followed the steep salinity gradient in the western Baltic Sea, being the main limiting factor for the development of *S. latissima* farms in the region. Consequently, the viability of *S. latissima* farming is expected to be greatest in the Skagerrak area and northern Danish Kattegat, where the species finds favourable salinity conditions (>23, Snoeijs-Leijonmalm and Andrén, 2017) in which to grow and produce biomass (*S. latissima* shows its photosynthesis and growth optima in salinities between 23 and 35; Gerard et al., 1987; Karsten, 2007; Peteiro and Sánchez, 2012). Interestingly, even if *S. latissima* attains much greater production under field conditions along adjacent oceanic areas, predicted productions yields for northern Denmark did not differ greatly from those reported, for example, for the Norwegian west coast (Göran Nylund, pers. comm.). The final biomass of *S. latissima* yield at farms depends strongly on cultivation practices and technologies

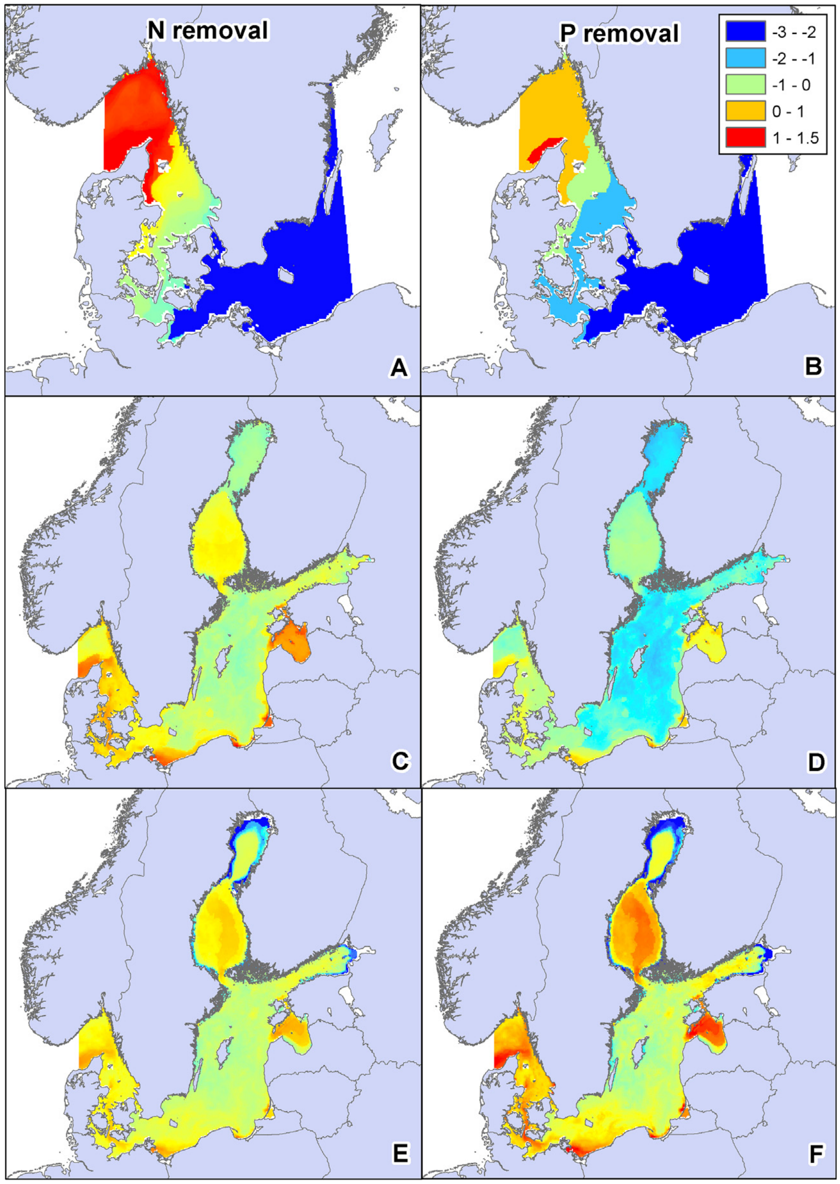

Fig. 4. The amount of N and P removal (kg per harvest) by farms of *Saccharina latissima* (A, B), *Ulva Intestinalis* (C, D) and *Fucus vesiculosus* (E, F). Note that the predicted amounts on colour bars are given in log_{10} scale.

applied (such as the design of the cultivation system or deployment timing), which help to compensate the effects of biotic and abiotic factors with consequences on production (e.g., salinity, exposure or fouling, Boderskov et al., 2021 and references therein). The growth of *S. latissima* decreases southward with the decrease in salinity along the western Baltic Sea (Nielsen et al., 2014, 2016) and with it, the possibility of attaining viable

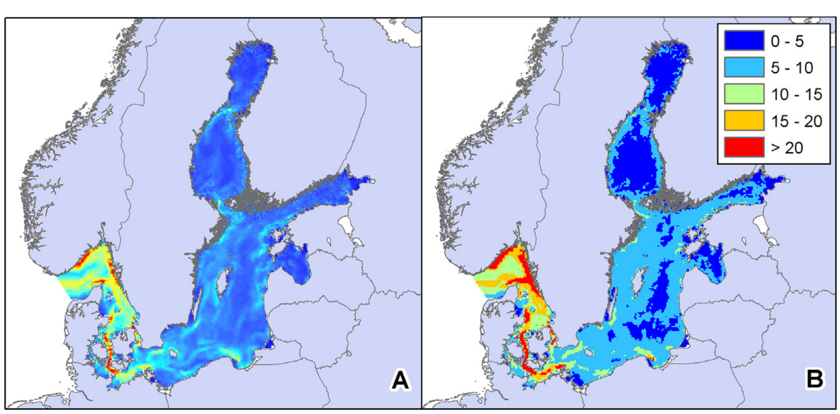

Fig. 5. The daily average travelling distance of surface water (km) during the deployment period of *Saccharina latissima* (A), *Ulva Intestinalis* and *Fucus vesiculosus* farms (B).

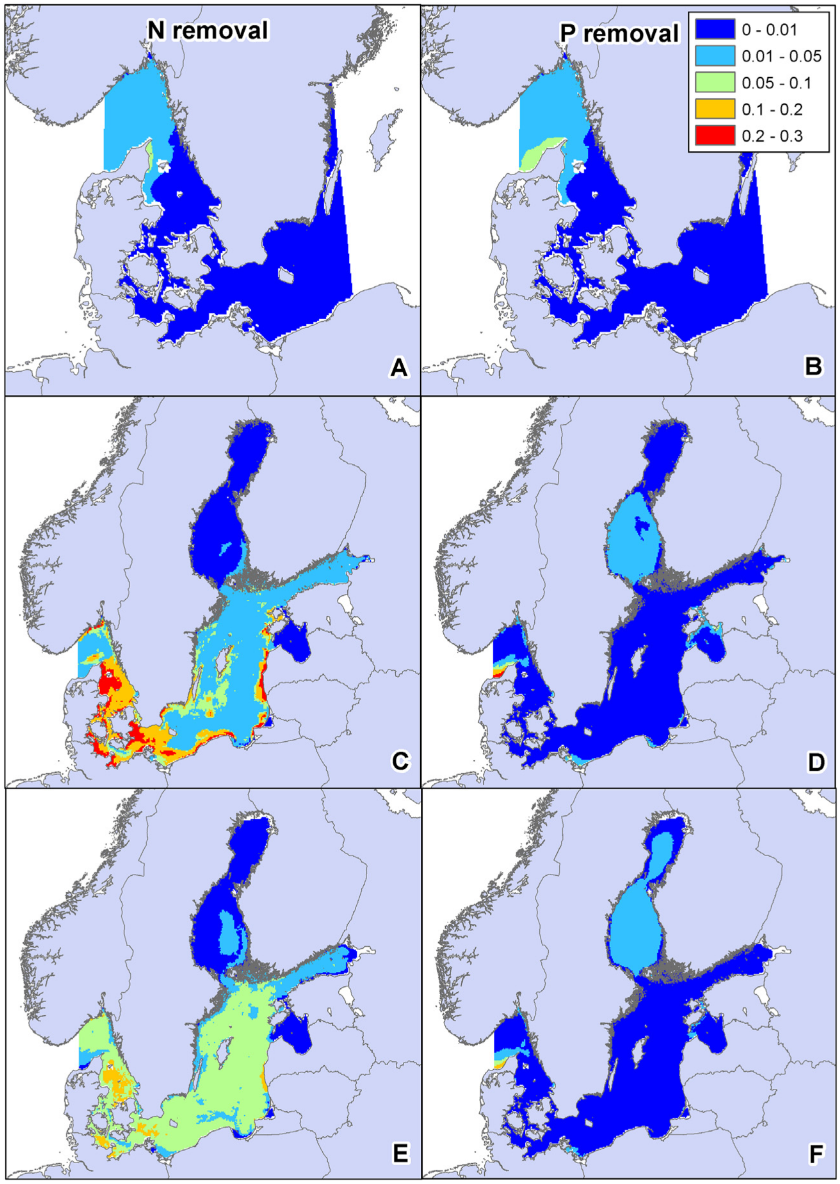

Fig. 6. Mean N and P daily removal by farms of *Saccharina latissima* (A, B), *Ulva Intestinalis* (C, D) and *Fucus vesiculosus* (E, F) relative to N and P stocks in percentage. This is calculated as N (P) uptake by a farm in a day divided by the mass of total N (P) in a grid cell of 1 km^2 and 10 m depth. Daily values are averaged over the period of farm deployment.

production levels for farms to function at a fully commercial scale. Although sea-based cultivation has been developed as far south as in the Kiel Fjord (Wang et al., 2019; Weinberger et al., 2020), ecophysiological studies have reported lower growth rates for *S. latissima* at the prevailing salinities of the area (i.e., 16, Bartsch et al., 2008 and references therein). This situation is expected to worsen further east. Salinity conditions beyond those prevailing in the Danish straits (<10) are expected to constrain severely the physiological performance of the species, compromising its photosynthetic machinery, dampening its growth and dramatically increasing mortality rates (Bartsch et al., 2008; Spurkland and Iken, 2011), rendering commercial sea-based production of *S. latissima* unfeasible.

4.1.2. Ulva Intestinalis

The high production levels predicted for both *U. intestinalis* and *F. vesiculosus* farms along the southern and eastern coasts of the Baltic Proper, and for *U. intestinalis* in the Gulf of Riga, provide auspicious estimates for the development of farming projects utilizing these species in less saline areas of the Baltic Sea. The wide salinity tolerance breadth of *U. intestinalis* allows the species to transiently endure salinities near 0 (Kamer and Fong, 2000) and to grow actively in salinities between 5 and 10 (e.g., Martins et al., 1999; Ruangchuay et al., 2012), making this species an ideal candidate for farming initiatives in low salinity waters that other commonly farmed macroalgae cannot osmotically withstand. As evidenced by the main and interactive effects estimated in our fitted models, light and nitrate availability as well as temperature outweigh the role of salinity in conditioning the capacity of *U. intestinalis* to produce biomass under farming conditions. Previous experiments indicate that nitrogen enrichment mitigates the negative impacts that lower salinities might have on *U. intestinalis*, allowing the species to proliferate in brackish systems (e.g., Kamer and Fong, 2001; McAvoy and Klug, 2005). Additional evidence has shown that light >90 μmol photons m^{-2} s^{-1} and temperatures >15 °C strongly stimulate the growth of germlings of this green alga and might help to compensate the effects of low salinities at this life stage (Kim and Lee, 1996; Kim et al., 2021). Thus, under the favourable nutrient conditions of the eutrophicated waters of the Baltic Sea and with abundant light levels, the standard farms received by the surface layers, *U. intestinalis* can maintain high production levels in spite of osmotic constraints (provided that salinities do not attain steady lethal levels). Moreover, if these conditions

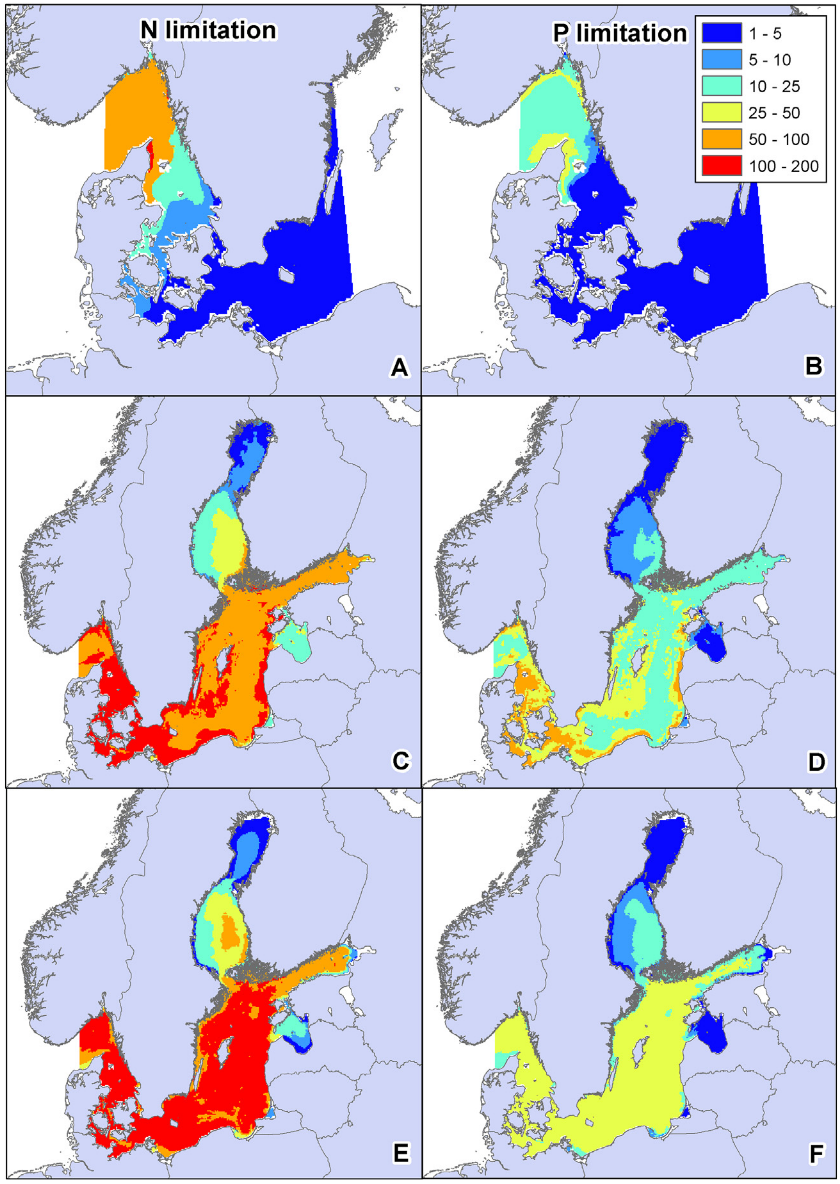

Fig. 7. Critical minimum distance between two farms (m) of *Saccharina latissima* (A - nitrogen, B - phosphorus), *Ulva Intestinalis* (C - nitrogen, D - phosphorus) and *Fucus vesiculosus* (E - nitrogen, F - phosphorus) to avoid nutrient limitation impacts on algal production yields.

couple with prolonged warm seasons, even higher production yields may be expected (e.g. as in the Gulf of Riga, which is a shallow, warm and nutrient rich environment). Therefore, it can be expected that farms producing *U. intestinalis* located on the coasts of Poland, Lithuania, Latvia and Estonia could be as productive as those established in the western Baltic Sea.

4.1.3. *Fucus vesiculosus*

The models suggest that *F. vesiculosus* also qualifies as an attractive species for farming in the eastern Baltic Sea. Despite exhibiting drops in productivity earlier in the salinity gradient than *U. intestinalis*, our predictions indicate that this species is still capable of considerable biomass production in the southern and eastern coasts of the Baltic Proper. In this context, previously described Baltic populations of *F. vesiculosus* locally adapted to the low salinity conditions (e.g. Kautsky et al., 2019) represent ideal primary sources for effective farming. Similar to *U. intestinalis*, light and nitrate availability were key determinants of the production potential of *F. vesiculosus*, partly offsetting the impacts of decreasing salinities. High nutrient concentrations have been proved experimentally to help *F. vesiculosus* tolerate reduced salinities (Nygård and Dring, 2008) and earlier studies have also shown that discharges of nutrient enriched sewage can stimulate the growth of the species under critical salinities (Waern, 1952; Pekkari, 1973). Large rivers in the southern Baltic Sea and in the Gulf of Riga transport significant amount of nutrients to the sea. The currents are not overly strong, thereby maintaining high nutrient concentrations in these coastal areas all year round with limited dilution to offshore waters (e.g. Soosaar et al., 2016). These conditions suggest that the nutrient rich waters of the Baltic Sea might help to boost the productivity of *F. vesiculosus* farms beyond the limits imposed by the prevailing brackish conditions.

4.2. Macroalgal farming: practical considerations for eutrophication mitigation

Farming of macroalgae in the Baltic Sea is today regarded as a promising approach both to increase and diversify the sea-based production of food and raw material and as an internal measure to mitigate the pervasive impacts of eutrophication. Attaining this goal requires the identification of species-specific suitable areas for farming and the development of cognizant strategies to expand macroalgal farming in the region. These strategies should consider both the constraints that might arise from increasing the density of farms and the capacity of farms to reduce nutrient loads in different waterbodies. Careful consideration should be given to the spatial configuration of farms in order to avoid exceeding the carrying capacity of the environment and assure sufficient distances between farms to prevent nutrient limitations on production yields (Campbell et al., 2019). Furthermore, the selection of farm sites must consider not only areas of optimal growth but also waterbodies suffering most from eutrophication, such as shallow coastal areas. Consequently, by modelling the dynamic of nutrients as a function of concentrations in the water, hydrodynamics and the rate of nutrient assimilation of macroalgae cultivated at defined standard farms, reductions in nutrient loads at species-specific farms and their effects on surrounding areas could be estimated.

Surprisingly, the propagation of nutrient reduction effects around standard farms was not extensive, indicating that the prevailing hydrodynamics and the availability of nutrients in the Baltic Sea allows the placement of farms in relatively close proximity (in the range of 100–250 m, and even less in some sub-basins). Higher propagation distances were found in areas of low nutrient and low water exchange (e.g., offshore areas in the Baltic Proper), while shorter distances were predicted in areas of high nutrient and high water exchange (e.g., western Baltic Sea, Gulf of Riga). Nutrient limitation between standard macroalgal farms in the Gulf of Riga is only expected at distances less than 10–20 m. Together with the already described species-specific environmental suitability for biomass production, the general estimated minimum placement distances for farms embolden the scaling-up of cultivation projects and the overall expansion of the industry.

U. intestinalis and *F. vesiculosus* farms offer an effective remedy to ease the burden of excessive nutrient loads in the Baltic Sea. The models indicate similar ability of these two species to sequester nutrients. A single farm can remove a few tens of kg of N or several kg of P per harvest, especially in coastal areas and sheltered bays that are phosphorus limited i.e. characterized by elevated ratio of nitrogen to phosphorus (Kõuts et al., 2021). Elevated removal is expected in the Gulf of Riga, the Bothnian Sea, and in the southern coastal areas of the Baltic Proper as well as in the Skagerrak-Kattegat area. Of note, even if the Gulf of Riga stands out as an area of particularly high nutrient removal capacity, the predicted sequestration can be somewhat overestimated as the coupled NEMO-ERGOM model reproduces nutrient fields of low quality in this area (e.g. Kõuts et al., 2021). Additionally, an important impact on available nutrient budget is also expected in open areas of the Gulf of Finland for both *U. intestinalis* and *F. vesiculosus*, but only for *U. intestinalis* along the coastlines. The width of this coastal zone, as depicted in the maps, matches the described area of high spring phytoplankton production in the Gulf of Finland (Lessin et al., 2009), giving rise to potential negative competitive effects for *F. vesiculosus*. The ability of *F. vesiculosus* to store nutrients in their thallus might be insufficient to cope with the accelerated depletion of nutrients caused by blooming phytoplankton, leading to lower growth and nutrient removal performance in this area. By contrast, *U. intestinalis* is a faster growing species (Wallentinus, 1984) that can better compete with phytoplankton for nutrients, thereby outperforming *F. vesiculosus* in the coastal areas of the Gulf of Finland.

Nutrient removal at macroalgal farms is a co-product of site-specific macroalgal productivity and nutrient availability. Thus, spatial differences in the growth pattern of macroalgae would lead to macroalgal farms having differing potential for eutrophication mitigation within the Baltic Sea. As *S. latissima* finds favourable growth conditions in the western Baltic Sea, only *U. intestinalis* and *F. vesiculosus* can be farmed in other subbasins to mitigate the pervasive impacts of eutrophication. Here, *U. intestinalis* shows greater potential as it thrives in highly eutrophicated less saline embayments where *F. vesiculosus* cannot grow. Moreover, given its shorter cultivation cycle, the annual nutrient removal potential of *U. intestinalis* is several times greater than that of *F. vesiculosus*. It is important to stress though that practical applications may differ from our modelled scenario, especially if farm configurations are significantly different than our standard farms (as different initial standing stocks and productivity result in different nutrient sequestration).

4.3. Macroalgal farming: application and future perspectives

The maps and underlying models offer essential input for the direct inclusion of sea-based macroalgae aquaculture in national strategies and maritime spatial planning across the Baltic Sea, which to date has been neglected (Camarena Gómez and Lähteenmäki-Uutela, 2021). These models explicitly incorporated experimental evidence on the effects of relevant environmental drivers on macroalgal growth and of production measurements obtained at actual farms, allowing to better represent cause-effects relationships in models of correlational nature (given the regional scale of the analysis), to increase the realism of obtained predictions on biomass production and to facilitate their extrapolation to real farms. Furthermore, the generated products helped to define suitable areas for the placement of macroalgal farms and to evaluate their effects on nutrient budgets of different water masses.

The latter aspect is very important as the sustainable expansion of macroalgal farming supports not only food security, sustainable agriculture and responsibly managed living aquatic resources, but also contributes to the regional targets of nutrient emission reduction in the Baltic Sea region (HELCOM, 2013). Moreover, farmed macroalgae are also recognized as sites of intense carbon sequestration and storage, thereby representing eco-industrial production systems that mitigate both marine eutrophication and climate change (Zhang, 2021). Nevertheless, macroalgal farming can realize their role in carbon sequestration only under specific management conditions (Duarte et al., 2013; Trevathan-Tackett et al., 2015). Thus, despite clear evidence that macroalgae contribute to carbon sequestration there is still considerable disagreement as to whether macroalgae and macroalgal farms meet the criteria to be considered within the blue carbon framework (Howard et al., 2017; Smale et al., 2018; Zhang, 2021).

To date, macroalgal farms are limited mostly to the westernmost parts of the Baltic Sea where some commercial scale farming solutions have been recently developed (Thomas et al., 2019). Consequently, the production cost of macroalgae in the Baltic Sea region remains uncertain, which makes it challenging to quantify the economic value of the nutrient removal by macroalgal farming in the Baltic Sea. Nutrient trading alone cannot probably cover the costs of farming in practice. However, as macroalgal farming relates to multiple ecosystem services including climate regulation, storm protection, biogeochemical cycling and provisioning of food and habitat, or refugia to support secondary production for wild capture fisheries (e.g. Corrigan et al., 2022), macroalgal farming significantly improves environmental sustainability and economic viability beyond nutrient mitigation. These aspects need to be investigated jointly in future studies to ensure viable macroalgal farming in the Baltic Sea region.

However, as this new information becomes available, the map layers developed in this paper can be combined with maps of other ecosystem services provided by macroalgal farms, as well as of other human uses in order to find synergies, trade-offs and avoid potential conflict over resources and/or space with other existing maritime sectors. These maps may also point out aspects that prevent macroalgal farming e.g. sites containing high loads of toxicants. When *S. latissima* or *U. intestinalis* is intended for human consumption, farms should be in areas with no chemical pollution to ensure high product quality. To operationalise the modelled data, the map layers of macroalgal farm production were published along with mussel farming potential (Kotta et al., 2020) in the Operational Decision Support System (ODSS) developed to support maritime spatial planning processes in the Baltic Sea. All environmental data from potential macroalgal cultivation sites, the results of the spatial modelling of production potential and effects on nutrients loads is accessible to all through the user-friendly ODSS online platform at http://www.sea.ee/bbg-odss/Map/MapMain. Through its analytical capabilities to synthesize and disseminate up-to-date information and knowledge to different end-users, the ODSS is designed to facilitate and improve the quality of decision-making processes of maritime spatial planners, scientists, policy actors and investors. Previously, stakeholders lacked the capacity to address the environmental aspects of macroalgal and mussel production in the Baltic

Sea as no data-driven tools relying on harmonized information were available. The models and maps provided here, and their open-access availability through the fully functional ODSS web application, provide scientific support for public authorities on the opportunities and challenges of farming native macroalgae and bivalve species as an internal measure to remove excess nutrients already present in the Baltic Sea. Just a few small-scale macroalgal and mussel farms can mitigate the adverse effects of coastal eutrophication, by efficiently recirculating nutrients from sea to land while providing valuable marine resources for fuel, food, feed, bioenergy and raw material. While internal measures for nutrient regulation cannot completely eliminate eutrophication, they can complement external measures, which are likewise themselves inadequate (Savchuk, 2018). Lastly, the maps can serve to reveal the potential of sea-based low trophic aquaculture production in the Baltic Sea region and to generate data-driven support for the required legislative framework.

5. Conclusions

The western and southern Baltic Sea exhibited the highest farming potential for the studied macroalgal species, along with a few promising areas being identified in the southern and the eastern Baltic Sea. Farms in these areas also have the highest efficiencies of nutrient removal. The results presented above provide factual data to support political decision making on internal measures for eutrophication control and to promote the sustainability of the Baltic Sea region through macroalgal farming for nutrient management. Eutrophication is a leading cause of impairment of many aquatic ecosystems including the Baltic Sea. While external measures to control nutrient inputs must be pursued, internal measures to restore water quality and enable ecosystem recovery must be implemented in a timely manner. Macroalgal farming is a promising low-impact and native species-based internal method for eutrophication control in the Baltic Sea and beyond.

CRediT authorship contribution statement

Conceived the study and wrote the paper: JK, RSK, FRB, HJ, AK, LL, RA, MF. Collected data: JK, UR, IM, FRB, AA, IB, PB, FG, MH, MJ, PaK, NK, PeK, TK, AK, IK, SL, GN, TP, HP, IP, MR, VS, WV, BY. Obtained funding and analysed data: JK, UR, IM, AK. All authors discussed the results and edited the manuscript.

Data availability

The datasets that were generated and/or analysed during the current study are freely available from the corresponding author on request.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.156230.

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Awash with contradiction: Capital, ocean space and the logics of the Blue Economy Paradigm

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ABSTRACT

Over the course of the past decade, the political economy of global ocean space has entered into a process of significant transformation. In this context, multilateral, corporate and financial attention dedicated to so-called 'blue growth' and 'blue economy' schemes has been extraordinary; consequentially spawning critical inquiries into the origins and motives behind these initiatives. Offering different analytical interpretations of contemporary blue economy politics, as well as their origins and effects, geographers have entered this debate with a strong focus on institutional discourses and policy agendas. Building on critical political economy of ocean space literatures, this paper emphasises instead the role of capital in appropriating and re-organising the seas according to its own needs. Our primary aim is to elucidate the territorial-economic tensions and geopolitical antagonisms that drive current trends by historicising the emergence of the Blue Economy Paradigm (BEP). The paper shows that a Procrustean political geography of ocean space increasingly poses a barrier to capitalist expansion.

1. Introduction

Under the triple banners of blue growth, blue economy and new ocean economy, the world has borne witness to the inception of a far-reaching reorganisation and expansion of capitalist value relations across the global oceans in recent years. In a bid to define the murky scopes of these initiatives, multilateral organisations and development financiers such as the Organisation for Economic Co-Operation & Development (OECD) and the World Bank have sought to consolidate a series of existing and emerging ocean industries that are usually seen as too disparate to be collapsed under a single sectoral rubric. Such are, for instance, "offshore wind, tidal and wave energy; oil and gas exploration and production in ultra-deep water and exceptionally harsh environments; offshore aquaculture; seabed mining; cruise tourism; maritime surveillance and marine biotechnology" (OECD, 2016: 13). Though a strongly unified conception is lacking, one idea has especially risen to salience amidst the recent ocean frontier renaissance: that of a blue ocean economy, which blends the vast unharnessed economic potentials of the global oceans with socio-ecological sustainability and/or 'green growth' frameworks (e.g. Soma et al., 2018).

Indeed, for many of its proponents, blue economies seem to exemplify triple win schemes, where (i) the wants and needs of coastal and island populations can be reconciled with (ii) cosmopolitan concerns for 'ocean health' and (iii) the capitalist growth axiom all at once (ECORYS, 2012; Patil et al., 2016; The Economist, 2017; World Bank and UNDESA, 2017). In the language of the World Wildlife Fund (WWF) (2017: 2), for instance, a "sustainable blue economy" institutes not only a much-needed panacea in times of ecological distress – it also holds the promise of "social and economic benefits for current and future generations, by contributing to food security, poverty eradication, livelihoods, income, employment, health, safety, equity, and political stability."

The general blue growth enthusiasm enveloping supranational institutions, state governments and development financiers has not gone undetected by academic scholarship. In a recent spate of articles, social scientists have begun to examine the catalysts, motivations and implications that underpin these trends, offering observations that run from mildly optimistic to highly worrisome scenarios (Silver et al., 2015; Winder and Le Heron, 2017; Barbesgaard, 2018; Dornan et al., 2018; Doyle, 2018; Klinger et al., 2018; Bennett et al., 2019; Wenhai et al., 2019). For many, the massive spurt in ocean governance and policy initiatives parallels a growing awareness of the ocean's untapped industrial development potentials, as well as a concomitant recognition of its paramount ecosystemic functions within the acute ecological

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dilemmas of the present. This line of interpretation goes on to assert that inevitable political struggles over spatial access, resource control and regimes of environmental protection can ultimately only be mediated through processes of accountable policymaking and deliberations on the 'type' of blue economy to mobilise and institutionalise (Doyle, 2018; Eikeset et al., 2018; Bennett et al., 2019). Moreover, several scholars point out that the blue economy notion appears to sit in a malleable, rather open-ended, discursive force field (Silver et al., 2015; Dornan et al., 2018; Keen et al., 2018; Voyer and van Leeuwen, 2019), with some assuming it to represent a "remapping" of the oceans by diverse networks of actors (Winder and Le Heron, 2017).

Several studies have been pronouncedly sceptical of the general thrust of blue economy initiatives, urging social scientists towards caution (Benjaminsen and Bryceson, 2012; Choi, 2017; Bond, 2019; Mallin et al., 2019). Echoing distress calls of global fisher movements and their growing wariness of a global ocean grab (Pedersen et al., 2014; Clapp et al., 2017; Brent et al., 2018), Barbesgaard (2018: 145) even suggests that the "increasingly hegemonic nature of the blue growth discourse in global policy processes […] is undermining and precluding progressive and transformative solutions." Behind the exclusive gatherings of transnational financial and corporate elites, such as the *Our Ocean Conference*, then lurks the suspicion that here a large blue washing project is in the making, which ultimately provides a convenient mask for a "sanitized ocean grab" (Brent et al., 2019).

Despite the generally shared ambivalence as to what the blue economy moment truly represents, a tacit consensus seems to hold throughout both the more favourable as well as the cautioning interpretations, that it is primarily a product of institutional discourses and performances characteristic of contemporary environmental politics; in this sense the blue economy is somewhat of an offshoot of the more senior yet equally flexible green economy agenda (see also Steinberg, 2008; Bailey and Caprotti, 2014). We recognise that analysing the distinct discursive functions of various emerging blue economy policies and initiatives, as has been attempted in the literature so far, is indeed a vital undertaking. Yet, conversely, it can be said that such inquiries easily skim over the long historical lineage of capitalist modes of enclosing, appropriating, carving up and commercialising the seas. Hence, in this paper, we posit that the blue economy moment may be more adequately investigated and understood as part of a *longue duré* transformation of capitalist relations with the sea.

To substantiate this hypothesis, we put forward a materialist reading of these relations, emphasising the historical geographical dialectics of capital accumulation, enclosure and territorial-organisational forms (especially UNCLOS) that presuppose and condition the current transformation of the ocean economy. Attending specifically to Marx's and Marxist geographers' inquiries into the contradictory nature of capital's spatio-temporal expansion,[1] we seek to depart from an overdetermining analytical focus on blue growth semantics and institutional politics. Rather, we intend to show how conflicting tendencies of capitalist spatialisation, technological-organisational transformation and mental conceptions of the ocean economy have long revealed the need for a substantive reconfiguration. This (temporary) arrangement, we contend, is found in a Blue Economy Paradigm (*hereinafter* BEP), which seeks to move the ocean economy beyond a whole host of barriers in the accumulation process at once. Ultimately, our theoretical foray suggests that the global inception of blue economy arrangements is likely to function as a catalyst for deepening existing forms of uneven geographical development, thus exacerbating social antagonisms around the use of coastal and marine environments in the future.

We begin by connecting some of the fundamental insights into the contradictory and crisis-prone nature of the ocean economy that lie dispersed across geographical and critical political economy literatures, most of which focus on the issues within individual sectors (*see* Section 2). This is followed by a critical review of recent blue economy-related interventions in geography and cognate fields (*see* Section 3). On this basis, we subsequently offer a theorisation of the emergence of the BEP and its potential ramifications (*see* Section 4).

2. Enclosed, appropriated and contested waters: a brief review of oceanic political economies

In the wake of the most devastating war in human history, the largest transformation of the space economy of capitalism with regards to the oceans was set into motion upon two proclamations made by U.S. President Harry Truman in September 1945 (Watt, 1979). The first proclaimed all known and potential resources on and beneath the continental shelf adjacent to the U.S. coasts under the state government's exclusive management and control (Dept. of State, 1945a); the second stipulated a U.S. prerogative to control and regulate fishery activities through the establishment of "bounded conservation zones" in the high seas contiguous to its coast, wherever U.S. nationals were engaged or planning to engage in commercial fisheries (Dept. of State, 1945b). Rather than being repudiated, the unilateral U.S. foray was essentially met with "emulation and acquiescence" and ignited a three decade lasting and well-documented state-led scramble for expanding maritime sovereignties all around the global oceans (Morell, 1992; Scharf, 2013: 107). Seeking to put a lid on inflationary claims rapidly encroaching on the remaining high seas and seabeds, a suit of conferences held from 1958 onwards sought to establish a legally binding international accord. This process culminated in the tedious negotiation of the 1982 United Nations Convention on the Law of the Sea (UNCLOS), whose 320 articles and 9 annexes finally came into force in 1994 (Prescott, 1975; Papadakis and Glassner, 1984; Glassner, 1990). Up to the present, UNCLOS has enabled the "largest single enclosure in history", extending state jurisdiction up to 350 nautical miles from the shoreline through the establishment of Exclusive Economic Zones (EEZ) and Extended Continental Shelves (ECS) (Campling and Havice, 2014: 714).

The most immediate outcome of this dynamic has been a political configuration that enables the spatial relations of oceanic capital accumulation and distribution to be formalised around a set of legal principles and dispute resolution mechanisms, thus creating a relatively transparent albeit inflexible global maritime order. Most importantly, states herein assume a key function "at the nexus of rent appropriation and other distributional struggles around surplus value, (perceived) 'national interest', geopolitics, resource management and industry regulation in EEZs" and ECSs (Campling and Havice, 2014: 715). Adopting a territorial political economy lens, Steinberg's (2001) seminal study on *The Social Construction of the Ocean* theorised the origins of this process within the contradictions of capitalism's distinct spatiality at sea. UNCLOS, he reasoned, reflected a compromise between differential needs of capital accumulation and circulation: on one hand those of spatially less mobile industries, which demand sovereign management regimes guaranteeing long-term legal security and stable governance; on the other those of hypermobile industries, commercial fleets and navies, which require smooth and unconstrained rite of passage across an idealised friction-free oceanic surface (see also Steinberg, 1999). The seemingly stabilising effect achieved by UNCLOS, however, could only ever be a temporary solution to mitigate the opposing and inherently crisis-prone dynamics of capital accumulation as well as the fresh forms of geopolitical competition they gave rise to. With the acceleration of uneven ocean space developments catering to a plethora of industrial (e.g. fishery and oil) and commercial (e.g. transport and tourism) needs, these conflictual tendencies would eventually resurface in new forms of struggle over resources, rent and access, both within and between different sectors (Steinberg, 2001).

[1] Our work is informed by Marx' critique of the political economy advanced in Volumes 1–3 of Capital as well as Marxist geographers' elaboration of the space economy of capitalism, especially Harvey (2006, 2013), and Smith (2010).

Against this general backdrop, we will now revisit some of the contradictory tendencies, which define the various sectors that constitute the ocean economy. We orient ourselves alongside the "robust, but small [and] critical literature" (Campling et al., 2012: 178) that has subjected the political economies of individual sectors to detailed scrutiny, limiting our survey to four distinct aspects: (i) fisheries, (ii) aquaculture, (iii) seabed extractivism, and (iv) marine conservation.

For the past 60 years, policy debates on fisheries have revolved around the question of whether and how common and presumed open access property regimes lead to economic and environmental crises (Mansfield, 2004; Campling and Havice, 2014; Barbesgaard, 2018). While not an exclusive feature of capitalism, capital's universal drive to establish forms of spatial organisation conducive to the rational and efficient exploitation of nature has fashioned the continuous evolution of marine fisheries "towards enclosure of open access regimes for hundreds of years" (Campling & Havice, 2014: 714). The particular property regimes that have crystallised as a result have determined struggles over the creation and distribution of surplus value stemming from the production of fisheries commodities. As Mansfield suggested in her analysis of EEZ fisheries management systems predicated on neoliberal types of property regimes, dynamics within the fisheries sector have influenced property questions well beyond the domain of fisheries, with significant implications for the "governing [of] access to and use of ocean resources" (Mansfield, 2004: 314; see also Mansfield, 2007). Despite the co-existence of different types of oceanic privatisation and property regimes, the overall effect of marine enclosures has been an exceptional concentration of economic power within the fisheries sector, to the ever-growing detriment of now-excluded coastal populations relying on small-scale fisheries for their social reproduction (Longo et al., 2015). Many studies have since followed Mansfield's avenue of critique to the scrutiny of market dynamics and competition specific to evolving fisheries production and consumption systems (Campling et al., 2012; Longo and Clark, 2012; Fabinyi et al., 2019); regimes of labour exploitation and resistance within the fisheries sector (McCall Howard, 2012; Sinha, 2012; Howard McCall, 2017; Mills, 2018; Belton et al., 2019; Vandergeest, 2019); and antagonisms arising from the appropriation of ground-rent within EEZ spaces (Campling and Havice, 2014; Barbesgaard, 2019). In contrast to the more mainstream policy-focused debates, where considerations of 'management' and 'governance' are largely construed in isolation from the uneven geographical development of global capitalism, many of these critics position the functions of emerging regimes of territoriality in relation to a political economic dialectic of oceanic appropriation and commodification.

In light of the accelerated proliferation of marine and inshore aquaculture industries since the 1990s, struggles for control and command over space and resources within the fisheries sector have been exacerbated considerably. Geographically speaking, this phenomenon has been especially transformative in labour intensive economies, where the sector was spurred on by governments and donor agencies as a means to replace stagnant capture fisheries and simultaneously secure foreign exchange. In India and Chile, for example, the rise of this industry was encouraged by the World Bank, which catalysed processes of enclosure and expropriation through large-scale credit-funded aquaculture developments (Vandergeest et al., 1999). Since the 1990s, scholarly inquiries have attempted to conceptualise the distributional struggles that resulted from increasingly uneven access to marine resources, as well as the large-scale destruction of mangrove forests (Vandergeest et al., 1999; Stonich and Bailey, 2000; Hall, 2003). More recently, the expansion of aquaculture production has been conveniently framed as a means to 'feed the world' (e.g. OECD, 2016), in manners that could sustainably alleviate the pressures on global fish stocks exerted by capture fisheries. Yet, by teasing out the sector's lasting dependency on capture fisheries for feed, critical scholarship has widened the focus of attention with regards to the socio-environmental problematic of aquaculture production (Longo et al., 2015; Saguin, 2016; Ertör and Ortega-Cerdà, 2019). Contrary to the assurances made by different donor-backed aquaculture initiatives, Ertör and Ortega-Cerdà (2019: 360) convincingly posit that "instead of providing a solution to declining fish stocks, the intensive marine aquaculture of carnivorous species only solves the crisis of capital in the short term, and its expansion ends up putting pressure on capture fisheries." In more abstract terms, this mode of marine food production lends temporary opportunities for the appropriation of relative surplus value to capital. As a consequence, however, it introduces new contradictions into the socio-natural metabolism by disrupting food production in small-scale fisheries, and ultimately accentuates the long observed depletion of the marine resource base (Longo et al., 2015).

Paralleling the expansion of capitalist relations in marine food production, the development of constantly revolutionising technologies for offshore oil extraction, has served as a promoter for the crisis in ocean governance defined by capital's differential territorial-economic requirements (Steinberg, 1999). The vertical geopolitics (see Elden, 2013) of this sector are recorded in a global oil infrastructure that relies on more than 3300 sub-seabed oil wells, 75,000 km of oil and gas pipelines along the seafloor, driving one-third of global seaborne trade on more than four thousand oil tankers (Watts, 2012: 441); with an estimated share of 34% of the total revenues generated in the oceans by 2010 (OECD, 2016). Perhaps more tangible than in the case of any other sector, it "manifests itself in the aggressive pursuit of economies of scale in production and refining, and in transportation", which has driven the "oil frontier" to the "ends of the earth, or more properly a mad gallop to the bottom of the ocean" (Bridge, 2008; Watts, 2012: 442). While much of the hydrocarbon political economy literature has developed separately from the critical literature on ocean space, Zalik (2009) and Chalfin (2015, 2018) have sought to integrate insights from both domains. Chalfin (2015: 102), in particular, deepens this linkage by discussing the re-ordering of ocean space necessary to turn the Western Gulf of Guinea into a "global hydrocarbon 'hot-spot'." The reproduction of capital through offshore oil ventures, she infers, is premised upon a specific mode of "terraqueous territoriality", which according to Campling and Colas (2018: 777) follows "the distinctly capitalist articulation of sovereignty, territory and appropriation in the capture and coding of maritime space." Chalfin shows how the Ghanaian state's "maritime territorial imperative is modified to fit the shape of petrocapital" (Chalfin, 2015: 115). Offshore hydrocarbon extraction is at once highly dependent on state-guaranteed fixed capital in the form of infrastructure and security, at the same time as it demands unconstrained logistical flows and capital mobility between urban spaces and the sea (Chalfin, 2018).

Notwithstanding the far greater political leverage of the oil sector, the political geography of the deep sea has been significantly gauged by the prospect of yet unexploited mineral deposits, occurring in the form of manganese nodules, hydrothermal vents and cobalt-rich crusts (Buzan, 1976; Glassner, 1990). After a short-lived 'seabed gold fever' lasting from the 1960s to the 1980s, a decline in commercial revenue prospects and thus lower incentives to develop deep sea mining (DSM) technology put activities on hold. To a certain degree, it was this temporary truce that allowed for a multilateral compromise between spatially mobile and immobile capital investments to be broached and for the eventual adoption of UNCLOS (Steinberg, 1999: 415). Currently, this arrangement finds itself under heightened pressure, as an ensemble of new extractive technologies, geopolitical scuffles over rare earth minerals and the rise of a mineral dependent 'green economy' have revived seabed mining endeavours both within EEZs and in the high seas (Mallin, 2018; Zalik, 2018). As Zalik (2018: 5) posits, current efforts to transform the high seas management regime are "product[s] of a neo-mercantilist drive on the part of state and affiliated fractions of capital to claim potentially valuable resources perceived as globally scarce." As we elaborate in Section 4, however, this particular neo-mercantilist drive is best understood as part and parcel of broader struggles around the resolution of the ocean economy's territorial-economic contradictoriness.

Last but not least, tensions have also deepened as a result of interventions portrayed as remedies to the widely-observed ruination of marine environments. In a seeming antithesis to the accelerating industrial and commercial expansion, and justified in concerns over biodiversity loss, climate and marine pollution, oceanic conservation has become a key feature of the ocean economy during the past two decades; it has significantly influenced the distribution of capital and territorial control across entire maritime regions. 12,000 Marine Protected Areas (MPAs) covering approximately 4.8% of global ocean space (MPAtlas.org, 2019) have also substantially reconfigured power dynamics in ocean governance – not least as public and private foundations have assumed a key stake in socio-ecological power struggles. As part of strategies advocated to achieve a better protection of marine biodiversity, conservationists are increasingly tapping into modes of governance that Dempsey (2016) dubs "enterprising nature". In this vein, successful conservation is tied to "salvation narratives" that espouse "stabilization, categorization, and organization as a road to better ocean management" (Boucquey et al., 2016: 5; Fairbanks et al., 2017). Whilst representing often well-intended efforts to achieve a temporary withdrawal of oceanic segments from productive exploitation, there is growing evidence that unevenness in spatial access and resource distribution is further entrenched and actively contested (Bennett and Dearden, 2014; Hill, 2017). Echoing critiques of green grabs and accumulation by conservation (Smith, 2007; Fairhead et al., 2012; Büscher and Fletcher, 2014; Apostolopoulou and Adams, 2015), social scientists have begun to conceptualise processes of dispossession under the rubric of 'blue grabs' and 'ocean grabbing' (Benjaminsen and Bryceson, 2012; Pedersen et al., 2014; Bennett et al., 2015; Foley and Mather, 2019). Furthermore, with the proliferation of Large Marine Protected Areas (LMPAs) from the 2000s onwards, marine conservation has more or less explicitly gained a geopolitical element (Leenhardt et al., 2013; Giron, 2016). Drawing from recent insights in the land grabbing literature that theorise capitalist mechanisms of long-term spatial and resource control (Borras et al., 2012; Holmes, 2012; Edelman et al., 2013; Tedesco, 2015), some have postulated that the nexus between LMPAs and the philanthropies of the superrich may represent a new formula for enclosure, termed "ocean control-grabs" (Mallin et al., 2019). This approach echoes conceptualisations of spectacular conservation enclosures within the dynamics of capitalist expansion and neoliberal natures (Igoe et al., 2010; Büscher et al., 2012; Büscher et al., 2014; Büscher and Fletcher, 2014; Fletcher et al., 2018), postulating a need to overcome the prevailing belief that ocean grabs must always "coincide with exclusion or immediately measurable socially conflicting outcomes" (Mallin et al., 2019: 9). Instead, individual conservation projects ought to be conceived as part of a larger picture, which accounts for the dialectical, often contradictory, evolution of political economic and geopolitical forces.

Broadly situated at the intersection of global environmental politics, political ecology, fishery systems studies, labour and resource geographies,[2] the scholarly accounts synthesised in the preceding paragraphs have yielded detailed empirical insights into the contested dynamics of enclosure, appropriation as well as different modes of oceanic capital accumulation. While seldom explicit, they circumscribe the ocean economy as a distinct – in many ways autonomously configured *yet* highly intertwined – part of the global capitalist economy. Before turning to a theorisation of the BEP on the basis of their proposed conceptualisations, we continue with an assessment of recent blue economy-related analyses put forth by geographers and other social scientists.

[2] The critical impetus of this field has developed partly alongside the "nascent scholarly turn to the oceans" in geography, which according to Connery (2006: 496) has set out to "confront the terrestrial character of knowledge disciplines." Whilst we recognise the insights provided by human geographers of ocean-space that privilege new ontologies and epistemologies, our subsequent inquiry into the ocean economy finds a more productive engagement with the Marxist and critical political economy traditions discussed in this section.

3. Emerging contours of the blue economy

As a vogue term in political and economic elite circles, the blue economy notion started gaining traction following the 2012 UN Conference on Sustainable Development (Rio + 20); approximately two decades after efforts began in the 1990s to develop so-called 'multi-stakeholder ocean governance' beyond the scope of UNCLOS and to institute relevant international research programmes (Vallega, 1999; Conservation International, 2003; Glover and Earle, 2004; Buxton, 2019). After 2012, a series of endorsements by development financiers started featuring the blue ocean economy more prominently on the maps of private and public investors, such as the World Bank's launch of a 6.4 Billion USD blue growth portfolio under its Blue Growth Initiative.[3] Stakes were successively raised through financial pledges on parts of several large development financiers. The European Investment Bank, for one, has been lending to ocean industries for decades. In 2019, it announced plans to expand its loans particularly to emerging sectors, including "offshore wind technology, blue biotechnology and environmental and coastal protection", in order to strengthen the role of private capital in blue growth schemes (European Commission, 2019: 107). Meanwhile, the Asian Development Bank broadcasted a USD 5 billion investment commitment in the form of 'blue bonds' and risk guarantees (ADB, 2019). In addition, a plethora of national governments, supranational entities, industry coalitions and several U.S.-based foundations have been actively promoting blue economy templates catered to almost all major maritime regions (ECORYS, 2012; Conservation International, 2014; FAO, 2014; IORA, 2015; Patil et al., 2016; European Commission, 2017; The Economist, 2017; World Bank and UNDESA, 2017; WWF, 2017). Especially with regards to the Pacific and the Caribbean, the blue economy has been staged as "a tool that offers specific mechanisms for Small Island Developing States and coastal countries to address their sustainable development challenges" (UN, 2013, 2015). Elsewhere it has been driven by the implementation of regional and national blue growth strategies from the Indian Ocean Rim Association (IOARA) to the African Union, with the latter recently devising the blue economy as the "new frontier of African Renaissance" (Ndhlovu, 2018).

In one of the first critical examinations, Silver et al. (2015) categorise competing blue economy discourses pervading the sphere of international ocean governance during Rio + 20. Ecological concerns, followed by economic and geopolitical considerations, the authors presume, were responsible for generating the spike in attention to the oceans: "Catalysts include ocean acidification and sea-level rise, overfishing and marine biodiversity loss, a growing consensus regarding the conservation and development potential of the high seas, and, interest from some countries in territorialising more ocean space" (ibid: 136). The blue economy, they argue, assumed a flexible function, fulfilling both ideological and technical interests of different "governance actors" (e.g. SIDS, International Organisations, NGOs, Scientists, corporations) in asserting their respective agendas within the meetings. In particular, the open-ended "precariousness of discourse" supposedly presented possibilities for marginalised actors "to further adopt or subvert the term in ways that advance diverse objectives, progressive politics, and governance practices in the largest remaining contiguous common spaces in the world" (ibid: 153). Picking up on this, a further study outlines emerging issues in "global oceans governance" more comprehensively (Campbell et al., 2016); it scrutinises how the political

[3] As of October 2019, the World Bank Group's "active Blue Economy portfolio is around $5 billion, with a further $1.6 billion in the pipeline" (World Bank, 2019).

interventions of different actors in governance processes play out across scales and hinge on mobilising different bodies of knowledge. The authors remain generally optimistic of the outcomes, arguing that "[n]ew actors and technologies could help break down old ideas about scale in the oceans, bridging scales or even descaling the complexity of ocean problems" (ibid: 536). However, these and related interventions (e.g. Doyle, 2018; Voyer et al., 2018) tend to conceptualise the 'discursive' and the 'political' in isolation from economic forces, which most of the literature reviewed in Section 2 conversely postulates as quintessential to grasp the political struggles and contestations over ocean space, without lapsing into economic determinism. More recently, scholarship has sought to examine regional blue growth trajectories and their grounded manifestations in various national contexts (see Childs and Hicks, 2019). With a few notable exceptions (e.g. Bond, 2019), these typically follow conceptions of the blue economy as a discursive-institutional power field, examining how it is mobilised and filtered through national political and economic processes (e.g. Carver, 2019; Schutter and Hicks, 2019).

By contrast, Winder and Le Heron (2017) contextualise the Blue Economy Moment within an ambit of increased geopolitical and geoeconomic tensions, which primarily arose from contestations to American hegemony over the seas (notably by China) and accompanying struggles between different factions of capital over the use of ocean space. Subsequently, however, they argue against theorising potential structures of hierarchy within blue economy-related activities. Rather, to "accommodate difference within Blue Economy", everything from "bio-prospecting", the "navy", "pipelines", to "feminist networks" and "fish" ought to be examined on a hierarchy-free ontological plain (ibid: 15). Subsequent responses and commentaries have been largely sympathetic to the proposed assemblage approach – with some encouraging Winder and Le Heron to explore the blue economy moment through a deeper consideration of the "more-than-human" (Bear, 2017; Foley, 2017).

Arguing against the backdrop of China's contemporary ocean economic ambitions, Choi (2017) emphasises that the blue economy must be historically read as a complex governmental project designed to facilitate capital accumulation and the rearrangement of people and resources. "Blue Economy practices of seeking economic ways to use space", she notes, "ironically leads to the representation of sea space as potential development space and eventually to more intensive and extractive uses of sea space as a consequence" (ibid: 39). Going further, Bond's (2019: 354) Marxist critique of 'Operation Phakisa', South Africa's blue economy initiative, cautions that it is insufficient to merely rely on the persuasive "power of ideas" in shaping struggles over economic projects. Instead, he suggests, it is vital to disentangle the underlying metabolism of capital accumulation, in order to contextualise the contradictory and crises-ridden dynamics of the contemporary moment: "Africa's coastlines reflect the increasingly carbon- and plastic-saturated character of oceans, pressure which gives local and global capitalism the opportunity to impose dangerous new accumulation strategies" (ibid: 343). He underpins the validity of this claim by revealing a series of both class-based and socio-ecological contradictions that set the limits for capital's pursuit of a quick blue fix. In this sense, the first requisite to align red and green resistance strategies, he holds, must be the attainment of "ideological clarity about what is at stake" (ibid: 359).

4. Capital, contradiction and the rise of the Blue Economy Paradigm

Picking up on Choi's and Bond's calls, we unpack the Blue Economy Paradigm (BEP) in this section. We approach this task by situating the world historical dynamics and geopolitical particularities that characterise the ocean economy within a Marxist critique of the political economy. To this end, we identify four developments as key to advance a theorisation of the nature of the BEP: (i) a historical shift away from a spatial organisation of the sea defined by the needs of commercial capital to one that better caters to the requirements of industrial capital; (ii) an expansion of spatially immobile and semi-mobile industrial machinery, whose valorisation is constrained by the territorial division of ocean space as codified in UNCLOS; (iii) a need to overcome ideological barriers to the expansion of capital accumulation; finally, (iv) a resultant acceleration of enclosure movements, accompanied by the emergence of new geopolitical imperatives. Whilst we acknowledge that our subsequent theorisation is far from complete and operates mostly at the level of generality, we offer this conception as a first foray to develop an alternative interpretation of contemporary blue growth politics.

4.1. From commercial capital to UNCLOS: spatial codification as a barrier to accumulation

Since the dawn of capitalism as a distinct mode of production, the seas have been essential to the reproduction of capital by facilitating the exchange of commodities, including labour, the steady supply of raw materials and the continuous expansion of the spheres of production, realisation and circulation (Braudel, 1983). In particular, "commercial capital" – which according to Marx (1981: 392–393) represents a form of capital that does not create value or surplus value directly[4] but "helps to extend the market", mediates the division of labour between the capitalists, "cuts down the turnover time" and empowers "capital to operate on a bigger scale" – has driven the absorption of global ocean space into capital's economic purview (see also Arrighi, 2010). Notably, "[t]he sea route, as the route which moves and is transformed under its own impetus" (Marx, 1973: 525), did not require state governments to provide and maintain costly geographically fixed infrastructures. From a historical geographical perspective, the formation of the capitalist world market was therefore pre-destined to become an oceanic pursuit, largely driven by the needs of this particular form of capital (Arrighi, 2010).

In this sense, Hugo Grotius' famous *Freedom of the Seas* (2004[1609]) doctrine was as much a geopolitical statement on the ascendancy of Dutch merchant capital at the hands of the VOC (*Vereenighde Oostindische Compagnie*) (Van Ittersum, 2006), as it became a striking illustration of capital's iron pursuit for "the creation of the physical conditions of exchange" that for Marx presupposed "the annihilation of space by time" across all hemispheres (Marx, 1973: 524). Uneven trans-oceanic trade[5] conducted by powerful "mercantile enterprises with military and naval strength" (Black, 2009: 38) easily permitted the realisation of capital in distant markets (and in transportation labour) in such mass and proportions as were necessary to recoup the quantity of capital first advanced in transportation, communication and military expenditures. The conscious amalgamation of naval force, financial resources and territorial rule during the 17th century ensured constant technological and geographical revolutions at sea (see e.g. Mahan, 1898; Sumida, 2006; Rüger, 2007). It also represented a form of state sponsorship for the interests of commercial capital (Braudel, 1983).

Countervailing tendencies demanding enclosures and the creation of fixed sea tenure regimes emerged as early as the 13th century (Campling and Havice, 2014). Nonetheless, for almost five centuries they remained subordinate to the organising imperatives of commercial

[4] As Marx qualifies, this attribute only applies when commercial capital occurs in its pure form. It is therefore primarily a theoretical abstraction to explain the process of circulation in an idealised sense (Marx, 1981: especially Chapter 17).

[5] The means by which favourable conditions of exchange were attained included the temporary closure of trade routes and harbours (*mare clausum*), the forceful exclusion of competitors (Arrighi, 2010: 157ff.), and violent histories of slavery.

capital. Even with the entry of terrestrial competitors to oceanic exchange, such as the transcontinental railway and highway systems, the geographical pivots of the respective hegemons (first Great Britain, later the United States) would reinforce the pre-eminence of commercial capital across the world's oceans (see Mackinder, 2004[1904]; Friedman, 2015). In generalised terms, thus, commercial capital's sway over the political geographical relations of the seas fundamentally outweighed those of industrial capital, and prevailed as the determining force driving spatial organisation until the 20th century. Only with the massive expansion of industrial fisheries and the introduction of new seaborne industries towards the end of the 19th century did an absolute need for an institutional foundation to mediate between capital's differential requirements finally arise.

This brings us back to the compromise brokered by the third conference of UNCLOS in 1982/1994 (*see* Section 2). Ideologically, UNCLOS was largely framed around bids for state-mandated resource protection (Mann-Borgese, 1968, 1975; Jacques, 2006) that followed Garett Hardin's (1968: 1243–1244) neo-Malthusian principles: "space is no escape" and "each herdsman seeks to maximize his gain." The supposed "tragedy of the commons" rationalised the need for a standardised global oceanic property regime on environmentalist grounds. Regardless of that, the politics of state enclosure could thrive purely on the 'coercive laws' of intra-state and intra-bloc competition for territory. Amongst a range of enabling factors, substantial impetus came from the decolonisation wave, which prompted many newly constituted governments to raise their political legitimacy through the assertion of sovereignty over maritime space and resources (Schurman, 1998; Campling and Havice, 2014). This proved even to be the case for freshly independent island states, where the creation of domestic regimes of marine industrial production remained a prospect for the distant future, whilst the primary aspiration was seen in the collection of rent from distant water fishing nations. Eager to capture part of the fisheries (and eventually seabed minerals) surplus, the Republic of Fiji, for one, was greatly involved in the negotiations and became the first state to sign and ratify UNCLOS (Government of Fiji, 2019). In other cases, the establishment of EEZs was initially opposed and the ratification of the new legal principles delayed, but ultimately the pressure to submit to the rationality of UNCLOS triumphed in most cases (Reiwaki, 1988). 'Geopolitical deadlines', such as the arbitrary 10-year limit to deposit continental shelf claims with the Commission on the Limits of the Continental Shelf (CLCS), compelled many state governments to accelerate scientifically supported enclosures (Russel and Macnab, 2008; Dodds, 2010; DOALOS, 2012, 2019). Where national bureaucracies were unable to keep up, capital-intensive economies and development financiers – such as the European Union in the case of the Pacific island countries (e.g. SPC SPC Agtd, 2012; PACNews, 2019; SPC, 2016) – sponsored the creation of domestic boundary delimitation and geological expertise to expedite the ocean-wide procurement of investment security and legal harmonisation.

Meanwhile, it was evident from the outset that the long-term mediation of capital's differential interests could not be resolved by the specific form of spatial organisation that was borne out of myriad legal trade-offs that UNCLOS stipulated (for details see Nandan, 1987). To the contrary, existing contradictions were likely to intensify, as Procrustean arrangements of this kind internalise a momentary balance of capital's tendencies, rather than offer a direct route to the *longue durée* expansion of accumulation opportunities (Harvey, 2006). At least three significant moments for crisis arose:

(1) Although UNCLOS presents itself as a well ironed-out "social plan", individual capitalists are in reality faced with "infinitely varied circumstances", for instance, unique business cultures, tax regimes, investment laws, etc., that have to be resolved independently (Marx, 1978: 252). The reality, even in a well-delineated and segmented ocean, is usually far more complicated and chaotic than possible for government-implemented initiatives to regulate. Over time, legal-institutional complexity mushrooms, and the various jurisdictions become increasingly difficult to navigate for investors and potential speculators. Geopolitical rivalries further deepen economic fragmentation within and between different sectors.
(2) Once a certain scale of spatial exploitation has been reached, economic activities (both industrial and commercial) run into conflict with each other; especially when capital begins to operate on a bigger scale and to concentrate in one place (Marx, 1976: 776-777). In light of the specific sensitivity of oceanic environments, where investments in one industry (e.g. subsea oilfield) immediately heighten the risks in another (e.g. offshore aquaculture or diving tourism), less and less investors take the risk to work across sectors.
(3) Territorial enclosure becomes the basis for the establishment of a peculiar regime of private property and the emergence of rent as an autonomous dynamic. As Campling and Havice (2014: 716) sharply remark: "[t]he development of property relations through the EEZ – an 'alien force' that disrupts the movement of capital in the sea – marked the possibility of states capturing ground-rent, primarily in the form of an access payment, which firms pay to fish in a state's EEZ."

The third moment is possibly the most significant. Whether one considers offshore energy generation, hydrocarbon extraction, aquaculture or marine biotechnology research, the same argument can, in principle, be extended to most other forms of industrial ocean use that are projected to exert rising spatial requirements on EEZ domains. The logical consequence of the relatively inflexible geopolitical corset created by UNCLOS is that an ever-rising mass of the industrial surplus will be siphoned off – in this case by state governments – thereby regulating the volume of capital available for expanded reproduction across individual sectors (Harvey, 2013: Ch. 10–11). Given the usual budgetary priorities of state governments, the surplus is likely to be re-invested in terrestrial infrastructures or debt servicing rather than channelled back into the ocean economy. The gravity of the EEZ as a deterrent to surplus value production and thus capital accumulation is therefore prone to become compounded the more the relative share of rent yielding industries rises (for projections see OECD, 2016). All else being equal, this view would suggest that the territorial economic conditions generated by the codification of ocean space during the 20th century must hamper rather than propel the valorisation of productive capital in the ocean economy as a whole. To compensate for this limitation, *a paradigmatic need* to expand the overall mass of industrial production in the ocean economy emerges. Against this backdrop, we now take a closer look at the ways in which the amplification of new territorial-economic contradictions has been pre-coded into the abstract space produced by the legal geography of UNCLOS.

4.2. UNCLOS, fixed capital and technological change

Within the ocean economy, capital productive of surplus value is reliant on the circulation of extraordinarily high amounts of fixed capital;[6] specifically, instruments of labour that can exclusively be operated at sea and that are marked by long valorisation cycles and high devaluation risks. Large machinery of this kind may be categorised by varying degrees of spatial mobility: At one end of the spectrum, highly mobile instruments comprise super tankers, freight and cruise ships or factory trawlers (Sibilia, 2018). Next, semi-mobile instruments range from jag-saw oil rigs, unmanned robots for seafloor extraction, to the first floating nuclear power plant (Soldatkin, 2019). At the opposed end, spatially immobile instruments include offshore aquacultures,

[6] Contrary to Ricardo's economic school, Marx understands fixed capital not as thing but "a process of circulation of capital through the use of material objects, such as machines" (Harvey, 2006: 205); thus a form of motion of capital (Marx, 1978).

windfarms, underwater cables, pipelines and soon floating cities (Starosielski, 2015; Huebner, 2020a). In each category, a jungle of financial, market, geopolitical, legal and environmental considerations determine investment risks and potential valorisation rates.

If we follow Marx's conception of capital as value-in-motion with an ever expanding radius (Harvey, 2006: 83), it immediately becomes apparent why the territorial configuration envisioned by UNCLOS generates an almost infinite amount of frictions and blockages for the circulation of fixed capital. Since formal decision-making power over a total aggregate of 137 million km^2 of nationalised ocean space has been put at the multifarious whims of 151 governments with fluctuating territorial-economic objectives, investments (particularly in the semi-mobile and spatially immobile categories) are never encouraged to expand at sufficient rates (for interactive map see Sea Around Us, 2016). For decades, territorial and jurisdictional scrambles over any additional nautical mile of EEZ and seabed, coupled with protracted maritime boundary negotiations, have created an antagonistic environment for any mildly risk-averse investor (Russel and Macnab, 2008). In this respect, the standoff between Suriname and Guyana over jurisdictional entitlements, Australia's clandestine theft of Timor-Leste's oil reserves, or the so-called South China Sea dispute all serve as prominent cases in point (Kuipers and Khan, 2007; Davidson, 2019; Fernandes, 2020). Simultaneously, dozens of regional, sectoral and international governance regimes (see Fig. 1) continuously add on new layers of institutional complexity, which in turn require the creation of costly, ever-expanding national bureaucracies (see Mandel, 1992; Koskenniemi, 2006).

Despite its decisive role in shaping the outcome of the UNCLOS negotiations (Glassner, 1990; Steinberg, 2001), the nascent deep-sea mining (DSM) sector has been particularly reflective of capital's (relative) difficulty to expand in the global oceans. As previously alluded to (*see* Section 2), UNCLOS has accorded sovereignty over the seabed and subsoil within EEZs and ECSs to states. Within their jurisdiction, states are allowed to install industrial facilities, operate large machinery and extract resources as long as no avoidable impediments on navigational freedoms arise. In spite of an initial rush, DSM has been held back by the high investments required to develop technologies that allow mining at these depths at a profitable rate of return (see especially Zalik, 2018). The recent spike in demand for 'green economy' inventories, such as copper for wind turbines, lithium for car batteries, as well as rare earths that feed into the production of laptops, cell phones and the next generation of ballistic missiles, has revived the DSM race of the 1970s (Teske et al., 2016; Sanderson, 2018). Proposed 'green new deal' legislations in the U.S. and the EU will guarantee a sustained increment in demands.

During the past two decades, commercial miners and so-called frontier investors have been closely following the Nautilus Minerals group, an industry front-runner that first secured an exploration licence through Papua New Guinea in 1997, and subsequently an extraction license for the Solwara 1 field in the Bismarck Sea in 2011. Through collaboration with a host of international technology developers, Nautilus hoped to assemble a viable production system, consisting of remotely operated underwater vehicles, a subsea slurry lift pump, a lifting system, and a production support vessel for the extraction of minerals (Kaschinski et al., 2019). Between 2006 and 2018, Nautilus secured USD 600 million through shareholders, a joint venture partner, and several loans (PwC, 2019). Yet, when the multinational mining company Anglo American withdrew in May 2018 – supposedly fearing jeopardy to its corporate image and in light of the continuous delay of operations (Hume, 2018) – the company's long dwindling stock-price tumbled. Afterwards, it was de facto "run by two billionaires: Mohammed Al Barwani, founder and owner of MB Holding …, and Alisher Usmanov, the principal owner of [Cyprus-based] Metalloinvest [and] CEO of Gazprom Investment" (Kaschinski et al., 2019: 38). In March

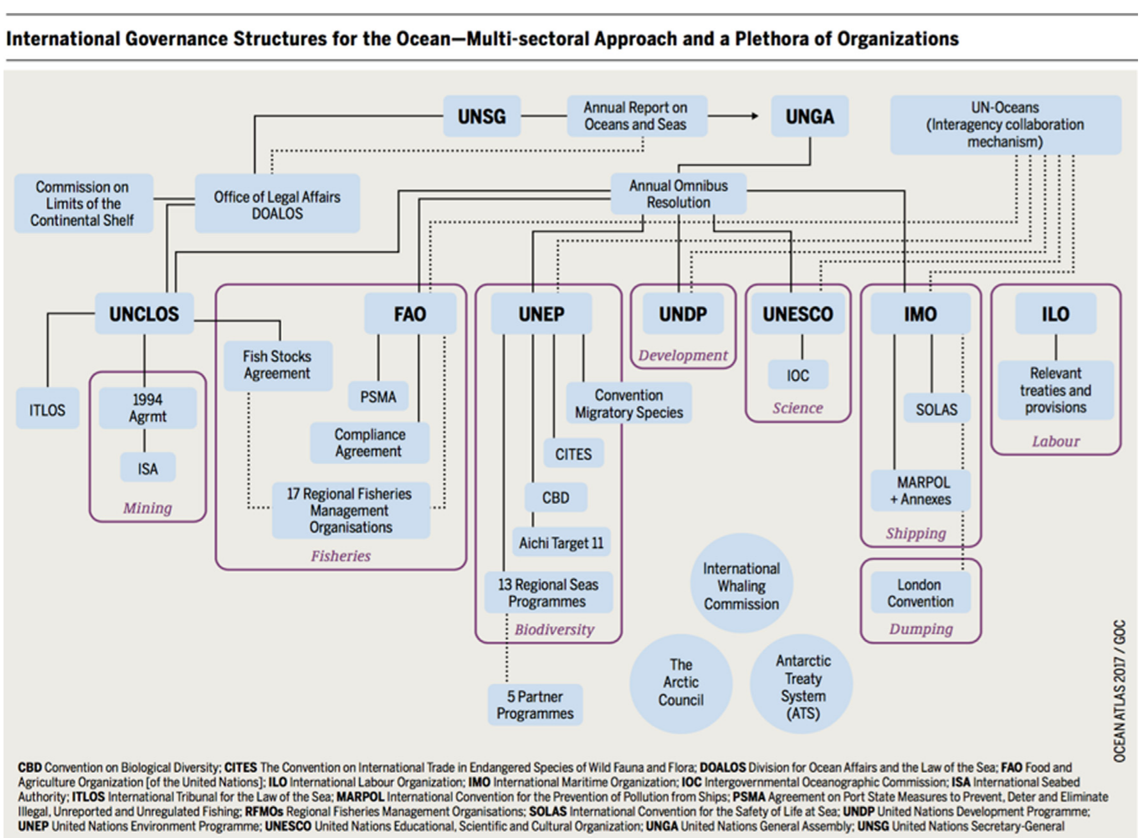

Fig. 1. Overview of multilateral legal and governance instruments concerning international ocean space. Source: Bähr (2017: 45). Reproduced under the Creative Commons "Attribution 4.0 International (CC BY 4.0)" license (https://creativecommons.org/licenses/by/4.0/en/legalcode).

2019, the company was delisted from the Toronto stock exchange and liquidation began later in the year (Stutt, 2019). At this stage, the monitor's report stated that it "will require further investment in excess of $200 million and require at least 18 months to complete the development and construction of its deep-sea mining system" (PwC, 2019: 13). In addition to socially and ecologically motivated protests by parts of local communities against Solwara 1 (Phillips, 2019), Nautilus was in the end unable to pay one of its technology manufacturers, leaving "its newly-built vessel languishing in a Chinese boatyard" (Sanderson, 2018). As Filer and Gabriel (2018: 1) remark about Nautilus' copper–gold prestige project, "it is unlikely that the costs of exploring the resource and developing the technology required to extract it will be covered by the revenues that it generates." In other words, successful valorisation was always contingent upon the rapid proliferation of this technology once completed. In many ways, the rise and fall of Nautilus is illustrative of the intersecting obstacles encountered by well-funded firms in establishing a sound economic basis for the circulation of fixed capital.

Beyond resources under state jurisdiction, the prospects for success of the DSM sector has long been frustrated by the obscure legal regime for mining concessions in the so-called 'Area', administrated under the formal auspices of the International Seabed Authority (ISA) (Fritz, 2015; Zalik, 2018). Following the edict "All rights in the resources of the Area are vested in mankind as a whole, on whose behalf the Authority shall act" – mineral resources beyond national jurisdiction were designated to be distributed fairly, mining technologies to be shared with 'developing countries', and disputes resolved through binding legal instruments (UNCLOS, 1982). Yet, many American, European and Japanese conglomerates, represented by their respective governments, were discontent with a range of provisions that had been strongly supported by socialist and other developing countries during the UNCLOS negotiations. First and foremost, the United States refused to sign the DSM agreement as the Reagan administration was worried that the country, "though a major naval power, would have little influence at the Authority that the convention created. Although the [ISA] is supposed to make decisions by consensus, nothing prevents the rest of the 'international community' from consistently voting against the United States, as regularly occurs in similar U.N. bodies…" In addition, the convention would have constrained the ability of U.S. submarines to spy within other countries' territorial waters, such as Iran and North Korea (Spring et al., 2007: 1).

Following the collapse of the Soviet Union, a coalition of industrialised countries managed to water down the previous compromise by imposing the 'Agreement relating to the Implementation of Part XI' on the rest of the UNCLOS signatories (DOALOS, 2016). Adopted shortly before UNCLOS came into force, this agreement retracted the earlier negotiated concessions to developing countries, by privileging 'market-oriented solutions' and evading previously stipulated technology and knowledge transfers (Zalik, 2018). Ever since, the once solemnly proclaimed 'common heritage of mankind' (Article 136 of UNCLOS) has been carved up by states that sponsor companies through the granting of exploration licenses issued by the ISA (Deep Sea Mining Campaign et al., 2019). Two Pacific island countries, Nauru (Nori Area)[7] and Kiribati (Marawa Area), for instance, have signed sponsorship agreements with DeepGreen[8] in the Clarion Clipperton Fracture Zone (CCFZ) under hardly transparent circumstances (Mallin, 2018; Deep Sea Mining Campaign et al., 2019; Lazenby, 2019): "DeepGreen prepared and funded Kiribati's application in return for [a yet undisclosed] off-take agreement in the CCFZ" (World Bank quoted in Greenpeace, 2019: 23). In terms of licensed seabed segments, China is currently ahead of the United Kingdom, with the "UK's venture with Lockheed Martin [representing] the single biggest project in the world, covering an expanse off Mexico larger than England itself" (Boren and Ross, 2019).

From the standpoint of capital, so far the successful launch of mining operations in the Area has proven to be even rockier than in state jurisdictions (Lodge et al., 2017). As the head of UK Seabed Resources, a subsidiary of Lockheed Martin, explains (quoted in Sanderson, 2019): "[u]ncertainty in the future regulatory regime for mineral exploitation remains the principal barrier to development of an environmentally responsible and commercially viable [DSM] industry" (see also Pecoraro, 2019). As Zalik (2018) emphasises, however, industry conglomerates embedded in the military-industrial complex strongly favour "to implement an exploitation regime in the absence of substantive ecological and fiscal regulation", since ecological consequences are as of yet incalculable (Miller et al., 2018). This observation is confirmed by a rapidly progressing seabed grab and the prevalence of predatory practices – including bribery and corruption allegations – reported with respect to several DSM pioneers and the ISA (Mallin, 2018; Deep Sea Mining Campaign et al., 2019; Greenpeace, 2019).

4.3. The production of ocean space

Many contemporary ocean policy and governance debates advance the view that present tensions of this kind owe to a "decision-making vacuum for many ocean industries", which cannot adapt fast enough to revolutions in technology (OECD, 2016: 150). Put simply, technological change is presupposed here as an independently operating law of history. This view prompts the erroneous conclusion that only through the implementation of an essentially different system of ocean governance – *a sustainable blue economy* – can the successful emergence of new industries, the growing resource needs of the green economy, and the impacts of climate change be catered to in a compatible manner (The Economist, 2017; WWF, 2017; European Commission, 2019; World Bank, 2019). Such representations tacitly distort the material history of innovation and technological change under capitalism, insofar as any underlying capitalist class interests here become entirely concealed behind a cosmopolitan façade of pragmatist-environmentalist concerns (Huebner, 2020b). "The development of the means of labour into machinery", Marx (1973: 694) countered, "is not an accidental moment of capital, but is rather the historical reshaping of traditional, inherited means of labour into a form adequate to capital." In order to constantly revolutionise the existing conditions of production to the benefit and sustenance of the capitalist class, capital absorbs the scientific capability for innovation, "the social brain", which "hence appears as an attribute of capital, and more specifically of fixed capital."

Still, as our brief glance at the nascent DSM sector has sought to exemplify, the circulation of fixed capital in the ocean economy witnesses a classic impasse, where "capitalist production seeks to overcome its own barriers and to produce beyond its measures", whilst it can "only bear a production that is based on the profitable allocation of the existing capital" (own transl. Marx, 1968: 119). But can this condition alone account for the salience of blue economy politics across the globe? In order to respond to this question, we need to consider the production of space as a dialectical process, in which several autonomously operating socio-economic forces intersect (Smith, 2010). Barriers for capitalist expansion in the oceans are not only of geopolitical, organisational and technological nature, but also firmly connected to prevailing mental conceptions of the seas, that is ocean space as a power-imbued abstraction (Steinberg, 2001). "Capitalism", Lefebvre (1991: 350) contemplated, would not become prevalent by merely "consolidating its hold on the land [and seas], or solely by incorporating history's precapitalistic formations. It also makes use of all

[7] On its website, DeepGreen (2019) boasts that the "NORI Area alone contains enough metal to potentially supply battery metals for 140 million electric vehicles."

[8] Attesting to the company's positionality within the wider ocean economy-nexus, DeepGreen is financially backed by the Danish marine logistics and energy giant Maersk.

the available abstractions, all available forms, and even the juridical and legal fiction of ownership of things apparently inaccessible to private appropriation…" In this regard, the sea has to become perceived as a level plain for capital accumulation in every regard: the ocean as an accumulation strategy (Smith, 2007).

One of the most extraordinary leaps into this direction has been realised by the proliferation of Marine Spatial Planning (MSP) initiatives since the 1990s, which seek to equalise tensions between commerce, traditional industries, emerging enterprises and ecological exigencies (Jay et al., 2013; UNESCO, 2019). Mostly predicated on the cataloguing of marine nature and the portioning of space into small blocks, the bulk of recent initiatives is following ecosystem service approaches, which price marine ecosystems in the name of protecting 'nature's capital' (Dempsey and Robertson, 2012). The World Wildlife Fund (WWF), for example, suggests to "account for the real costs of exploiting ocean resources" (Hoegh-Guldberg, 2015: 5) by assigning a price on the ocean's so-called "asset-base", estimated at USD 24 trillion. Even more so than in the case of terrestrial ecosystems, the commodification and marketisation of the oceans is preached under the omnipresent tune of crises convergence. Yet, whilst finance capital is in the midst of concocting new strategies for the accumulation of ocean nature (e.g. Credit Suisse and McKinsey, 2016; Encourage Capital, 2016), much of this enterprise appears to be caught up in endless circles of deliberating how to reconcile the economic (exchange value) and ecological (use value) qualities of nature (see also Harvey, 1996; Dempsey and Suarez, 2016). The most immediate consequence, however, is the introduction of new political and financial actors, ever more regulations and jurisdictions, and an extension of rent seeking, which brings us back to all the previously discussed frictions and blockages.

5. Conclusion

> People in the 21st century will surely be much more sea-minded than we are today, and the sea will play a greater role in international relations than ever before in history. Control over marine resources, over important shipping lanes, over the best sites and means for generating energy from the sea, will most certainly contribute substantially to a radical realignment of power relationships among States (Glassner, 1990: 124).

Reminiscent of the history of commercial capital's rule over the oceans (Braudel, 1983: 376), ocean space as imagined under the BEP appears to command a return to hierarchy: minimising spatial rivalry, creating stable environments for the circulation of fixed capital, and allowing industrial production to expand in a relatively calm sea. Rather than merely signifying another spatio-temporal fix for capital, the present blue economy moment, as we have argued, marks the beginning of a reconfiguration required to overcome the tensions generated by the UNCLOS compromise. On one hand, the BEP seeks to overcome these tensions by striving towards more centralised, hierarchical forms of economic governance. On the other hand, the BEP further conditions the rivalry between maritime powers driving the expansion of oceanic accumulation, since geopolitical command over marine resources, transport corridors and the distribution of surplus stemming from maritime industries remains highly contested. China's Maritime Silk Road (MSR), integral to the aspirations of the Belt and Road Initiative (Choi, 2017; He and Wang, 2017; Flint and Zhu, 2019), for instance, poses a direct challenge to the geopolitical terms in which the blue economy has been cast under American and European dominated initiatives. The conjunctural implications of an institutional structure dominated by one or the other bloc will significantly affect the dynamics of accumulation, circulation and valorisation of capital throughout the entire ocean economy in the future. At present, however, geopolitical contestation mainly catalyses both violent as well as concealed movements of ocean grabbing, ocean control grabbing and seabed grabbing, with often moderate or no benefits for immediate capital accumulation.

Bringing the political economic and the geopolitical elements under a more developed conceptual umbrella is therefore a vital undertaking, which unfortunately lies beyond the scope of this paper. Reiterating Choi (2017: 40), it is precisely here where a geographer's "critical eye on questions of knowledge, space, and power" becomes indispensable. Bearing in mind the complex ways in which geopolitics and political economy intersect in the oceans, there is considerable scope for critical geographers and political economists to become much more theoretically and conceptually engaged in this debate (see also Harvey, 1985; Colás and Pozo, 2011; Sparke, 2017). We have little doubt that even a partial realisation of contemporary global blue economy ambitions will have far-reaching and very real consequences for millions of people. Therefore, the present terrain of struggle and possibilities for critical engagement could be greatly amplified by a vision of the ocean economy as encompassing as that proposed by the OECD (2016); yet, one that *does not* pivot around the material needs of capital. In our view, hardly any emancipatory dynamics should be expected to transpire as long as this process is coordinated at the level of elusive and exclusive elite circles, where technocratic-managerial choices are privileged in the resolution of socio-environmental crises. "Power", Lefebvre (1991: 388) reminds us, "aspires to control space in its entirety, so it maintains it in a 'disjointed unity', as at once fragmentary and homogenous: it divides and rules". As much as there is a continued demand for detailed empirical studies to inform the many struggles fought out within individual sectors and domains (see Section 2), it is high time to align resistances to ocean grabs, industrial expansion and environmental destruction with general anti-capitalist critiques that consider the ocean economy in its entirety.

CRediT authorship contribution statement

Felix Mallin: Conceptualization, Methodology, Investigation. **Mads Barbesgaard:** Conceptualization, Methodology, Investigation.

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ARTICLES FOR FACULTY MEMBERS

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Cleaning up seas using blue growth initiatives: Mussel farming for eutrophication control in the Baltic Sea

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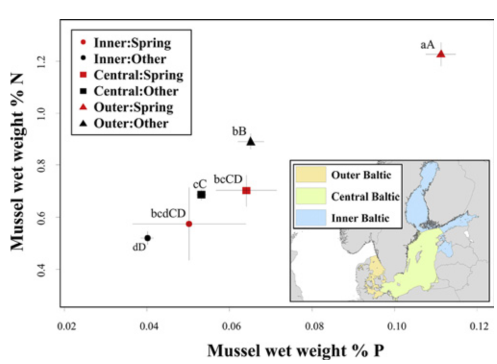
HIGHLIGHTS

- Mussel farming is a viable internal measure to address Baltic Sea eutrophication.
- Rates of nutrient removal depend on salinity at the regional scale and food availability at the local scale.
- Cost effectiveness of nutrient removal by mussel farming depends also on farm type.
- Total farm area needed for achieving HELCOM nutrient reduction targets is realistic.

GRAPHICAL ABSTRACT



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ABSTRACT

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Eutrophication is a serious threat to aquatic ecosystems globally with pronounced negative effects in the Baltic and other semi-enclosed estuaries and regional seas, where algal growth associated with excess nutrients causes widespread oxygen free “dead zones” and other threats to sustainability. Decades of policy initiatives to reduce external (land-based and atmospheric) nutrient loads have so far failed to control Baltic Sea eutrophication, which is compounded by significant internal release of legacy phosphorus (P) and biological nitrogen (N) fixation. Farming and harvesting of the native mussel species (*Mytilus edulis/trossulus*) is a promising internal measure for eutrophication control in the brackish Baltic Sea. Mussels from the more saline outer Baltic had higher N and P content than those from either the inner or central Baltic. Despite their relatively low nutrient content, harvesting farmed mussels from the central Baltic can be a cost-effective complement to land-based measures needed to reach eutrophication status targets and is an important contributor to circularity. Cost effectiveness of nutrient removal is more dependent on farm type than mussel nutrient content, suggesting the need for additional development of farm technology. Furthermore, current regulations are not sufficiently conducive to implementation of internal measures, and may constitute a bottleneck for reaching eutrophication status targets in the Baltic Sea and elsewhere.

1. Introduction

Eutrophication is a global threat to many aquatic ecosystems and its negative effects are particularly pronounced in semi-enclosed estuaries and regional seas (Diaz and Rosenberg, 1995; Conley et al., 2009a; Rabalais et al., 2009). Excessive amounts of nitrogen (N) and phosphorus (P) from present-day and legacy sources support massive algal blooms which results in widespread and increasing oxygen free “dead zones” (Breitburg et al., 2018), increasing susceptibility to ocean acidification (Cai et al., 2011), reduced biodiversity and loss of ecosystem functions and services (Smith, 2003; Riedel et al., 2016). In the Baltic Sea, a multi-jurisdictional water body, >40 years of international efforts to reduce external nutrient (N and P) inputs have failed to solve the eutrophication problem (Fleming-Lehtinen et al., 2015; Andersen et al., 2017). Today, 97% of the marine area is considered as degraded due to eutrophication (HELCOM, 2018, Fig. 1) and despite significant reduction in external loads, the total P pool in Baltic Sea waters continues to increase (Savchuk, 2018) and internationally agreed upon water quality targets are still not met. To date, management actions have primarily focused on minimizing external loads, i.e., terrestrial point sources and diffuse nutrient inputs. Agriculture is targeted in many cases (Larsson and Granstedt, 2010) but the internal loads of legacy P released from marine sediments (Vahtera et al., 2007; Conley et al., 2009a) and atmospherically fixed N are often neglected (Vahtera et al., 2007), as are non-food nutrient sources (Hamilton et al., 2018).

Aquaculture is a key component of the EU Blue Growth strategy (EC, 2012) and can have significant positive and negative effects on water quality. Aquaculture is the fastest growing food-producing sector and currently represents nearly 50% of global fish, crustacean and mollusc production (FAO, 2018). Marine bivalves, e.g., mussels, oysters, clams and other shellfish, are often referred to as extractive species as these filter feeding species act as nutrient sinks by ingesting particles suspended in the water column. Importantly, harvesting of cultivated mussels removes both N and P, thereby improving water quality in affected areas (Carlsson et al., 2012; Kraufvelin and Díaz, 2015).

Aquaculture can also make a positive contribution to circularity and nutrient recycling. Most internal eutrophication control measures make P unavailable for re-use through, e.g., bottom water oxygenation to change sediment redox status and the binding of P to iron (Stigebrandt et al., 2015) or aluminium treatment to effectively immobilize P in the sediment (Rydin et al., 2017). Unlike the aforementioned measures, harvesting of internally produced biomass, (i.e. farmed mussels) offers the potential for efficient recirculation of nutrients from sea to land. Harvested mussels can be used to produce feed for chickens (McLaughlan et al., 2014) or fish (Vidakovic et al., 2015), as well as for human consumption (Gren et al., 2009). Harvested mussels can also be used for bioenergy production (Hu et al., 2011; Nkemka and Murto, 2013), or as a soil amendment.

The failure to control Baltic Sea eutrophication through external nutrient load reduction measures has highlighted the need for in-situ (internal) methods to lower nutrient concentrations in the water column, e.g. through geoengineering (Stigebrandt et al., 2015; Rydin et al., 2017) or biomass harvesting (Gren et al., 2009). Intensive fishing of commercial or non-commercial fishes (e.g., three-spined stickleback, round goby) has been proposed as an alternative means for removing nutrients from the Baltic Sea. However, this could have unknown and potentially catastrophic consequences for marine biodiversity due to the role as top or intermediate predators that these species have in littoral habitats. While internal measures for nutrient regulation are not a universal means of controlling eutrophication, they should be considered when feasible external measures have been tried and found to be inadequate (Savchuk, 2018). It should be noted, however, that many internal measures have been associated with high costs for nutrient removal (Lurling et al., 2016) as well as undesirable secondary effects such as damage to benthic habitats (Stadmark and Conley, 2011), potentially harmful shifts in thermal regime (Conley, 2012) and/or food web impacts (Naylor et al., 2001). The Baltic Sea region is an important test case highlighting the opportunities and challenges of farming native bivalve species as an internal measure to mitigate the adverse effects of coastal eutrophication. The region has a long, well-documented history of ecosystem deterioration, high data density and multiple cross-border environmental management actions to counter marine eutrophication (Reusch et al., 2018).

Farming of the ubiquitous blue mussel species complex (*Mytilus edulis/trossulus*, Stuckas et al., 2009) has been proposed as an internal measure for eutrophication control in the brackish Baltic Sea (Lindahl et al., 2005; Gren et al., 2009; Petersen et al., 2014; Schröder et al., 2014; Ozoliņa, 2017; Kiessling et al., 2019). Mussel farming has also been criticized as being not cost effective (Hedberg et al., 2018) and harmful to the environment (Stadmark and Conley, 2011).

Blue mussels are marine species and form hybrid zones within the Baltic Sea (Stuckas et al., 2009). While individuals are able to survive down to salinities of 4–5 practical salinity units (PSU), they grow better in high salinity conditions where they do not need to expend as much energy on osmoregulation (Maar et al., 2015). Blue mussels are primary consumers and usually the dominant species (i.e. main contributor to abundance and biomass) in the environments where they occur, and consequently their sustainable harvest is not expected to produce cascading effects or other impacts on the stability of the food web.

Blue mussel farming relies on recruitment of free-swimming larvae (veligers) from wild populations that are entrained into the water column and passively dispersed from natural mussel reefs. After dispersal,

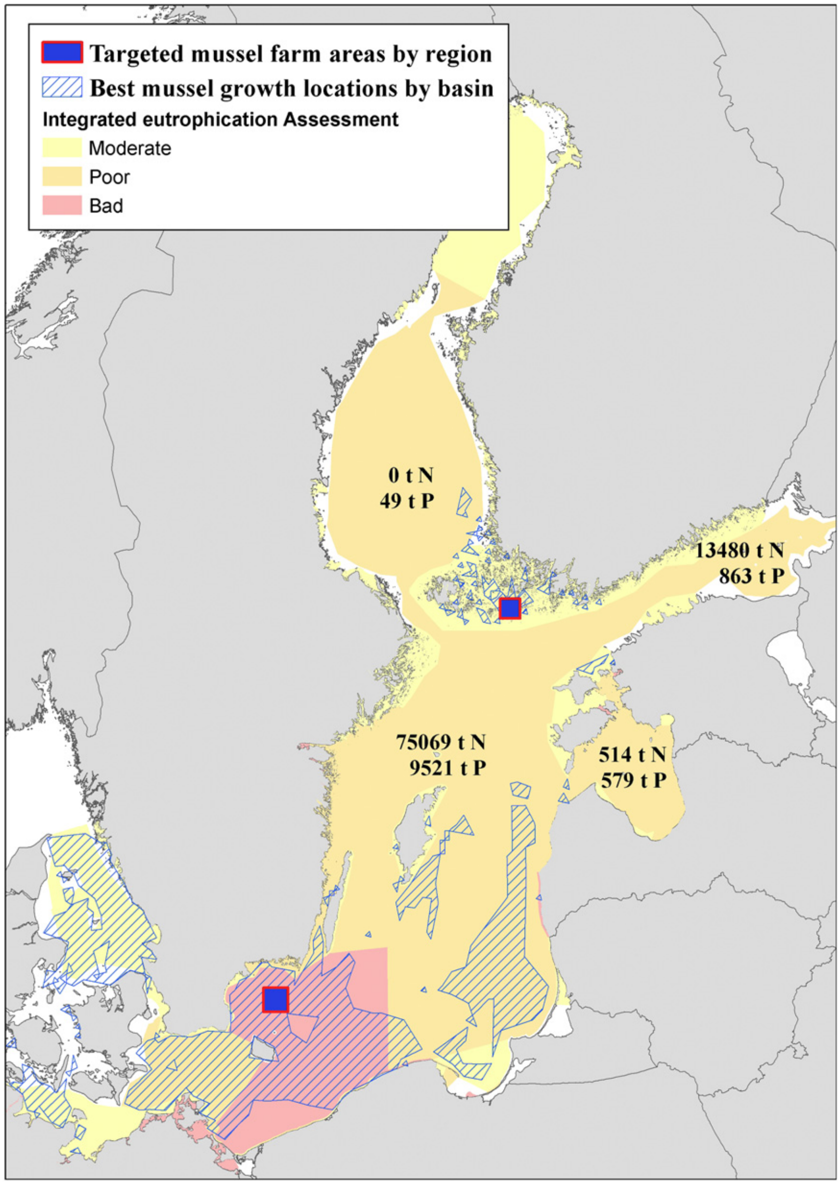

Fig. 1. Areas of the Baltic Sea (coloured; 97% of its total surface area) that currently have unacceptable water quality with respect to eutrophication. Different colours indicate different water quality classes. The 2013 HELCOM Ministerial Meeting agreed on the amount of reduction in emissions for nitrogen (N) and phosphorus (P) in different sub-basins of the Baltic Sea in order to meet goals of the Baltic Sea Action Plan. However, trend-based estimates demonstrate that the maximum allowable nutrient inputs are still exceeded in the Central and Inner Baltic Sea. The excesses are shown as numbers in the different sub-basins. Blue hatched areas show the best mussel growth location separately for Outer, Central and Inner regions predicted by the model. Within these regions, blue rectangles show the surface area of future mussel farms that are needed to meet the basin-specific goals of nutrient load reduction defined in the Baltic Sea Action Plan.

veligers attach themselves to available substrates, including objects in the water column, e.g., mussel farms. Thus, determining how to best allocate areas suitable for mussel farming requires consideration of the connectivity between candidate farm sites and natural mussel reefs in order to define areas that do not require artificial mussel seeding.

Farms using ropes with high surface area per unit length, i.e. ribbons, Swedish bands or so-called "fuzzy ropes" promote higher rates of larval settlement. After settlement, it is necessary to account for the way in which salinity, food availability and wave action affect growth rates and to select sites with the highest harvest potential. A typical Baltic Sea mussel farm has an area of a <5 ha and consists of 10–100 km of rope suspended at different depths (Holmer et al., 2015; Kraufvelin and Díaz, 2015). Cost effectiveness of the farms is dependent on nutrient and salinity levels as well as the type of equipment for culturing mussels, with specialized ropes that optimize veliger recruitment being the most effective for culturing the small mussels found in the Baltic. Harvest rates are usually expressed in units of mass of mussels per metre of rope. Mussels are harvested one to two years after recruitment, depending on site productivity. As farmed mussels spend their entire life suspended in the water column, they are less affected by contaminated sediments than benthic dwelling organisms but can be susceptible to contamination by algal toxins (Sipiä et al., 2001).

A synthesis of a large number of recent measurements of farmed mussel growth in the Baltic Sea and a new model chain for predicting growth and nutrient removal potential across key environmental gradients are presented. The relationship between wild mussel production and predicted nutrient removal through harvest of farmed mussels was quantified by modelling occurrence of wild mussels throughout the whole Baltic Sea. A biophysical dispersal model was used to analyse direction and distance of larval drift from each natural mussel reef. Next, spatially explicit and empirically modelled growth rates of farmed mussels were combined with measured N and P concentrations in mussels harvested from production-scale farms to quantify nutrient removal potential. Finally, farm-scale nutrient removal estimates were upscaled to predict the total area of mussel farms needed to make a meaningful contribution to reducing Baltic Sea eutrophication.

2. Material and methods

2.1. Study area

The Baltic Sea is shallow, brackish and has almost no tide but experiences intense seasonality in temperature and inflow. It is heavily affected by eutrophication with N and P concentrations showing decreasing and increasing trends, respectively (HELCOM, 2018; Savchuk, 2018).

For most of the analyses presented here, the Baltic Sea was divided into Outer (Kattegat and Belt Sea), Central (Northern Baltic Proper, Western and Eastern Gotland Basins, Gdansk Basin and Bornholm Basin) and Inner regions (Bothnian Bay, Bothnian Sea, Archipelago Sea, Åland Sea, Gulf of Finland and Gulf of Riga), representing the gradient from the near-oceanic (Outer) to brackish-water conditions (Fig. 2).

Despite salinity constraints, several characteristics of the Baltic Sea favour mussel farming for eutrophication control. First, the Baltic Sea is very eutrophic and food is only rarely a limiting factor for mussels (Kotta et al., 2015). Thus, within suitable habitat ranges, elevated resource availability can compensate for growth limitation associated with reduced salinity (Kotta et al., 2015). Second, high nutrient concentrations in the water require in-situ removal actions for which mussel farming is promising. Finally, more than forty years of international agreements and land-based measures have failed to solve the problem of Baltic Sea eutrophication; large amounts of money have been allocated to reduce inputs from land with variable, often minimal, effects (Helin, 2013).

2.2. Mussel farms

Harvest data are reported from three farms, one each in the Outer, Central and Inner Baltic (Table 1 and Fig. 1). The Kumlinge farm (Inner Baltic) is located in the Åland archipelago. It was established in spring 2010 and harvested in November 2012. The farm technology consisted of four 120 × 3 m nets with a mesh size of 15 cm fastened to floating

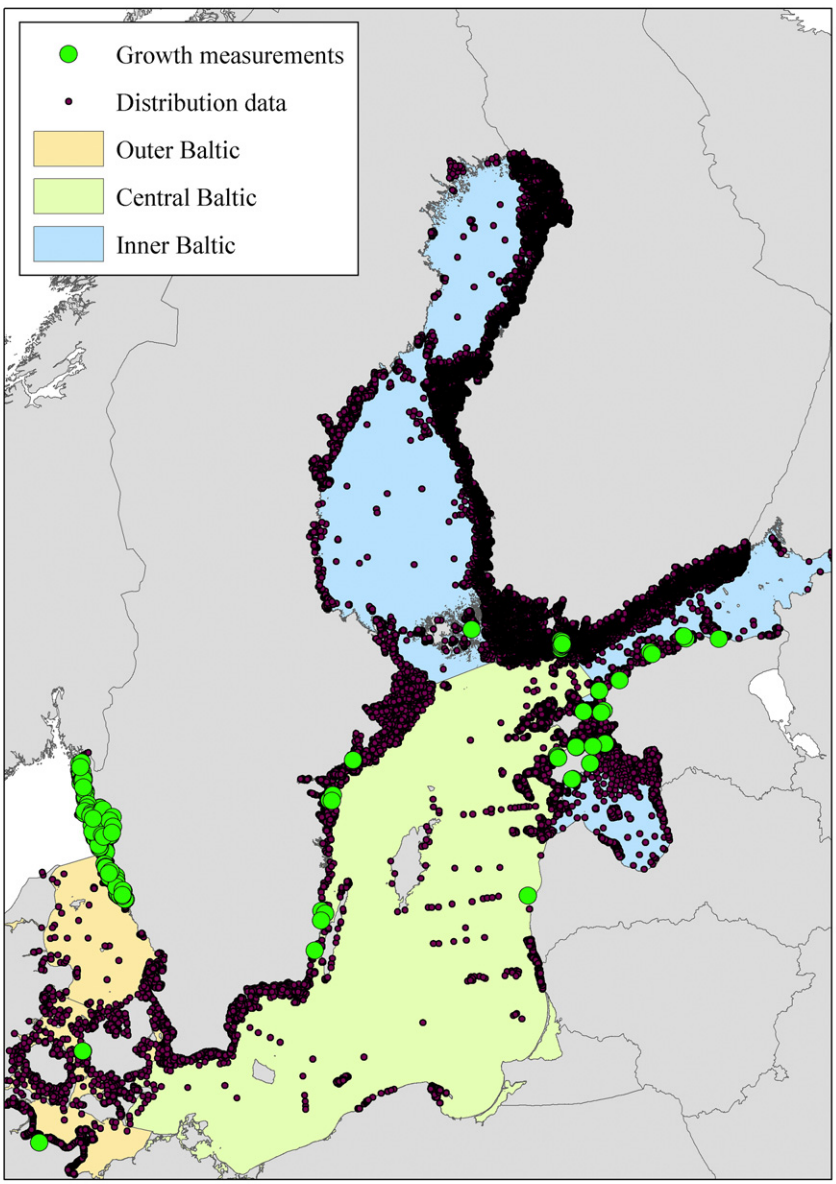

Fig. 2. Location of sampling points for the distribution and growth of blue mussels. Colours depict different sub-regions of the Baltic Sea.

Table 1
Summary of environmental conditions, nutrient removal and economic factors for three blue mussel farms in the Baltic Sea.

Variable	Unit	Kumlinge	Sankt Anna	Kiel
Latitude		60.2147° N	58.3564° N	54.3755° N
Longitude		20.7524° E	16.9368° E	10.1634° E
Region of the Baltic Sea		Inner	Central	Outer
Average salinity		6	6	15
Chlorophyll *a* (mean/max/min)	mg m^{-3}	2.0	2.0/3.5/1.0	2.3/4.5/0.9
Farm technology		Nets	"Spat catching" rope	Ropes with collector bands
Nitrogen removal at	kg ha^{-1}	83	140	148
harvest	g m^{-1}	3.74	23.26	22.25
Phosphorus removal	kg ha^{-1}	6.4	10.8	10.8
at harvest	g m^{-1}	0.29	1.80	1.63
Farm size	ha	0.90	4.0	0.30
Long line length	km	20	24	2
Long line density	km ha^{-1}	22.2	6.0	6.7
Observed biomass	tonnes	14.4	81.50	5.00
yield	kg m^{-1}	0.72	3.40	2.50
Modelled biomass yield	kg m^{-1}	0.75	1.3	14.7
Investments	€ kg^{-1}	5.45	0.35	0.36
Operational expenses	€ kg^{-1}	3.08	0.17	1.49
Total costs	€ kg^{-1}	8.52	0.52	1.85
N removal cost	€ kg^{-1}	1638	76	208
P removal cost	€ kg^{-1}	21,300	981	2846

plastic pipes. The average water depth was 8 m and average bottom water current speeds were 3–4 cm s^{-1} (Kraufvelin and Díaz, 2015). The Sankt Anna farm (Central Baltic) is located on a sheltered site in the Swedish Östergötland archipelago. The farm was established in spring 2016 and harvested in October 2018. The farm technology consisted of "spat catching" rope developed by Quality Equipment Ltd. and optimised for settling of small mussels. Ropes were hung at a depth of 2–12 m. Average water depth at the site was 20 m and bottom water current speeds were low. The Kiel farm (Outer Baltic) is located near Kiel, Germany. The farm technology consists of ropes with collector bands and socks optimised for the production of large mussels. Ropes were suspended at depths of 1–3.5 m and average water depths ranged between 7 and 11 m (Schröder et al., 2014). The farm was established in 2011 and the first harvest took place in September 2012.

2.3. Spatial mapping

The blue mussel distribution data were combined from different sources: benthos database of the Estonian Marine Institute, University of Tartu (http://loch.ness.sea.ee/gisservices2/liikideinfoportaal/); the VELMU database, Finnish Environment Institute (http://www.ymparisto.fi/en-US/VELMU); the database of the Swedish National Monitoring Programme (http://sharkdata.se/), benthic inventory data collected by AquaBiota (http://www.aquabiota.se/en/researchservices/inventories-using-underwater-video/), the database of Marine Research Institute, Klaipeda University; EurOBIS (http://www.eurobis.org/) and EMODnet (http://www.emodnet-biology.eu/portal/) (Fig. 2). Altogether, data from 226,031 stations from coastal hard and soft bottom habitats of the Baltic Sea were included in this study. This dataset was based on a regional sampling and sample processing protocol developed for the HELCOM COMBINE programme (HELCOM, 2015). The stations included were sampled at least once in summer (June to August) between 2005 and 2015. On hard bottoms, blue mussels were collected by divers using a standard bottom frame (0.04 m^2) and/or a hand-held drop camera operated from small motorboats with recording devices operated on the surface. On soft bottoms, samples were collected using different benthos grabs (sampling area 0.02–0.1 m^2). Quantitative samples were sieved in the field using 0.25 mm mesh screens. The residues were stored at −20 °C and subsequent sorting, counting, weighing and measuring of blue mussels were performed in the laboratory.

Oxygen measurements under the farms were made with a JFE Advantech optical DO sensor (https://www.jfe-advantech.co.jp/eng/ocean/rinko/rinko3.html).

The majority of existing experimental measurements of mussel growth in the Baltic Sea ($n = 14{,}944$) were used to model the potential growth and yields across the key environmental gradients. This includes the original data of the INTERREG Baltic EcoMussel and Baltic Blue Growth projects as well as data from different national research initiatives from Estonia, Finland, Sweden, Denmark and Germany (Fig. 2).

2.4. Mussel tissue analysis

Nutrient content was analysed for 124 samples of blue mussel tissue. In each case, 100–150 g of fresh material (shells, soft tissue and associated water) were analysed in the following manner. Whole frozen mussels were removed from the freezer and thawed. A portion of the thawed mussels (shells, soft tissues and associated water) were manually crushed using a mortar and pestle. Between 100 and 150 g of the crushed mussels were weighed. This weight is reported as the sample wet weight. The samples were then freeze-dried at −80 °C and weighed. They were then oven dried at 105 °C (to remove any residual moisture) and weighed again to determine dry mass and dry matter fractions.

Prior to the nutrient analysis, dried material was filtered through a 1 mm sieve. Total N measurements were performed by the laboratories of Swedish University of Agricultural Sciences using the total Kjeldahl nitrogen (TKN) method. Total phosphorus (P) concentrations were analysed by Agrilab AB. Samples were acidified using sulfuric acid. P concentrations were obtained using ICP-AES.

2.5. Statistical analysis of nutrient concentrations

In order to account for regional variability in the nutrient content of mussels, samples were classified into those obtained in the Outer, Central or Inner Baltic Sea. These three functionally different regions were used to account for the regional-specific nutrient accumulation in mussels when assessing the potential of nutrient removal through harvesting.

Because the sampling design was unbalanced, i.e., the same number of samples were not available for the different months across regions, only the samples collected from the Outer Baltic were used to define the best way of grouping the samples obtained in the different seasons for subsequent analyses. A Tukey's Honest Significant Difference (HSD) post-hoc test of an ANOVA predicting wet weight P concentrations as a function of month indicated that samples from March, April, May and June belonged to the same group (spring) and had no overlap with the group of samples collected in other months (other). This grouping was corroborated by the analysis of wet weight N concentrations.

To facilitate the comparison with mussel harvest values, which are typically reported as total mass of mussels (i.e. shells, soft tissue and associated water), ANOVA analyses were performed on wet weight concentrations. Pairwise differences were assessed using the Tukey's HSD test. The ANOVAs tested for the fixed effects of region (Outer, Central and Inner), season (spring or other) and their interaction.

2.6. Modelled environmental variables

Care was taken to select the most relevant ecological variables in order to reach the most robust predictions about the role of the environment for blue mussel occurrence and growth. When the variable selection is inadequate, a model may include irrelevant variables and its predictive power is low (MacNally, 2000). Earlier studies have shown that water salinity, temperature conditions, and food availability (a product of phytoplankton concentration and water flow) mostly shape the distribution and growth of blue mussels at the Baltic Sea scale (Kotta et al., 2015).

Model inputs for the physical and biogeochemical conditions in the Baltic Sea were obtained from the products BALTICSEA_ANALYSIS_FORECAST_PHY_003_006 and BALTICSEA_ANALYSIS_FORECAST_BIO_003_007 at the Copernicus open access data portal (http://marine.copernicus.eu/services-portfolio/access-to-products/). These physical products covering the whole Baltic Sea area contain data with hourly resolution and 25 vertical levels. The biogeochemical data are served with 6-h resolution and 25 vertical levels. For both products, the horizontal grid step is regular in latitude and longitude and is approximately 1 nautical mile. The physical product is based on simulations with the HBM ocean model code (HIROMB-BOOS-Model). The biogeochemical product is based on simulations with the BALMFC-ERGOM version of the biogeochemical model ERGOM, originally developed at IOW, Germany. The BALMFC-ERGOM version has been further developed at Danish Meteorological Institute (DMI) and Bundesamt für Seeschifffahrt und Hydrographie (BSH). The BALMFC-ERGOM model is run online coupled with the HBM ocean model code. In the analyses presented here, annual averages of salinity and current velocity and summer averages (June to August) of temperature and chlorophyll *a* concentration were used.

In addition to the aforementioned data layers, depth data acquired from the Baltic Sea Bathymetry Database (Baltic Sea Hydrographic Commission, 2013) were used as a modelling input variable for predicting blue mussel presence and growth. The locations of hard bottom areas were obtained from the EMODnet portal (http://www.emodnet.eu/) and unpublished sediment data were collated from Finnish Environment Institute, Geological Survey of Sweden, and the Bundesamt für Seeschifffahrt und Hydrographie. Wave exposure data were produced by Aquabiota, using the Simplified Wave Model method (SWM; Wijkmark and Isæus, 2010). The SWM method calculates the wave exposure for mean wind conditions using a nested-grids technique to take into account long distance wind effects on the local wave exposure regime. This method results in a pattern where the fetch values are smoothed out to the sides, and around islands in a similar way that refraction and diffraction make waves deflect around islands. Then a depth-attenuation correction was applied to the SWM in order to estimate depth-attenuated wave exposure (Bekkby et al., 2008). For maps of environmental variables, see Supplementary Fig. 1.

2.7. Modelling the occurrence of blue mussel reefs along environmental gradients of the Baltic Sea

In the case of distribution data, all samples having positive coverage or biomass were considered as indicative of mussel presence and all other samples were considered as absences. The occurrence probability of wild blue mussels on seafloor was modelled as a function of depth, salinity, temperature, wave exposure and the presence of hard or mixed substrate with sand, boulders and bedrock. These substrate types are known to be good habitats for blue mussels in the Baltic Sea area (e.g. Westerbom, 2006). A binomial Generalized Additive Model (GAM) with logit link function was used for modelling occurrence. Possible over-fitting was limited by constraining the degrees of freedom of model covariates.

2.8. Hydrodynamic connectivity model

The connectivity structure among all mussel reefs in the Baltic Sea area was estimated with a biophysical model of larval dispersal. Blue mussel larvae may drift in the water column for up to 30 days (Bayne, 1965). The biophysical model combined flow fields from an ocean circulation model with a Lagrangian particle-tracking model simulating transport of individual larvae from spawning to settling locations. The ocean current velocity fields were produced with the three-dimensional NEMO-Nordic model (Hordoir et al., 2013, 2015), a regional configuration of the NEMO ocean engine (Madec, 2010) covering the Baltic Sea, the Kattegat, the Skagerrak, and most of the North Sea. The model has a horizontal spatial resolution of 3.7 km and 84 vertical levels with depth intervals of 3 m at the surface and 23 m for the deepest layers. The model has open boundaries between Cornwall and Brittany, and between the Hebrides Islands and Norway with tidal harmonics defining sea surface height (SSH) and velocities, and Levitus climatology defining temperature and salinity (Levitus and Boyer, 1984). The applied model had a free surface and the atmospheric forcing was based on the re-analysis dataset ERA40 (Uppala et al., 2005). Runoff was based on climatological data from several databases for the Baltic Sea and the North Sea. Validation of the NEMO-Nordic showed that the model correctly represents both tidally induced and wind driven SSH anomalies (Hordoir et al., 2015).

To simulate larval drift trajectories, the Lagrangian particle-tracking model TRACMASS (De Vries and Döös, 2001), that calculates transport of particles using stored flow field data from the ocean model, was used. The velocity, temperature and salinity were updated with a regular interval for all grid boxes in the model domain (in this study - every three hours), and the trajectory calculations were performed with a 15-min time step. Particles simulating larvae of blue mussels were released from the model grid cells (3.7×3.7 km^2) that overlapped with the mussel reef areas. From each grid cell, 294 particles were released on three occasions between June to July as this time corresponds to a planktonic larval phase of blue mussels in the Baltic Sea region (Kautsky, 1982). Each larva was forced to drift in one of three depth intervals: 25% of larvae between 0 and 10 m, 50% of larvae between 10 and 15, and 25% of larvae between 15 and 30 m (Corell et al., 2012). The pelagic larval duration (PLD) was set to either 20 or 30 days with equal probability, and settlement was assumed at the location when the PLD was completed. All these simulations were repeated for 8 years (1995–2002), representing a range of North Atlantic oscillation index values (NAO; Hurrel and Deser, 2009), which is known to correlate well with the variability in circulation pattern, making a total of 670,000 released particles. A grid cell was considered to receive recruits if larvae spawned at any of the reefs in the Baltic Sea range settled at the specified grid cell (Supplementary Fig. 2).

2.9. Modelling the growth of blue mussels along environmental gradients of the Baltic Sea

Blue mussel growth was modelled as statistical relationships between environmental variables and mussel growth yield experimentally evaluated all over the Baltic Sea region. Only the environmental variables known to affect regional patterns of Baltic Sea mussel growth (salinity, temperature, chlorophyll *a*, exposure to waves) were included in the model. It was assumed that new larvae can settle from 1st to 30th of June and only in the grid cells that are connected to mussel reefs (see previous subsection). The growth simulations were based on dry weight of mussels as opposed to length (this allowed for negative growth during periods of resource limitation and for greater flexibility when dealing with gamete production). The model assumed that the new larvae appeared in June. Yields were normalized with the total incubation time (to produce data for yield per day) but a linear pattern was observed within a year, thus allowing to extrapolate the predictions to 365 days. Two year predictions were calculated from one-year predictions using a coefficient obtained from individual growth patterns.

Gaussian GAMs with an identity link function were used for modelling. Possible over-fitting was reduced by constraining the degrees of freedom of model covariates. Final growth model included salinity and interaction between wave exposure and chlorophyll *a*. Two random factors were used to model the dependence inherent in the growth data. First, for a combination of farm area and year to allow for yearly variation in different farming areas. Second, for a combination of place

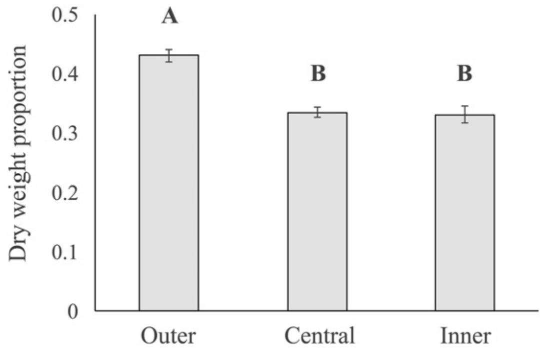

Fig. 3. Mean and standard errors (bars) of the mean dry weight proportion in the Outer, Central and Inner Baltic Sea. Letters depict statistically significant differences between groups (Tukey's HSD test results at $p < 0.05$) and levels are statistically significantly different if they do not have any letters in common.

(within area) and year to allow for yearly variation within areas. Thus it was assumed that yields for two farms from the same area or place from the same year are more similar than yields for two farms from different areas or places from the same year. To normalize the residual distribution, the yield per day was fourth-root transformed.

For prediction, it was assumed (based on empirical knowledge) that no further gain can be obtained from wave exposure values above 200,000 which represents a transition from moderately exposed to exposed areas (Kotta et al., 2015). Blue mussel growth was deemed impossible at salinity values below 3.5 (Riisgård et al., 2014). The available growth data was more evenly spread along the north-eastern and south-western coasts as compared to central coasts of the Baltic Sea. Hence, in these sparsely sampled areas, growth for locations far from any growth assessment was estimated by spatial extrapolation. However, with respect to salinity, the main factor explaining mussel growth in our model, extrapolations are not extensive, since the growth data spans the salinity gradient.

To quantify meaningful effect sizes of the two components (salinity vs chlorophyll *a* and exposure to waves) in the study area, predictions of two-year yield were obtained for six different combinations of predictor values, as follows. First, for each predictor the 2.5% quantile (low), the median and the 97.5% quantile (high) were determined. To assess the interaction effect of chlorophyll *a* and wave exposure, salinity was kept at its median value while four different value combinations (low-low, low-high, high-low, high-high) were assigned to the other two predictors. To assess the effect of salinity, the other two predictors were kept at their respective medians while two different value combinations (low and high) were assigned to salinity.

2.10. Nutrient removal at harvest

The mass of N and P removed during harvest at the three farms was estimated by multiplying reported wet weight harvest values and least squares mean estimates for "other season" wet weight nutrient percentages for the three regions of the Baltic. These estimated percentages were obtained from analyses of variance (ANOVA) of N and P tissue concentrations from 124 composite samples (Supplementary Tables 2 and 3).

3. Results

3.1. Analyses of farmed mussels

A total of 9478, 1516 and 4912 mussel samples were harvested and measured from farms in the Outer, Central and Inner Baltic Sea (three major analysis regions, Fig. 2). Average densities and individual wet weights (±SE) of harvested mussels were 2654 ± 77 individuals m^{-1} (individuals per metre of rope) and 0.50 ± 0.02 g ww (wet weight) in the Outer Baltic; 4998 ± 329 individuals m^{-1} and 0.20 ± 0.01 g ww in the Central Baltic and 2326 ± 24 individuals m^{-1} and 0.16 ± 0.001 g ww in the Inner Baltic, respectively.

In total, 124 composite samples of whole mussels (shell and soft tissue) were available for dry matter and nutrient analysis. Samples of blue mussels from the Outer Baltic had significantly higher dry matter content (42.5%) than mussels from the Central (34.0%) or Inner (32.6%) Baltic (Supplementary Table 1, Fig. 3). Region, season and their interaction accounted for 62.3% and 67.7% of the total observed variation in mussel tissue N and P percentages (Supplementary Tables 2 and 3). Nitrogen concentrations were highest in Outer Baltic samples from spring (1.23%), followed by those obtained for the same region in other seasons (0.89%). There were no significant differences among spring Central Baltic samples (0.70%), Central Baltic samples from other seasons

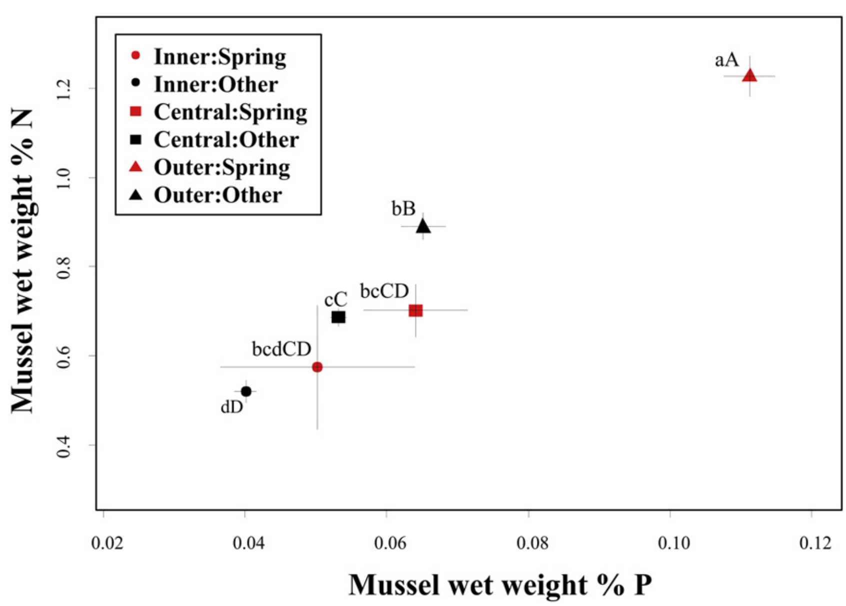

Fig. 4. Mean (filled shapes) and standard errors (bars) of nitrogen (N) and phosphorus (P) content in farmed mussels expressed as a percentage of wet weight in spring vs other seasons in the Outer, Central and Inner Baltic Sea. Letters depict statistically significant differences between groups (Tukey's HSD test results at p < 0.05) with capital letters denoting N and lowercase letters P groups. N and P levels are statistically significantly different if they do not have any letters in common.

(0.69%), and spring Inner Baltic samples (0.57%). Inner Baltic samples from other seasons (0.52%) were significantly lower compared to all other contexts except Inner Baltic spring samples (Supplementary Table 2). Observed phosphorous concentrations followed similar trends to those of N (Supplementary Table 3). The highest P concentrations were measured in spring Outer Baltic samples (0.111%) and the lowest in mussels from the Inner Baltic in other seasons (0.040%). Phosphorous concentrations in spring Central (0.060%) and Inner Baltic (0.050%) samples were significantly lower than in spring Outer Baltic samples and did not differ from Outer Baltic samples obtained in other seasons (0.065%). As for N, P concentrations did not statistically differ between seasons in mussels from the Central (spring: 0.060%, other: 0.053) and Inner (spring: 0.050%, other: 0.040%) Baltic (Fig. 4).

Biomass yield and economic information were available for three production farms: Kumlinge (Inner Baltic), Sankt Anna (Central Baltic) and Kiel (Outer Baltic) (Table 1). Although the higher salinity and chlorophyll *a* levels at Kiel may suggest a greater potential for mussel biomass production and hence nutrient removal, this difference was not manifested. In fact, nutrient removal was higher in Sankt Anna (23.3 g N m^{-1} and 1.8 g P m^{-1} line) than either Kiel (22.2 g N m^{-1} and 1.6 g P m^{-1} line) or Kumlinge (3.7 g N m^{-1} and 0.3 g P m^{-1} line). Production costs were approximately four times higher at Kiel (1.85 € kg biomass harvested^{-1}) than at Sankt Anna (0.52 € kg biomass harvested^{-1}). Costs were much higher at Kumlinge (8.52 € kg biomass harvested^{-1}). Differences in production costs were the main driver of the large difference in nutrient removal costs which were lowest at Sankt Anna (76 € kg $N)^{-1}$ and 981 € kg P^{-1}) and higher at the other two farms.

3.2. Modelling of biomass yield and regional nutrient removal

Spatially explicit estimates of farm biomass yield were predicted as a function of site salinity, exposure to waves and food availability (i.e. chlorophyll *a* concentration) (Fig. 5). The model explained 82.3% of the variation in the data. Modelled patterns of biomass yield were driven by salinity at the regional scale and food availability at the

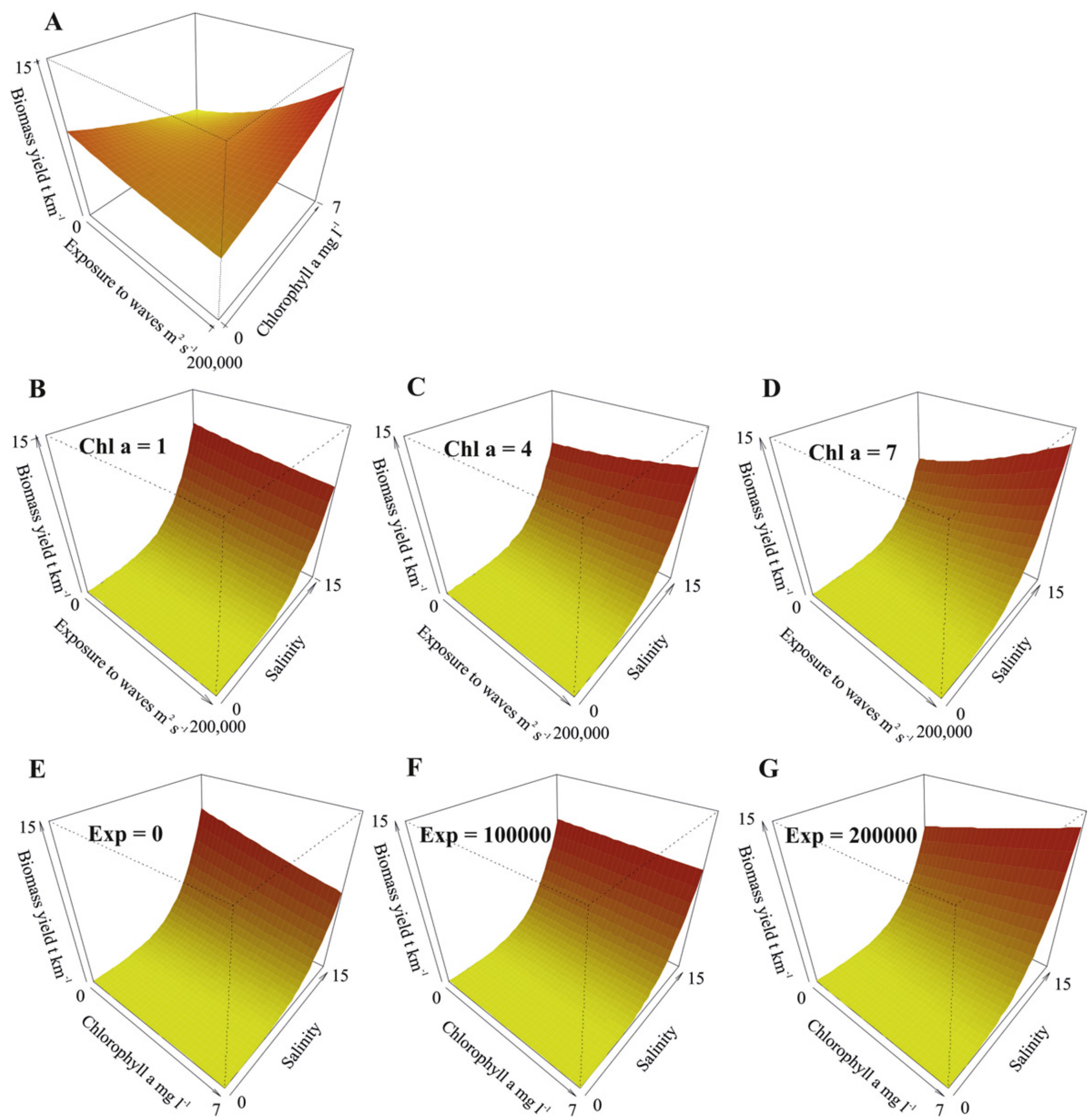

Fig. 5. Overview of the blue mussel biomass yield model and obtained response curves. Estimations refer to biomass yields obtained two years after the establishment of the farms. Panel A shows the interactive effects of exposure to waves and chlorophyll *a* concentration (i.e. food availability) at a salinity of 7.5 psu. Panels B-D show the interactive effects of exposure to waves and salinity at low, medium and high chlorophyll *a* concentrations. Panels E-G show the interactive effects of salinity and chlorophyll *a* at low, medium and high exposure levels.

local scale. On the model scale, the effect of salinity was estimated to be linear (and positive) which translated to a quartic effect on the response scale. The interaction between food concentration and exposure to waves (a good proxy of water movement and exchange) was more complex. At low water movement, elevated chlorophyll *a* concentrations were associated with low biomass yield of mussels, whereas at moderate to good water exchange, increasing chlorophyll *a* resulted in the raised biomass yield. The overall effect size of salinity was about 13 times as large as the effect size of the aforementioned interaction. The random effects, accounting for the inter-annual and spatial variation not explained by the mean trends in salinity and the interaction between wave exposure and food availability, explained approximately 50% of the total variance. The model does not simulate disastrous loss of harvestable mussel biomass associated with severe storms or harmful algal blooms.

Response curves predicting mussel yield as a function of environmental conditions (Fig. 5) were combined with spatial data on salinity, wave exposure and surface chlorophyll *a* concentrations to produce pan-Baltic estimates of potential rates of biomass removal that can be obtained using farmed blue mussels (Supplementary Fig. 3). The model extrapolation power was assessed by predicting the average yield in the Kiel mussel farm that was not used for model fitting. On the model scale, the average yield was predicted to be only 10% smaller than what was actually measured. Higher growth was predicted at higher salinities and/or better food regimes, i.e. the Outer and Central Baltic. Predicted biomass yield was highest in high-salinity areas of the

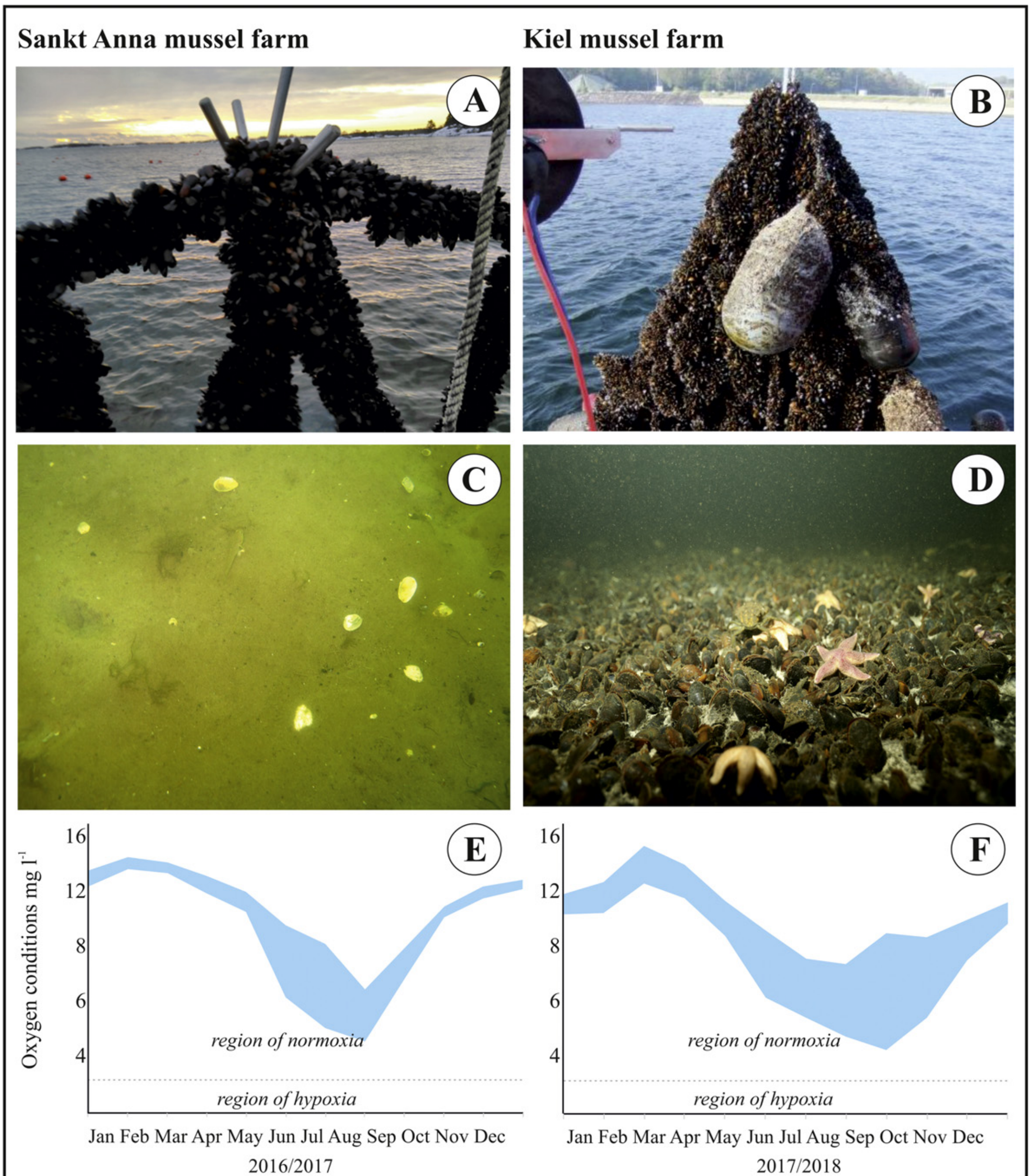

Fig. 6. Long line removed from the water at Sankt Anna (A) showing mussel growth. View of mussel farm at Kiel showing floats on which lines are suspended (B). Panels (C) and (D) show the environment underneath the same farms. Blue surfaces of panels (E) and (F) show variability in oxygen conditions (mg l^{-1}) measured at the sediment-water interface underneath the farms and dotted lines indicate the region of hypoxia and normoxia (for further data see http://www.sea.ee/bbg-odss/Ocean/OceanMain).

Outer Baltic where it was estimated at 15 kg m^{-1} per harvest. With declining salinity, predicted biomass yields varied between 1 and 3 kg m^{-1} in the Central Baltic. In marginal (Inner Baltic) regions, predicted biomass yields never exceeded 1 kg m^{-1}. Patterns in modelled rates of biomass removal are similar to the observed patterns of N and P content (Fig. 4), which are higher in the Outer Baltic than in either the Central or Inner Baltic.

The harvest data from the three example farms (Table 1) can be put into a regional context by comparing them to regional modelled rates of biomass removal (Supplementary Fig. 3). The observed harvest at Kumlinge is similar to model projections while the actual harvest at Sankt Anna is 2.5 times larger than model projections and the Kiel harvest is 5 times smaller (Table 1). Mussels grow larger in waters that are more saline and therefore their substrate (i.e., the settlement rope) becomes quickly saturated and competition between mussels for space is high. A multi-layered structure of large mussels is very unstable and even moderate storms can remove outer layers from suspended ropes. Many detached mussels were observed underneath the Kiel farm, whereas no such losses were recorded in Sankt Anna (Fig. 6). Nevertheless, the full potential of high-salinity areas is demonstrated based on harvest data from experimental fuzzy ropes deployed in Kiel farm over a year and such substrates hosted nearly 10 kg mussels m^{-1} (Supplementary Fig. 4).

When evaluating the potential of mussel cultivation as a mitigation tool to reach regional nutrient reduction targets, a surprisingly small marine area would need to be used for mussel farms in order to close the remaining nutrient reduction gaps, i.e., 900 km^2 for the Central Baltic and 600 km^2 for the Inner Baltic (Fig. 1). When farms are established at optimal growth locations and optimal density, then nutrient removal during mussel harvest can compensate up to 100% of the local and a large part of the regional nutrient loading. Although the modelling results presented here suggest a higher efficiency of mussel farms at high salinity, the factual evidence suggests that Outer Baltic farms are not necessarily more efficient in nutrient removal as compared to Central Baltic farms. Importantly, the predicted total area of farms needed for achieving HELCOM nutrient reduction targets could be achievable under the current marine spatial planning regime in the Baltic Sea.

4. Discussion

Marine eutrophication is a pervasive and growing threat to global sustainability (Conley et al., 2009b). While all reasonable efforts to reduce nutrient inputs from land to sea must continue, internal measures are also needed to ensure the timely recovery of eutrophicated systems (Savchuk, 2018). Extractive harvesting of farmed native bivalve species, including *M. edulis/trossulus*, is a sustainable, low-impact (Petersen et al., 2014, 2019), circular (Spångberg et al., 2013) and potentially cost-effective (Gren et al., 2009) internal measure for eutrophication control (Suplicy, 2018). While arguments have been made against the use of internal measures such as mussel farming (Stadmark and Conley, 2011) or geo-engineering (Conley, 2012), there can be little doubt that internal measures must be considered when all feasible external measures for nutrient load reduction have been explored, applied and found to be inadequate or insufficient.

The Baltic Sea is a plausible representation of the likely future state of other coastal seas globally (Reusch et al., 2018) and the accumulated knowledge for this region may serve as a useful future management model for other internationally managed seas. Mitigation has already been largely successful for recovery of Baltic Sea top predators (Reusch et al., 2018) and some fish stocks (Eero et al., 2012). External loads of both N and P from the surrounding catchment have declined (Reusch et al., 2018; Savchuk, 2018) but average N concentrations are decreasing slowly, if at all, while P concentrations continue to increase (Savchuk, 2018). This mismatch between the successful reduction of terrestrial nutrient inputs and failure to observe corresponding improvements in water column nutrient concentrations is due in part to the ongoing release of nutrients accumulated in marine sediments (Vahtera et al., 2007).

The predicted nutrient removal by mussel harvesting largely follows the spatial patterns of mussel growth, i.e., farms in the Outer Baltic are expected to have higher yields than in other Baltic Sea regions. Harvest weight (kg m^{-1}) is linearly related to mussel size (Nielsen et al., 2016) and blue mussels do not grow as rapidly in brackish waters as they do in fully marine environments. While the small size of harvested mussels poses challenges for feed or food production, the data presented here suggest that the overall potential for nutrient removal does not diminish along the salinity gradient, except for the innermost parts of the Baltic Sea (Table 1, Supplementary Fig. 3). While it is important to prioritize high salinity sites in order to enhance the yield, even at reduced salinities in the central Baltic Sea, a one hectare mussel farm with a density of appropriate ropes may yield hundreds of tons of biomass per harvest cycle. Furthermore, the harvest strategy can be optimised as smaller mussels may be more efficient at nutrient removal due to lower detachment rates as density dependent losses can reach 50% in oceanic regions with high biomass production (Haamer, 1996).

Unlike earlier studies (Dahlbäck and Gunnarsson, 1981; Hartstein and Stevens, 2005), the monitoring of all existing mussel farms in the Baltic Sea region offers no evidence to suggest that blue mussel farms in the Baltic Sea have any negative effects on the local oxygen conditions at the sediment–water interface (Aigars et al., 2019). While others have suggested that mussel farms can cause promote lower sediment oxygen concentrations associated with a reduction in bioturbation or excessive accumulation of organic matter (Stadmark and Conley, 2011), the opposite phenomenon was observed at the Kiel mussel farm where an increase in bioturbation led to higher sediment oxygen concentration (Aigars et al., 2019). When sediments remain oxygenated, there is unlikely to be any additional internal loading of P. However, oxygenated conditions in the sediment under farms can suppress denitrification (Carlsson et al., 2012).

Shellfish farming generally has lower environmental impacts than other forms of aquaculture (Forrest et al., 2009; Kraufvelin and Díaz, 2015). Farmed blue mussels do not require any nutrient external inputs. This means that unlike other forms of aquaculture, all of the nutrients removed during harvest make a positive contribution to regional eutrophication reduction and a valuable regulative ecosystem service in eutrophic waters (Suplicy, 2018; Petersen et al., 2019). However, the potential for localised nutrient enrichment in the immediate vicinity of mussel farms does exist in very sheltered areas (e.g., Stadmark and Conley, 2011; Holmer et al., 2015) and in such areas the possibility of undesirable local eutrophication must be recognised and addressed.

Furthermore, farms can provide additional habitat for colonization to supplement natural mussel reefs lost to anthropogenic impacts, especially human-facilitated invasion impacts of benthic predators. In the Baltic Sea, the most relevant invasive predator is round goby, which causes large-scale losses of benthic blue-mussel populations (Skabeikis et al., 2019), e.g. one case-study location is estimated to have lost 23% of its 230km^2 pre-invasion mussel reef area due to round goby predation (Liversage et al., 2019). Suspended mussels will attract negligible predation from such benthic predators, thus mussel farming will help restore overall population levels. If a switch does occur from natural mussel reefs to suspended farm mussels, this may involve a reduced local-scale per-capita impact on eutrophication because material excreted from suspended mussels will have greater dispersal and dilution by water movements (Hartstein and Stevens, 2005) rather than direct benthic retention. In addition, aquaculture activities often produce benthic shell debris deposits (Sanchez-Jerez et al., 2019) which increase sediment porosity and oxidised sediment layer depth, as well as infaunal bioturbation (Zaiko et al., 2010). These benefits may be expected following extended establishment of mussel farms.

Using mussel farming as an internal measure to mitigate eutrophication in the Baltic requires the development of appropriate legislative instruments (Ozoliņa, 2017) and resolution of sea-use conflicts along maritime spatial planning process (Kannen, 2014). The model-predicted locations of mussel farms for achieving eutrophication reduction targets do not take multiple sea-use conflicts into account, especially tourism and fisheries (Lindahl et al., 2005). While maritime spatial planning tools for optimizing interests of various stakeholders are well developed, the tools do not yet incorporate the implementation of mussel farming. Careful planning of large-scale mussel farming could avoid unacceptable environmental impacts or conflicts with other uses. Farms should be located in semi-exposed or exposed areas with good water circulation where negative local effects to benthic habitat quality are unlikely. Additionally, predation can compromise the production of bivalves in otherwise suitable areas. Therefore, the risk of losing biomass to, e.g., the eider ducks (*Somateria mollissima*) in the Outer Baltic must be assessed before initiating a full-scale mussel production. Other technical challenges including storms, epiphytes, and in some regions ice, will also need to be considered and lessons learnt from previous mussel farming programmes need to be applied (National Research Council, 2010). Furthermore, farm technology adapted to the culturing of small mussels should be used whenever possible to maximize yields. Blue mussel farming as a mitigation measure is particularly efficient to counteract diffuse nutrient emissions as to date there are few other effective options to remove nutrients that have already reached the sea. Commercial mussel farming can also contribute to rural sustainability by providing jobs in economically depressed areas. It may also contribute to a clean-up of the local marine environment with benefits for local tourism, recreation and other cultural ecosystem services.

5. Conclusions

Eutrophication is a leading cause of impairment of many aquatic ecosystems globally. While external measures to control nutrient inputs must be pursued, there is also a need for internal measures in order to restore water quality and enable ecosystem recovery in a timely manner. Blue mussel farming is a promising low-impact and native species-based internal method for eutrophication control in the Baltic Sea and beyond. Mussels filter the water for phytoplankton and trap nutrients which are then removed from the aquatic environment through harvest, allowing nutrient reuse as part of the circular economy. Blue mussel farming in the Baltic Sea not only provides a tool for nutrient mitigation, but also contributes to the social and economic sustainability of rural areas. These results presented here provide factual data to support political decisions on internal measures for eutrophication control and promote the sustainability of the Baltic Sea region through mussel farming for nutrient management.

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.

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Author contributions

Conceived the study and wrote the paper: JK, MF, AK, KL, LB, PRJ. Collected data: MR, FRB, PB, IB, ED, SK, PaK, PeK, OL, ML, MML, MM, ANS, HOK, MO, SK, JR, AŠ, EV, HS. Obtained funding and analysed data: JK, MF, AK, KH, PRJ, AV. All authors discussed the results and edited the manuscript.

Data availability

The datasets that were generated and/or analysed during the current study are freely available from the corresponding author on a request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.136144.

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Digital supply network design: a Circular Economy 4.0 decision-making system for real-world challenges

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ABSTRACT

This research introduces the idea of 'Circular Economy 4.0' to reflect the emergence of 'digitalised' sustainable supply networks. While often characterised by enhanced productivity and resource/energy efficiency, current perspectives are largely descriptive with limited practical relevance. A hierarchical decision-making framework and a multi-level simulation modelling and optimisation technique are constructed to explore the interplay between Circular Supply Chains and Industry 4.0. The real-world case of blue-green algae as renewable feedstock – to derive value-added omega-3 oils and biofertilisers – is investigated to develop 'Circular Economy 4.0' perspectives. The emerging circular supply network utilises micro-factories (i.e., photobioreactors), continuous manufacturing technologies (i.e., piezoelectric transducers), and drone operations for feedstock availability monitoring. This study contributes to theory and practice by building on the limited empirical research exploring determinants of successful transitions in Circular Economy-Industry 4.0 network contexts. Four design principles are proposed that capture the interplay between digital technologies and network design configurations, e.g., centralised – semi-centralised – decentralised. Modelling is developed across macro-, meso-, and micro-levels of analysis. Results demonstrate significant gains in terms of resources utilisation and market dynamics, enabled by the adoption of digital operations in a circular economy context, with initial insights on the evolution of such networks.

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KEYWORDS
Circular Economy; Industry 4.0; sustainable supply network design and management; hierarchical decision-making framework; multi-level simulation modelling and optimisation technique

1. Introduction

Sustainability pressures along with on-going radical advancements in digital technologies are driving the establishment of value-added production and consumption systems (de Sousa Jabbour, Jabbour, Foropon, et al. 2018), in which the circularity of energy and material flows could promote economic growth, environmental stewardship and social benefits (Geissdoerfer et al. 2017). In particular, the need for circular supply network operations is prominent to generate greater resilience to climate change (Ellen MacArthur Foundation 2019), specifically considering the: (i) rising demand for finite natural resources (Calvo, Valero, and Valero 2017); (ii) often-improper management of significant end-of-life product volumes (Sivakumar et al. 2018); and (iii) projections indicating that middle-class consumers will increase by three billion globally by 2030 (World Economic Forum 2014). To this end, Industry 4.0 has the potential to unlock Circular Economy dynamics across industrial supply networks in a cost-effective and sustainable manner (de Sousa Jabbour, Jabbour, Filho, et al. 2018), through enabling: (i) higher level of connectivity among actors and smart equipment, real-time data monitoring, and human-machine interaction for operational efficiency (Yang et al. 2018); (ii) automated wastage collection, sorting, treatment and processing for production efficiency (Nascimento et al. 2019); and (iii) increased information processing capability and transparency for uninterrupted logistics/information flows (Bag et al. 2020).

Policy-makers, academics and industry stakeholders are exploring the expected benefits that might arise from the integrated application of Circular Economy operational models and Industry 4.0 principles in manufacturing networks (Lin 2018). This interplay is also encouraged by the United Nations in the context of the 2030 Agenda for Sustainable Development (United Nations 2015), while the Ellen MacArthur Foundation (2015) stressed the enabling role of investments in digital technologies with regards to fostering the transition towards Circular Economy paradigms. Industry-wise, digital manufacturing technologies are now considered sufficiently mature to support Circular Economy value propositions to enable operations excellence (Lieder and Rashid 2016), for example, in terms of optimised material stock and flows (Srai et al. 2016). In this regard, the Operations Management literature is being populated by analysis frameworks and assessment tools which aim to either facilitate the configuration of circular supply chains

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(Srai et al. 2018), or promote the integration of technological innovations in supporting sustainability in value networks (Bechtsis et al. 2018).

Nevertheless, research investigating the interplay between Circular Economy and Industry 4.0 is still embryonic (de Sousa Jabbour, Jabbour, Filho, et al. 2018); notably, Nobre and Tavares (2017) presented bibliometric data for the period 2006–2015 demonstrating the sparsity of scientific studies jointly examining these topics. Specifically, the authors reported that less than 0.25% of the reviewed Circular Economy-focussed studies considered digital technologies while the detachment between scientific research and industrial applications was also evident. More recently, Tseng et al. (2018) identified only three relevant published articles studying the nexus of these topics. Existing studies mainly provide a descriptive perspective of the link between Circular Economy and Industry 4.0 while myopically discussing the implications of digitalisation in the lifecycle management of products and processes (Rosa et al. 2020). Also, extant research on capturing the causal relations between Circular Economy and digital technologies from a systems perspective is scant (Luthra et al. 2018), while the documented operationalisation of Industry 4.0 in Circular Economy applications is nascent (Kouhizadeh, Zhu, and Sarkis 2020). Moreover, practical challenges relating to the digitalisation of supply chains for circular operations are also overlooked in studies conducted to date (Fatorachian and Kazemi 2018). Hence, the current literature is inadequate in informing relevant business strategies and in fostering the deployment of smart manufacturing networks that might be more environmentally friendly, flexible and economical (Luthra and Mangla 2018). To this effect, further case-based studies and additional empirical research is required to inform the management of circular supply chain operations enabled by Industry 4.0 for supporting sustainability, including productivity improvements, waste reduction, resource use efficiency, remanufacturing, reusing, and recycling. By extension, and potentially to a greater extent, is the need for the application of decision-making tools that could assist organisations in making informed and more effective a priori evaluations of sustainable supply networks' designs (Allaoui et al. 2018).

Industry 4.0 is deemed an enabler of end-to-end circular supply networks, principally with regard to the classical '3R' concept (i.e., reuse, recycle, remanufacture) that is closely related to Circular Economy (Nobre and Tavares 2017). Documented circular supply chain and digital manufacturing paradigms include the exploitation of citrus waste to produce active pharmaceutical ingredients (Lapkin et al. 2017), and the utilisation of smart cells for remanufacturing carburised steel shafts (Yang et al. 2018). However, a knowledge gap exists with regards to the operationalisation of the synergy between circular supply chain strategies and Industry 4.0. This research – in investigating the case of renewable feedstock platform technologies – contributes to the Operations Management domain by enhancing the understanding of the relationship and interplay between circular supply networks and Industry 4.0. More specifically, this study demonstrates emerging and innovative operational capabilities within the discussed setting by addressing the following research questions (RQs):

- RQ#1 – How might the interplay between Circular Economy and Industry 4.0 be best represented, in enabling 'real-world' transitions to sustainable supply chains?
- RQ#2 – Which major hierarchical decision-making determinants best support the adoption of Industry 4.0 applications, in enabling the configuration of circular supply network operations?
- RQ#3 – How does the digitalisation of operations affect the configurational design and performance of the aforementioned circular supply networks?

Motivated by the study of Fatorachian and Kazemi (2018) and building upon the research agenda proposed by de Sousa Jabbour, Jabbour, Filho, et al. (2018), we introduced a conceptual framework to address RQ#1. The framework depicts the rotary co-action of Circular Economy and Industry 4.0 as the 'backbone' towards the transition to circular supply networks. With specific drivers and goals, the proposed framework particularly focuses on the real-world case of the valorisation of blue-green algae into biofertilisers for food crop farms and omega-3 oils for fish feed in the UK. The response to RQ#2 identified the hierarchical decision-making process that applies to all stakeholders involved in the design and management of circular supply chains enabled by digital technologies. Simulation modelling and optimisation assessments were utilised to investigate the impact of digital manufacturing and renewable feedstock monitoring systems on circular supply chain operations in an attempt to address RQ#3.

This research followed a mixed-methods approach to answer all three questions. In particular, a synthesis of Circular Economy and Industry 4.0 research evidence was conducted to address RQ#1. Thereafter, a critical taxonomy of studies in the extant literature was utilised to answer RQ#2. Finally, a multi-level simulation modelling and optimisation analysis approach yielded robust and informative results which assisted in answering RQ#3 and revealed directions for future research.

The remainder of this paper is structured as follows: Section 2 presents the background underpinning this research, while Section 3 outlines the relevant materials and methods. Section 4 identifies the natural hierarchy of the decision-making process for the design and management of circular supply networks enabled by Industry 4.0 applications. Section 5 then composes a multi-level simulation modelling and optimisation approach that captures impacts of digitalisation on the configuration and performance of circular supply networks. The application of the proposed framework is demonstrated for the UK case with the modelling results and discussion presented in Section 6. Finally, Section 7 concludes this research and highlights implications, limitations and suggestions for future research.

2. Research background

2.1. Circular Economy and Industry 4.0

The literature investigating Industry 4.0-driven sustainable supply network operations is rather limited. Jensen and

Remmen (2017) discussed the role of information exchange interfaces in supporting product stewardship throughout the life cycle of industrial products in manufacturing industries (e.g., automobile, aircraft and shipping) to promote the transition towards circular economy whilst ensuring information security and confidentiality. Additionally, Tseng et al. (2018) discussed the role of Big Data and the Internet of Things (IoT) in fostering industrial symbiosis under the umbrella of Circular Economy. The authors identified related gaps that prevent the implementation of '3R' strategies across industrial networks, further supporting the lack of integrated Industry 4.0 solutions – in end-to-end supply chains – as the main challenge in applying Circular Economy models. Furthermore, Bressanelli et al. (2018) identified eight functionalities enabled by IoT and Big Data analytics and studied the associated impact on the drivers of Circular Economy through a case study on a household appliances retailer. An original roadmap for the interplay between Circular Economy and Industry 4.0 was discussed by de Sousa Jabbour, Jabbour, Filho, et al. (2018), which specifically highlighted the value of digital manufacturing technologies in applying the ReSOLVE business model.

The need for leveraging digital technologies to migrate towards Circular Economy paradigms is specifically pronounced for the chemical industry as the sector mainly relies on petrochemical feedstocks. Projections show an anticipated increase in demand for chemicals of circa 45% during the next decade (ExxonMobil 2015). Hence, the exploitation of sustainable chemical feedstocks for the engineering of commercial products, typically petrochemical-based, is highly advocated as in the case of plastics manufactured from plant-derived lignocellulosic biomass (Artz and Palkovits 2018), or in the 'green' paracetamol paradigm produced from either citrus waste or waste from Kraft paper and pulp industries (Tsolakis and Srai 2018).

The benefits of digitalisation and automation for the chemical industry, in a sustainability context, are well recognised by research and business communities. From an academic perspective, Industry 4.0 technologies are expected to promote industrial sustainability through enabling chemical process integration, production modularity and real-time decentralised decision-making (Kamble, Gunasekaran, and Gawankar 2018). Furthermore, business experts recognise the potential of Industry 4.0 in supporting sustainable chemical supply chain planning and scheduling decisions owing to (Van Thienen et al. 2016): (i) inherent technological capabilities of improved end-to-end supply networks visibility; and (ii) advanced data gathering mechanisms and supply chain analytics that lead to better-informed demand forecasting.

2.2. Theoretical lens

The embodiment of Circular Economy principles in traditional supply chain design and management has strategic, structural and scoping implications that impact the transition towards real-world circular supply networks (De Angelis, Howard, and Miemczyk 2018). In addition, Industry 4.0 is documented to impact supply chain management by improving material flows, information sharing, coordination and integration (Dallasega, Rauch, and Linder 2018).

In this research, we adopted the view of Srai et al. (2018) who identified four theme areas of analysis for configuring circular supply networks enabled by renewable feedstocks, namely: (i) feedstock; (ii) technology; (iii) market; and (iv) value and viability. Notably, we view circular supply chains as networks where discarded material is being collected, processed and utilised as input to establish value networks in diverse industries (Tsolakis, Kumar, and Srai 2016). From an Industry 4.0 perspective, we considered the 'Sustainable Supply Chain Cube', proposed by Bechtsis et al. (2017), which captures the triple-helix sustainability implications of intelligent vehicles in logistics. To this effect, the proposed mechanism that captures the interplay and combined rotary effect of Circular Economy and Industry 4.0 for achieving sustainable supply network operations is presented in Figure 1.

Whereas a typical supply chain is a linear network of suppliers, manufacturers, markets and end-consumers, we argue here that the sustainability transition mechanism of such traditional networks may be 'motorised' by the two 'wheels' of Circular Economy and Industry 4.0. On one end, the Circular Economy 'wheel' consists of the four theme areas of analysis suggested by Srai et al. (2018), i.e., 'renewable

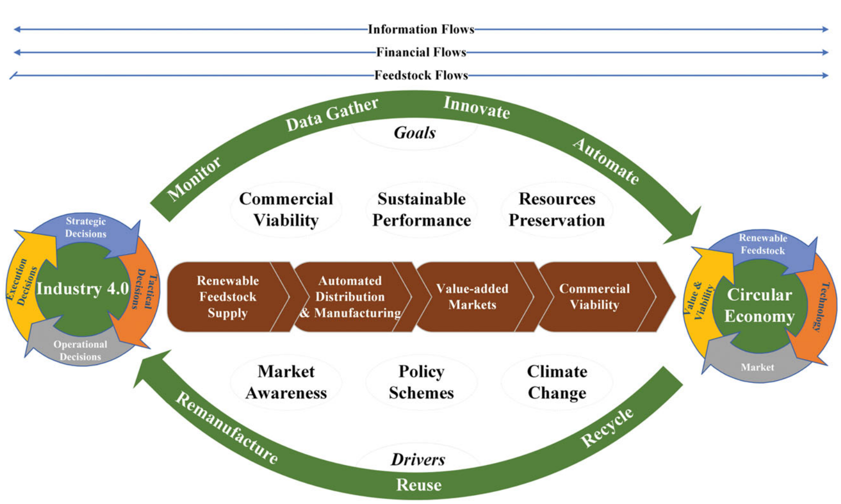

Figure 1. Framework capturing the transition towards sustainable supply networks, empowered by the interplay between Circular Economy and Industry 4.0.

feedstock – technology – market – value and viability', which is specifically attributable to supply chains enabled by renewable feedstocks. It is essential to consider the macro-level dynamics across the feedstock, technology, market, and value and viability theme areas to identify required interventions within the Circular Economy space (e.g., reuse, recycle, remanufacture). On the other end, leveraging Industry 4.0 in manufacturing systems requires a set of strategic, tactical and operational decisions (Marques et al. 2017). Furthermore, as a range of intelligent autonomous systems are able to perform a spectrum of supply chain processes, decision-making at the execution level is a key component of the Industry 4.0 'wheel' (Bechtsis et al. 2017). The rotation of the Industry 4.0 'wheel' enables data monitoring and gathering to accordingly automate operations and promote innovation from an end-to-end network perspective. Finally, the interplay between the Circular Economy and Industry 4.0 'wheels' to mobilise the transition towards sustainable supply chain operations necessitates awareness of the industrial system and how this may be influenced by internal and external drivers such as institutional trends, industrial developments and firm level strategies (Harrington and Srai 2012).

Our proposed framework differentiates itself from the roadmap proposed by de Sousa Jabbour, Jabbour, Filho, et al. (2018) in that we exemplify the synergistic effect of Circular Economy and Industry 4.0 sustainability transition powers, and we further integrate these in a supply chain context. However, both studies share the common vision of driving sustainable operations management.

3. Materials and methods

The rationale of using a mixed-methods approach is to achieve a greater understanding of complex supply chain management phenomena by combining qualitative and quantitative research evidence (Lyons, Um, and Sharifi 2020). The basic terminology and research approach relevant to this study are detailed in subsections 3.1 and 3.2, respectively.

3.1. Basic terminology

Considering that the focus of this research is the interplay between Circular Economy and Industry 4.0, it is essential to define these terms in the context in which they are employed. Thereafter, the idea of 'Circular Economy 4.0', introduced in this research, is defined.

3.1.1. Circular Economy

The Circular Economy paradigm, which has attracted interest in both political circles and in the research and practitioner literature, emphasises the application of reuse, recycle and remanufacture to manage waste, extend products' life cycle, and support economic growth (Mangla, Luthra, Mishra, et al. 2018). The European Commission posited that: '*In a circular economy the value of products and materials is maintained for as long as possible; waste and resource use are minimised, and resources are kept within the economy when a product has reached the end of its life, to be used again and again to create further value*' (EC 2015).

In this research, as the emphasis is on the circularity of renewable feedstocks, a circular supply network is defined as a chain of operations that aims to exploit naturally occurring substances, e.g., algae as a renewable feedstock, in order to derive value-added chemicals with commercial applications in diversified industries. In this bio-based context, Industry 4.0 is regarded as the set of enabling technologies for the '*… efficient utilisation of inexpensive and renewable resources for the production of target compounds*' (Zhang, Babtie, and Stephanopoulos 2012, p.360).

3.1.2. Industry 4.0

The current fourth industrial revolution discourse, propagating amongst global academic and industrial agendas, is firmly positioned within the manufacturing realm (Liao et al. 2017). Furthermore, an associated key theme is that digitalisation can promote more efficient, agile and customer-focussed industrial supply networks (Xu, Xu, and Li 2018). Hence, research and practice efforts focus on supporting the transition towards a 'smarter' manufacturing landscape which can been characterised by enhanced production responsiveness, economic viability and environmental sustainability (Wang et al. 2016). Representative proposals constituting the fourth industrial revolution often tend to be differently positioned, i.e., 'Industrie 4.0' in Germany, 'Industrial Internet' in the US, or 'Factories of the Future' in the European Union. Herein, the term 'Industry 4.0' is adopted owing to its popularity in the academic literature (Liao et al. 2017).

Despite the plethora of 'labels' attributed to Industry 4.0, according to Hofmann and Rüsch (2017), the underlining notion is common: to leverage the interplay among cyber systems, information sharing technologies, and physical systems to enable industrial value creation at product design, production, distribution, consumption and disposal levels. The multi-echelon implications of Industry 4.0 provide the potential for unravelling sustainable value creation in end-to-end industrial supply networks (Luthra and Mangla 2018).

According to Stock et al. (2018), the basic Industry 4.0 technologies include: (i) cyber-physical systems; (ii) cloud computing; and (iii) digital twins and digital shadows, where a combination of these technologies may enable sustainable development. At an operational level, this research complements this list of technologies with the assertion that sensory-driven intelligent vehicles could be used for monitoring feedstocks or executing hazardous manual tasks for evidence-based decision-making (Bechtsis et al. 2018).

3.1.3. Circular Economy 4.0

Building on the descriptions outlined in subsections 3.1.1 and 3.1.2, this research introduces the term 'Circular Economy 4.0'. In the context of our real-world demonstrator case, we propose a pertinent definition as follows:

> Circular Economy 4.0 is the design, analysis and management of circular economy-focused operations enabled by Industry 4.0

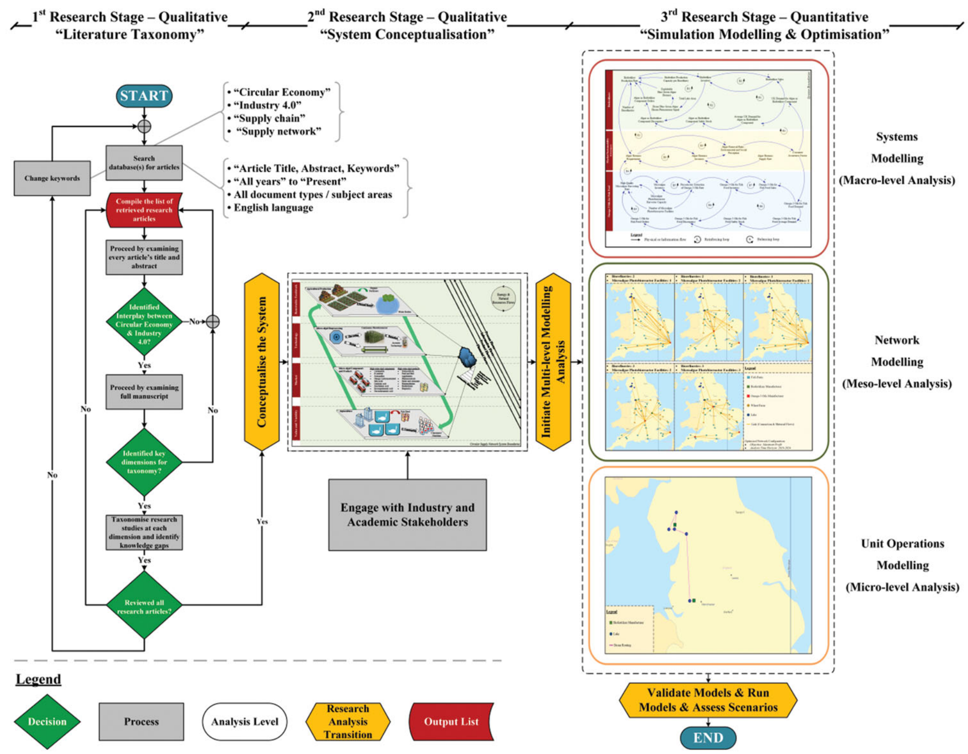

Figure 2. Research methodology flowchart.

technologies, in order to efficiently utilise renewable feedstocks for promoting sustainability and configuring value-added manufacturing networks.

3.2. Research approach

This research integrates qualitative and quantitative evidence to generate valid arguments in the Operations Management domain. In this regard, the object of scrutiny is both primary and secondary research. Specifically, three research stages were elaborated, namely: (i) literature taxonomy; (ii) system conceptualisation; and (iii) simulation modelling and optimisation. The methodology flowchart underpinning this research is depicted in Figure 2.

3.2.1. Literature taxonomy

As one of the objectives of this research is to identify a major hierarchical decision-making framework that supports the adoption of Industry 4.0 applications in configuring circular supply networks, we synthesised knowledge from the existing literature. To ensure scientific integrity, we taxonomised articles retrieved from the Scopus® and Web of Science® databases as these catalogue a broad range of peer-reviewed journals in the Natural Sciences and Engineering fields (Mongeon and Paul-Hus 2016). To identify peer-reviewed articles jointly investigating Circular Economy and Industry 4.0, we performed Boolean searches using appropriate keywords. In particular, the terms 'circular economy', 'circular' and 'industry 4.0' were searched either separately or in combination with the terms 'supply chain' and 'supply network'. We selected the 'Article Title, Abstract, Keywords' category in Scopus® and the 'Topic' category in Web of Science® while the timespan was set from 'All years' to 'Present' in both databases. The collected articles were then accepted or rejected in terms of further review based on their content. Our analysis was limited to journal articles written in English; we identified a limited number of papers written in German which were excluded from our taxonomy. Pertinent references cited in the reviewed articles were used as supplementary secondary sources.

As of the 19th of February 2020, a total of sixteen articles jointly investigating Circular Economy and Industry 4.0 were identified. Relevant studies are being published since 2017 and the increasing number of recent article publications highlights the nascent character and emerging interest in the topic. Notably, almost all the reviewed articles were published in different journals, thus indicating the novel, yet inclusive, nature of this research domain. The allocation of the reviewed publications by journal and year is summarised in Table 1.

Table 2 summarises the main elements of the reviewed literature. The vast majority of the reviewed studies are limited to a critical discussion about the opportunities, challenges and barriers associated with the joint analysis of Circular Economy and Industry 4.0. This indicates a lack of real-world case studies exploring the actual impact of the synergistic application of the two principles in the context of sustainable supply chain management. Moreover, the examined case studies are limited to very brief discussions on project intentions or pilot projects, without actually demonstrating any real-world implications. Regarding the discussed enabling technologies, these are limited to Big Data and IoT, further demonstrating that researchers conceptualise the utilisation potential of cyber-physical systems without considering technical details or functional specifications at an operational level.

Table 1. Published articles by journal and year.

	Publication Year			
Journal	2017	2018	2019	2020
Annals of Operations Research		•		
Applied Sciences		•		
Benchmarking			•	
Computers and Industrial Engineering		•		
Computers in Industry			••	
International Journal of Information Management			•	
Journal of Cleaner Production				•
Journal of Manufacturing Technology			•	
Management Decision			•	
Procedia Manufacturing	•			
Resources, Conservation and Recycling		•	•	•
Sustainability		•	•	

3.2.2. Simulation modelling and optimisation

In order to pragmatically demonstrate the interplay between Circular Economy and Industry 4.0, we applied a multi-level simulation modelling and optimisation approach. The multi-level modelling approach allows researchers to attain higher flexibility in capturing supply chain operations, depending on the level of abstraction, while contemporarily harnessing the advantages of every utilised method (Wang, Brême, and Moon 2014). In particular, the overall modelling approach was developed across three levels of analysis based on Srai et al. (2017), to investigate the enabling role of Industry 4.0 with regard to upstream and downstream circular network operations, namely: (i) macro-level analysis – modelling and simulating the market-demand dynamics and the overall behaviour of the digital-enabled circular supply system; (ii) meso-level analysis – modelling the emerging supply network structure and optimising its configuration based on economic efficiency; and (iii) micro-level analysis – optimising the routing of an autonomous agent informing the scheduling of supply chain operations. Specifically, at the micro-level, the unit of analysis was considered to be an autonomous vehicle, as opposed to a manufacturing process or plant (Srai et al. 2017). The modelling approach was developed under different Industry 4.0 technology scenarios to demonstrate the interplay between the circularity of renewable feedstocks and digital applications at different levels of analysis.

At the macro-level, the market-demand dynamics of the considered circular supply system were modelled and simulated by leveraging the System Dynamics principles. The methodology has been used to model complex systems by capturing the causalities and feedback mechanisms that determine the dynamic behaviour of industrial networks (Sterman 2000). The structural elements of System Dynamics are the causal loops and the stocks and flows that render the methodology appropriate for strategic decision-making (Tsolakis and Anthopoulos 2015). In particular, causal loops refer to directed arrows among parameters and variables of a system denoted by either a positive ('+') polarity (i.e., the effect changes accordingly to the cause – reinforcing feedback, R) or a negative ('−') polarity (i.e., the effect changes reversely to the cause – balancing feedback, B). System Dynamics is also recommended as a mapping methodology for investigating industrial network systems enabled by renewable feedstocks, and has been specifically used in the case of 'green' pharmaceuticals produced from naturally occurring or wasted terpenoid compounds (Tsolakis and Srai 2018).

At the meso-level, the configuration of the considered circular supply network is operationalised by determining production capacities and locations of manufacturing sites as well as the underpinning material flows. The simulation of a supply network's behaviour in discrete time can then inform tactical and operational decision-making (Chatfield, Harrison, and Hayya 2006). Finally, at the micro-level, the optimal routing of an unmanned aerial vehicle (also known as drone) – used to monitor the status of renewable feedstock sources – was calculated.

3.2.3. Modelling validation and verification

Modelling validation and verification are essential for simulation-based studies to ensure the reliability of the provided outputs (Swisher et al. 2001). Validation examines whether the 'right model' was formulated (Balci 1998), while verification determines whether the modeller developed the 'model right' (Banks et al. 2009).

The proposed System Dynamics simulation model was validated and verified based on tests described by Sterman (2000). In terms of validation, typical tests were applied including the logical interpretation of the attained results, the rational behaviour of the system against different sensitivity analysis scenarios, and the extreme-condition tests. All authors counter-examined the model to verify its structural consistency and avoid possible unintentional changes in the input parameters. Furthermore, the simulation component of the software tool Supply Chain Guru® was used to validate the optimal supply network designs in addition to the routing of the drone (Manataki, Chen-Burger, and Rovatsos 2014).

4. Critical taxonomy

The resulting hierarchical decision-making framework demonstrates the multi-faceted and complex nature of circular supply network operations enabled by Industry 4.0 applications. Table 3 presents a synopsis of the identified decisions along with the supporting research. A key expectation from Industry 4.0 is the higher level of material flows' monitoring across supply chains; however, at an operational level digitalisation benefits are attributed to the functional characteristics of the used equipment/machinery.

5. Real-world demonstrator case

The interplay between Circular Economy and Industry 4.0 is demonstrated using the real-world challenge of blue-green algae bloom growth in major lakes across the UK. These blooms – which can be toxic for people, animals and plants – typically develop during the spring period and only decline at the onset of winter conditions (Moorhouse et al. 2018). The main UK locations that encounter the blue-green algae issue are Windermere, Ullswater, Coniston Water, Killington Reservoir and Pennington Flash (UK Environment Agency 2018). The hazardous effect is attributed to the presence of microcystins, a family of chemically stable cyclic hepatotoxins

Table 2. Critical taxonomy of the existing literature.

Author(s)	Year	Journal	Methodology	Nature of Research	End-product	Country/Region	Enabling Technology
Belaud et al.	2019	Computers in Industry	Case study	Qualitative; Quantitative	Bioenergy; Biomaterials; Biomolecules	France	Big Data
Bressanelli et al.	2018	Sustainability	Case study	Qualitative	Household appliance retailer	Northern Europe	Big Data; IoT
Cezarino et al.	2019	Management Decision	Case study	Qualitative	N.S.	Brazil	N.S.
Daú et al.	2019	Sustainability	Observations	Qualitative	Glass building structures; Photovoltaic panels; Water	Brazil	Internet of Services; IoT
de Sousa Jabbour, Jabbour, Filho, et al.	2018	Annals of Operations Research	Critical discussion	Qualitative	N.S.	N.S.	Additive Manufacturing; Cloud Manufacturing; Cyber-physical Systems; IoT
Dev et al.	2020	Resources, Conservation and Recycling	Case study	Quantitative	Refrigerators	India	Additive Manufacturing; Cloud Computing
Garrido-Hidalgo et al.	2019	Computers in Industry	Case study	Quantitative	Desktop and laptop computers	Spain	Cloud Computing; IoT
Jensen and Remmen	2017	Procedia Manufacturing	Critical discussion	Qualitative	Automobiles; Aircrafts; Ships	N.S.	Enterprise Information Systems
Lin	2018	Computers and Industrial Engineering	Case study	Qualitative	Recycled glass	Taiwan	Big Data; IoT
Martín-Gómez et al.	2019	Resources, Conservation and Recycling	Case study	Quantitative	Urban furniture	N.S.	Big Data; Cloud Computing; Cyber-physical Systems; IoT
Nascimento et al.	2019	Journal of Manufacturing Technology Management	Interviews	Qualitative	Electrical kitchen appliances; Furniture; Plastic products; Computer hardware; Television sets	N.S.	Additive Manufacturing; Big Data; Cloud Computing
Rajput and Singh	2019	International Journal of Information Management	Review	Qualitative; Quantitative	N.S.	India	IoT; Robotic Automation
Rejikumar et al.	2019	Benchmarking	Review	Qualitative	N.S.	N.S.	Cyber-physical Systems
Tseng et al.	2018	Resources, Conservation and Recycling	Critical discussion	Qualitative	N.S.	N.S.	Big Data; IoT
Yadav et al.	2020	Journal of Cleaner Production	Case study	Quantitative	Automobiles	India	N.S.
Yang et al.	2018	Applied Sciences	Case study	Qualitative	Carburised steel shafts	Singapore	Big Data; IoT; Robotic Automation

Symbols: N.S. for 'Not Specified'; IoT for 'Internet of Things'.

Table 3. Critical taxonomy of the extant research studies.

Decision	S	T	O	References
• Adopt a life-cycle corporate thinking and suitable industrial processes	•			Belaud et al. (2019); de Sousa Jabbour, Jabbour, Filho, et al. (2018); Jensen and Remmen (2017); Nascimento et al. (2019); Yadav et al. (2020); Yang et al. (2018)
• Apply real-time monitoring systems for product status and maintenance requirements			•	Bressanelli et al. (2018); de Sousa Jabbour, Jabbour, Filho, et al. (2018); Dev, Shankar, and Qaiser (2020); Garrido-Hidalgo et al. (2019); Jensen and Remmen (2017); Rajput and Singh (2019); Rejikumar et al. (2019); Yang et al. (2018)
• Identify and assess sustainability performance indicators		•		Belaud et al. (2019); Dev, Shankar, and Qaiser (2020); Tseng et al. (2018); Yadav et al. (2020)
• Enable post-consumption tracking and tracing for exploring valuable waste feedstocks	•			Bressanelli et al. (2018); de Sousa Jabbour, Jabbour, Filho, et al. (2018); Dev, Shankar, and Qaiser (2020); Jensen and Remmen (2017); Yang et al. (2018)
• Enable product upgradability		•		Bressanelli et al. (2018)
• Establish information sharing interfaces to allow data exchange, ensure confidentiality and enable performance assessment	•			Bressanelli et al. (2018); de Sousa Jabbour, Jabbour, Filho, et al. (2018); Jensen and Remmen (2017); Tseng et al. (2018); Yang et al. (2018)
• Identify human-technology synergy	•			de Sousa Jabbour, Jabbour, Filho, et al. (2018); Rajput and Singh (2019); Rejikumar et al. (2019)
• Identify existing and required data sources, architectures and uncertainties		•		Belaud et al. (2019); Martín-Gómez, Aguayo-González, and Luque (2019)
• Identify operations to automate		•		Jensen and Remmen (2017); Nascimento et al. (2019); Rejikumar et al. (2019)
• Monitor consumer-data and assess end-user service level		•		Jensen and Remmen (2017); Lin (2018)
• Monitor production status and condition			•	Belaud et al. (2019); de Sousa Jabbour, Jabbour, Filho, et al. (2018); Yang et al. (2018)
• Monitor resources appropriation and waste generation			•	Bressanelli et al. (2018); Cezarino et al. (2021); Daú et al. (2019); de Sousa Jabbour, Jabbour, Filho, et al. (2018); Lin (2018); Nascimento et al. (2019); Rajput and Singh (2019); Tseng et al. (2018)
• Monitor suppliers		•		de Sousa Jabbour, Jabbour, Filho, et al. (2018); Jensen and Remmen (2017); Yadav et al. (2020); Yang et al. (2018)
• Monitor the flows and 'digital' life-cycle of materials and end-products		•		Cezarino et al. (2021); de Sousa Jabbour, Jabbour, Filho, et al. (2018); Jensen and Remmen (2017); Nascimento et al. (2019); Yang et al. (2018)
• Understand stakeholders' expectations over the sustainability output of circular operations enabled by Industry 4.0	•			Cezarino et al. (2021); Jensen and Remmen (2017); Lin (2018)

Symbols: S for 'Strategic'; T for 'Tactical'; O for 'Operational'.

produced by cyanobacteria (Bourne et al. 2006). At the same time, algae sludge is a rich source of organic nutrients with the associated protein content being nearly 62% of the total solids (Zhong et al. 2012); however, the commercial potential of this protein source remains unexploited. Typically, the disposal of algal sludge retrieved from inland water bodies is unstructured, further resulting in severe secondary environmental pollution (Yan et al. 2012).

To this end, the circular exploitation of algae biomass for synthesising value-added intermediates or end-products, e.g., biofertilisers and omega-3 oils as feed additives in fish farms, could promote the triple-helix of sustainability. However, the key research challenge is the lack of robust approaches that could be applied for investigating the design transformations (e.g., centralised – semi-centralised – decentralised configurations) and performance assessment of emerging circular supply systems enabled by the interplay with Industry 4.0 implementations.

Traditionally, linear supply networks exploit natural resources and utilise virgin raw material as inputs, in a 'take-make-dispose' mode of operations, with significant environmental, economic and social ramifications (Nasir et al. 2017). Figure 3 captures the parallel structure and unsustainable nature of a linear supply network system of operations for the production of conventional fertilisers and fish feed.

From a circular economy viewpoint, algal sludge constitutes a valuable renewable feedstock source for circular supply network operations to provide: (i) low-cost high-quality biofertilisers, as it is a nutrient-rich candidate for the solid-state fermentation of plant growth-promoting rhizobacteria (Zhang et al. 2014); and (ii) premium-price high-purity omega-3 oils, to be used as feed supplement in salmon fish farms, to ultimately deliver elevated levels of omega-3 long-chain fatty acids intake to humans (Shepherd, Monroig, and Tocher 2017).

Soil degradation is a major challenge for the UK agriculture with estimated annual costs ranging between £0.9 and 1.4 billion (Graves et al. 2015), which can be mainly attributed (47%) to the loss of organic carbon in the soil. In this regard, the use of inorganic fertilisers and nutrient runoff phenomena from agricultural fields to water bodies has contributed to the degradation of the high or good quality status of the UK surface water bodies from 36% in 2012 to 35% in 2017 (Joint Nature Conservation Committee 2018). For significant crops grown in the UK, like wheat which is cultivated on 1.7 million hectares (Department for Environment and Food and Rural Affairs 2018), the use of algae-based fertilisers could help replace overused volumes of chemical fertilisers and pesticides while returning carbon and nutrients to the soil. The application of algae-based biofertilisers alleviates eutrophication in water bodies due to the reduced use of nitrogen and phosphorus, while algae is further circulated as a value-added input to agricultural farms thus mitigating

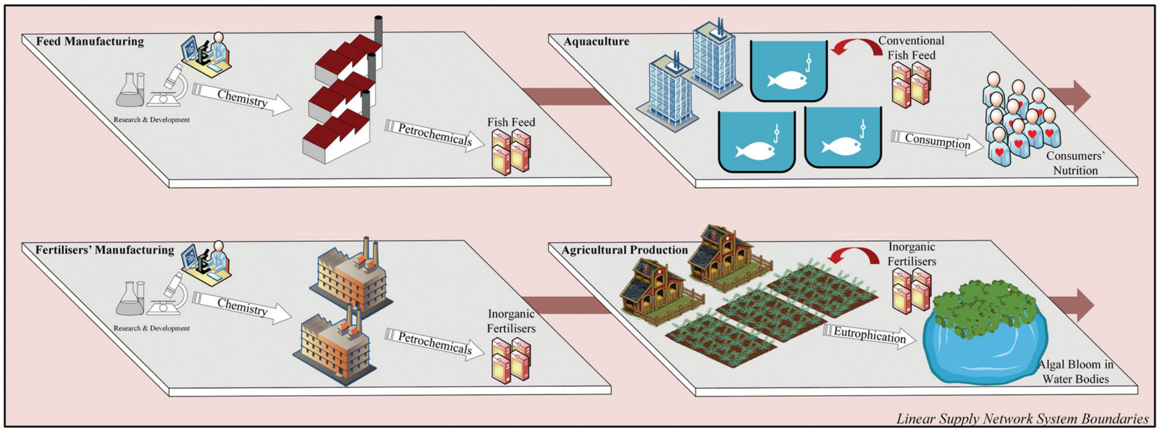

Figure 3. Linear system structure of fertilisers and fish feed supply chains.

the magnitude of the algal bloom phenomenon (Zhang et al. 2014).

In addition, the international market for omega-3 oils was valued at US$33 billion in 2016, demonstrating strong growth in recent years with a compound annual growth rate of over 14%, while projections point to a market value of US$57 billion in 2025 (Statista 2017). Algae is a fundamental source of omega-3 fatty acids (e.g., eicosapentaenoic and docosahexaenoic acids) which constitute major nutritional elements for fish and seafood used to satisfy human dietary and nutritional needs (Stiles et al. 2018). However, these long-chain acids are not available via commercial protein substitutes (e.g., soybeans, pea seeds, corn gluten). The co-production of diverse products is proven to benefit both the sustainability of algae-based platform technologies and the economics of their respective manufacturing supply networks (Soto-Sierra, Stoykova, and Nikolov 2018). Therefore, the transition towards sustainable supply chains may be empowered by the interplay between Circular Economy and Industry 4.0, as demonstrated in Figure 4. The automation hierarchy underpinning the Industry 4.0 application, towards establishing operationally efficient and sustainable value networks, was adopted by Bechtsis et al. (2018).

5.1. Case description

We consider a circular supply network system that valorises blue-green algae, collected from targeted UK lakes, into biofertilisers for wheat farms and omega-3 oils for fish feed. Along with the renewable feedstock source echelon, the stages of manufacturing and retailing/consumption are also considered. Operations at the wholesaling echelon are not captured as the wholesalers are also regarded as retailers/consumers.

From an Industry 4.0 perspective, considering the geographical area of each of the identified UK lakes along with the recursive nature, variant duration and intensity of the algal bloom phenomenon, we assumed the use of a drone as a representative digital application for monitoring the targeted surface water bodies. In this sense, drone-enabled inspection allows the real-time monitoring of algae bloom growth to timely inform the effective planning and scheduling of harvesting operations at the collocated biofertilisers manufacturing plants. Following the biofertiliser formulation, extracted high-quality microalgae strains are transported to a number of distributed manufacturing facilities equipped with indoor closed-loop photobioreactors in cylindric shape for the continuous cultivation of microalgae strains to produce high-quality health-promoting ingredients (Pankratz et al. 2017). An Industry 4.0 application in these facilities is represented by the use of piezoelectric transducers to assist microalgal cell membrane lysis for the downstream biodegradation of biomass for high-value bioactive component extraction (Struckas et al. 2017). The sensors-enabled continuous manufacturing process in the distributed micro-factories enables enhanced agility when compared with the dominant centralised batch manufacturing technology.

We assume that the required synthesis pathways for algae-based biofertilisers, along with the acoustic extraction technology of omega-3 oils from microalgae, are applied at an industrial-scale level. Regulations about the safe exploitation of blue-green algae for biofertilisers and omega-3 oils for feed are also assumed to be flexible, in a similar fashion to end-to-end digital demonstrators (facilitated by pre-competitive consortia in the pharmaceuticals sector) that are not constrained by current regulations (Harrington, Joglekar, and Srai 2018). The system and network model descriptions are detailed in Appendix I.

5.2. Model development

Model development at the macro-, meso- and micro-levels is underpinned by the same secondary data. However, the structure of the models along with the elaborated data are different, considering the nature of the simulation modelling approaches performed at each level of analysis.

The intense algal bloom phenomenon in the identified lakes can generally be considered to be seasonal, appearing from June to September on an annual basis (Binding et al. 2018). The area of the five targeted water bodies in the UK, which were severally affected by possibly toxic algal blooms in the summer of 2018 (Pinkstone 2018), were: (i) Windermere, area: 1,473 ha; (ii) Ullswater, area: 890 ha; (iii)

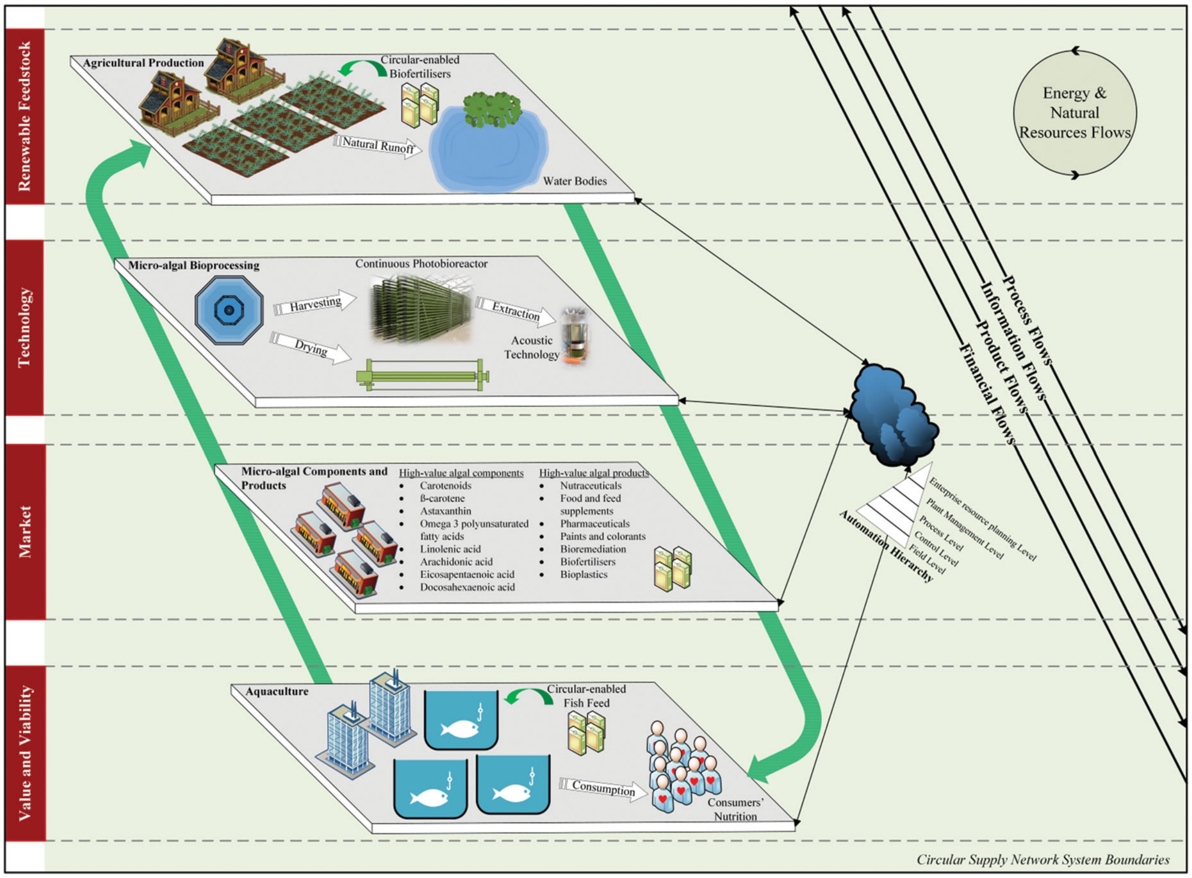

Figure 4. Circular system structure of biofertilisers and omega-3 oils for fish feed supply networks enabled by Industry 4.0.

Coniston Water, area: 470 ha; (iv) Killington Reservoir, area: 57 ha; and (v) Pennington Flash, area: 70 ha. We considered that the algal sludge was accumulated over the total lake surface area of 2,960 ha. As drones can inform in real-time about the progression of the blue-green algal bloom phenomenon, we incorporated a function capturing the delay of the transmitted information to commence circular supply chain operations with a smoothing factor equal to 1/30 (i.e., the delay in receiving the information is equal to a day). We assume that – on average – 60% of the collected blue-green algae biomass is exploitable due to physico-chemical specifications. The natural drying period of the collected blue-green algae biomass, to reduce moisture content, was assumed 7 days (Hu et al. 2013). The average algae biomass extraction rate was selected to be 7.7 kg/ha (Branigan 2008) with a volatile matter factor of 70.13% (Hu et al. 2013).

Furthermore, we assumed that the collected algae biomass from the lakes is transported to nearby manufacturing plants for the production of biofertilisers, a high-volume and low-value product; according to Tripathi et al. (2008), microalgae inoculants in biofertilisers replace about 25–30% of standard nitrogen content. We assumed an annual biofertilisers production capacity per plant of 18 tonnes, with a typical utilisation rate of 80%. We further considered that the demand for nitrogen (as a fertiliser nutrient) in the UK was 1,026 thousand tonnes in 2015/2016, with an average growth rate of 2.3% during the last decade (AIC Statistics 2017). The share of biofertilisers in the total nitrogen-based fertilisers market accounts for about 10% (Bio-FIT 2017). We also consider a safety stock period for the manufactured biofertilisers of 2 months.

During biofertilisers production, high-quality microalgae strains are isolated, collected and transported to a network of distributed digital micro-factories enabled by indoor multi photo-stage photobioreactors for the continuous, industrial scale cultivation of the selected microalgae strains. The microalgae cultivation is followed by the continuous extraction of omega-3 oils for fish feed, a low-volume and high-value product. Specifically, we assumed a photobioreactor capacity of 10,000 L and a maximum microalgae growth rate of 0.52 g/L (Concas et al. 2016). Sets of novel piezoelectric transducers, leveraging acoustic energy fields, are used for harvesting and extracting intracellular lipid content from microalgae biomass. In particular, the accumulation ratio of the extracted omega-3 oils was assumed to be 25% (Concas et al. 2016). As in the case of biofertilisers, the safety stock period for omega-3 oils for fish feed was assumed to be 2 months.

Finally, biofertilisers were assumed to be transported to wheat farms while the extracted omega-3 oils towards fish farms to be used as an additive to the feed. The omega-3 oils market demand was considered as a sigmoid function of consumers' sustainability awareness towards the blue-green algae removal (see Appendix I), with further feed supply and financial implications. Indicatively, the average UK fish meal imports during the period 2010–2014 were 71.1 thousand tonnes (Marine Management Organisation 2015).

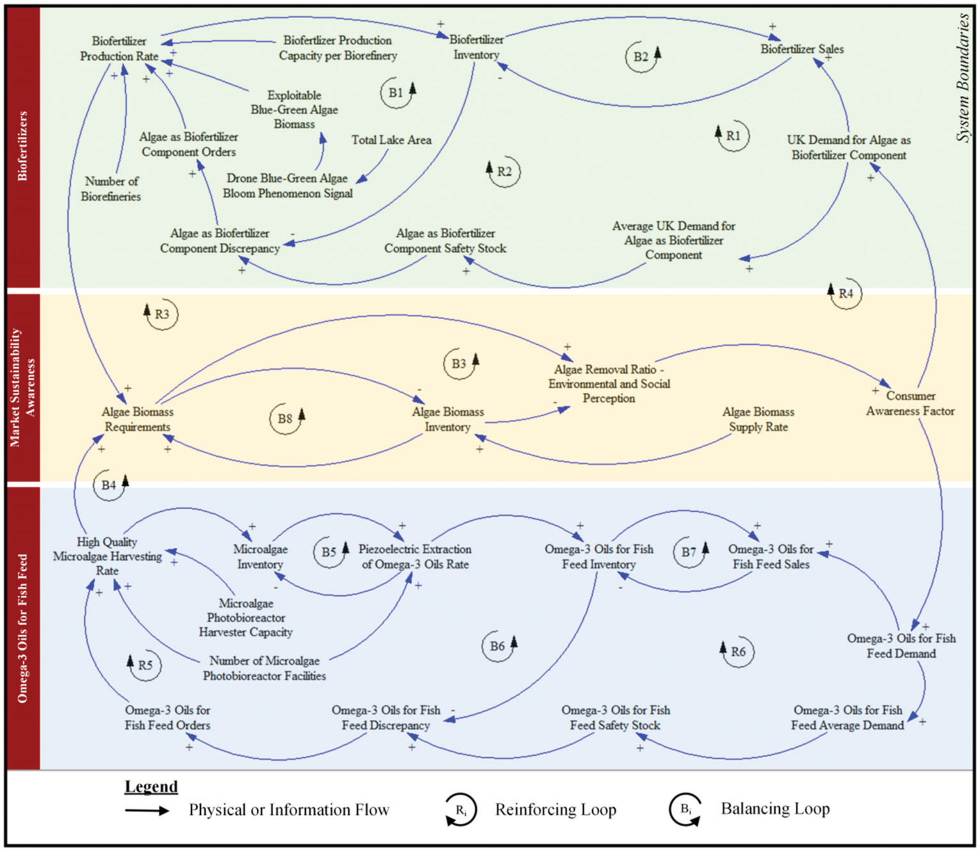

Figure 5. Causal loop diagram of the algae-based circular supply network system enabled by digital technologies.

A total of ten (10) alternative modelling scenarios were explored to investigate the interplay between Circular Economy and Industry 4.0 by considering the following parameters:

- Number of Biorefineries, for the manufacturing of biofertilisers – two (2) or three (3).
- Number of micro-factories, i.e., Microalgae Photobioreactor Facilities, for the microalgae harvesting and extraction of omega-3 oils – one (1) or two (2).
- Omega-3 Oils Extraction Time – a working day (1/26) for the piezoelectric-based digital-enabled continuous manufacturing technology or three working months (78/26) for a conventional batch manufacturing technology.

5.2.1. System modelling (macro-level)

The circular supply network's system complexity and non-linear behaviour are captured via fourteen (14) feedback loops. In particular, six (6) reinforcing and eight (8) balancing loops define the behaviour of the system, as specified in Table A1 in Appendix II. The causal loop diagram of the system under study is illustrated in Figure 5. The development of the causal loop diagram was based on literature evidence and was verified though our engagement with chemical engineers, technology providers, entrepreneurs and supply chain experts involved in the acknowledged research project. A detailed analysis of the development phase of the causal loop diagram extends the scope of this research.

The System Dynamics approach involves the transformation of the developed causal loop diagram into a dynamic simulation model. The structural elements of the model include stock variables (represented by rectangles), flow variables (represented by valves), time delays (represented by marked lines), auxiliary variables (represented by circles), and constants (represented by diamonds). The continuous nature of the simulation is attributed to the integral equations underpinning the structure of the model to express the accumulation of flow variables in stocks.

The System Dynamics simulation model was developed using the Powersim® Studio 10 Academic software package. We set a strategic time horizon of five years while we selected a time step of a month. Table A2 in Appendix II summarises the mathematical formulation that justifies the System Dynamics simulation model. The stock and flow diagram of the circular supply network system under study is depicted in Figure 6.

5.2.2. Network and unit operations modelling (meso- and micro-levels)

The network simulation model was formulated, optimised, analysed and visualised using Llamasoft Supply Chain Guru®, a software tool that requires understanding over the required data inputs and user interface. The advantages of the tool specifically apply in the optimisation capabilities (Bassett 2018).

The fundamental elements of the developed network simulation model include: (i) products – five (i.e., surface

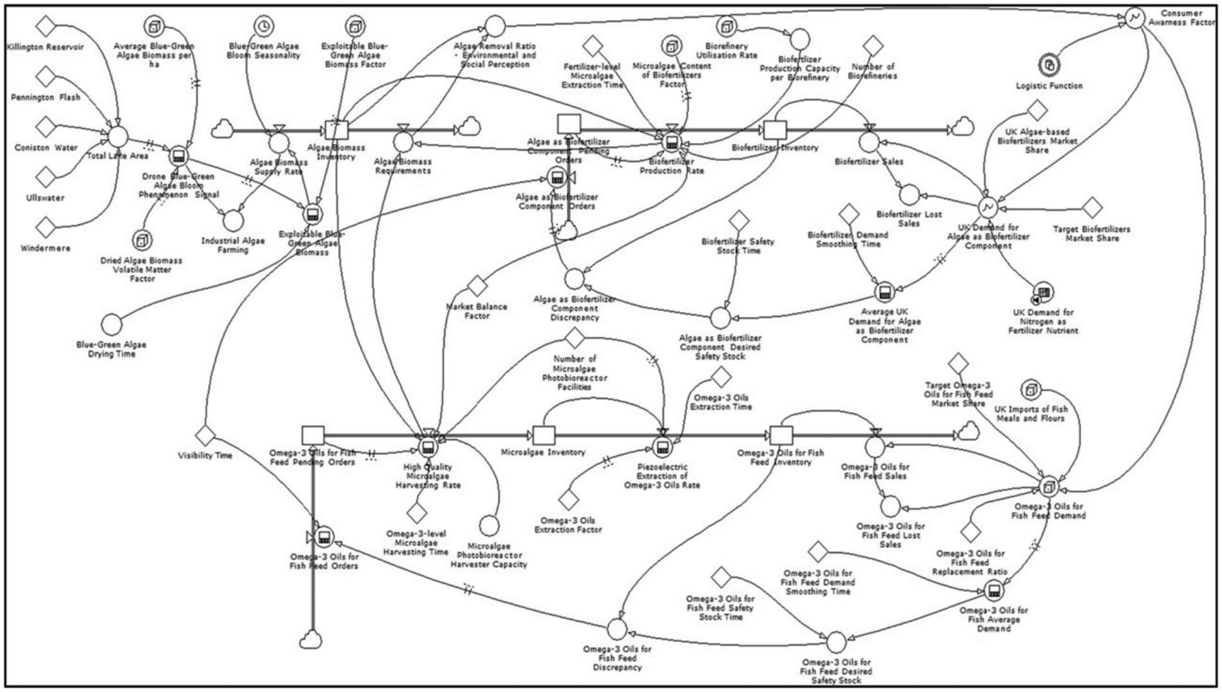

Figure 6. Stock and flow diagram of the algae-based circular supply network system enabled by digital technologies.

wastewater; algae biomass for biofertilisers; microalgae biomass for omega-3 oils; omega-3 oils for fish feed; biofertiliser); (ii) supply, manufacturing and retail/consumption sites – variable number depending on the scenario (i.e., five lakes; two or three biofertilisers production plants; one or two omega-3 oils production plants; nine wheat farms; twenty-five fish farms); (iii) demand in wheat and fish farms; (iv) sourcing policies; (v) transportation policies; and (vi) inventory policies. The coordinates of the biofertilisers and omega-3 oils manufacturing plants were generated by leveraging the principles of the centre of gravity method applied to the location of the considered UK lakes and wheat and fish farms, respectively. The coordinates of actual wheat and fish farms were retrieved from secondary sources.

6. Results and discussion

In this section, we first summarise the findings of the critical taxonomy and propose a hierarchical decision-making process framework. We then insert the simulation modelling and optimisation results in terms of the examined real-world case.

6.1. Decision-making process

The hierarchical decision-making process clearly depicts the multi-dimensional, yet unexplored, domain of circular supply chains enabled by Industry 4.0. Specifically, at a strategic level, it is vital that a vision and industrial/corporate expectations of Industry 4.0 applications are set in terms of the circularity of wasted/discarded products and renewable materials at the post-consumption stage. In addition, interfaces that enable the synergy between the human element and technology is essential to ensure a high adoption rate of Industry 4.0 in operations.

At tactical and operational levels, extant studies reveal that the monitoring of product-related data across circular supply chains dominates the related decisions. In addition, leveraging existing databases and real-time monitoring of material- and product-centric data, particularly at the supply and consumption echelons, are considered key to the establishment of circular operations in terms of scheduling and quality assurance. To this effect, the involved supply chain stakeholders should mainly agree on the operations to automate and on the structure of the relevant data to be gathered. Table 4 presents a synopsis of the resulting hierarchical decision-making process.

6.2. Modelling methodology

We conducted 1,000 simulation runs and network optimisation per each scenario to derive robust results, as summarised in Table A3 in Appendix II.

6.2.1. System modelling (macro-level)

Evidently, the different scenarios do not appear to have any impact on the inventory position of biofertilisers and omega-3 oils from month 0 to month 6 due to the seasonal appearance of the algal bloom phenomenon. Therefore, the developed model during this initial simulation period resulted in expected behaviour (i.e., zero values) as we did not consider any initial inventory of algae biomass and due to the modelled information and production time delays.

Figure 7 illustrates the dynamic behaviour of the system in terms of '*Biofertiliser Inventory*'. The use of two manufacturing plants results in a stable biofertiliser inventory of

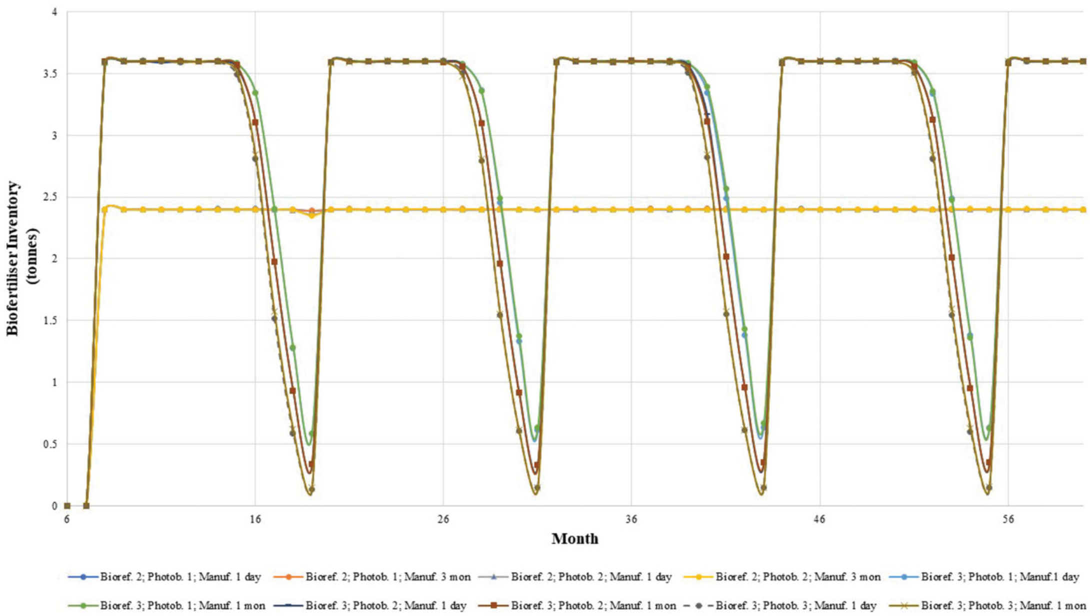

Figure 7. Dynamic behaviour of biofertiliser inventory.

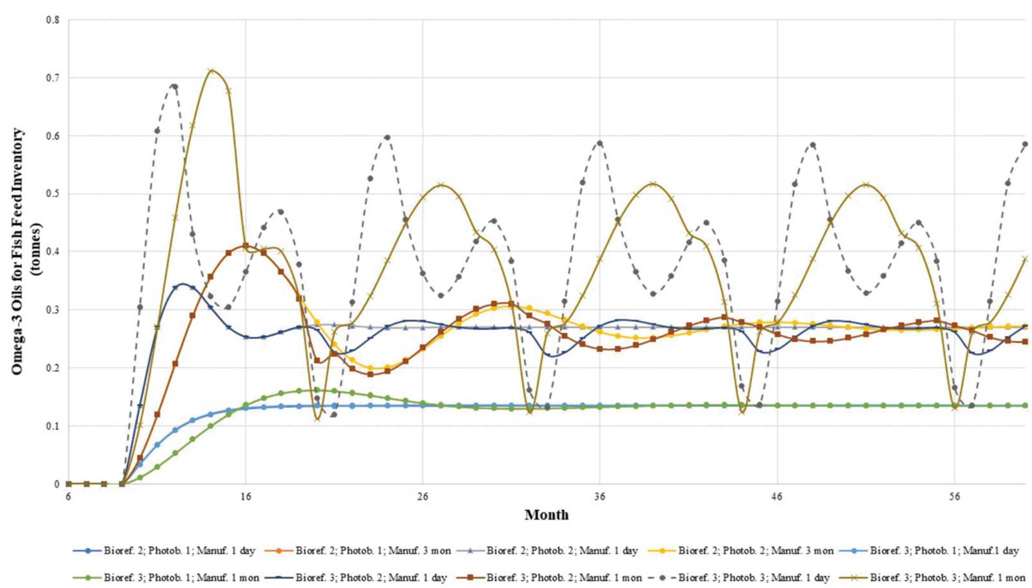

Figure 8. Dynamic behaviour of omega-3 oils for fish feed inventory.

about 2.5 tonnes throughout the analysis time horizon. However, due to the prevalence of the reinforcing feedback mechanisms, enabling a third facility leads to significant fluctuations but with lower average inventory during the time horizon of analysis. The production lead time seems to have a negligible effect on the inventory. For high-volume low-value products, like biofertlisers, digital manufacturing does not appear to offer compelling benefits as scale of production appears to be more preferable.

Furthermore, Figure 8 demonstrates the dynamic behaviour of the system in terms of '*Omega-3 Oils for Fish Feed Inventory*'. When one or two digital enabled micro-factories are utilised, with a corresponding number of photobioreactors and piezoelectric transducer equipment, the inventory for omega-3 oils reaches an equilibrium in time, thus facilitating the planning and scheduling of supply network operations. Logically, considering the system under study, the use of two micro-factories raises the omega-3 oils inventory position compared to the use of merely one facility. This stability in inventory is preferable to facilitate the transition towards circular supply networks, probe the market, and demonstrate the feasibility of the emerging manufacturing paradigm.

Markedly, the utilisation of a third production facility causes significant fluctuations in the resulting inventory, a case that is typically not preferable in manufacturing operations. However, as Industry 4.0-enabled supply network operations aim to balance demand and supply, such fluctuations are legitimate and in a future distributed manufacturing landscape would require the appropriate infrastructure to

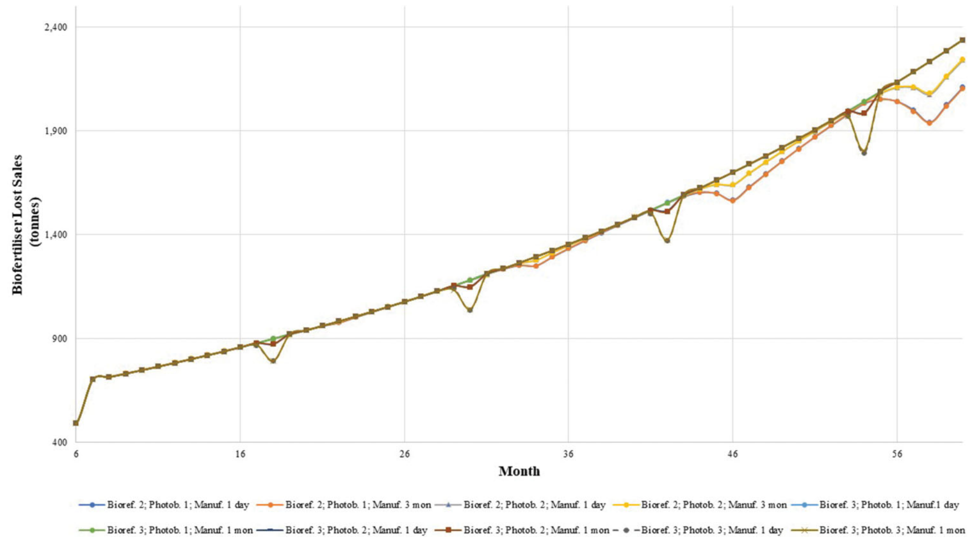

Figure 9. Dynamic behaviour of biofertiliser lost sales.

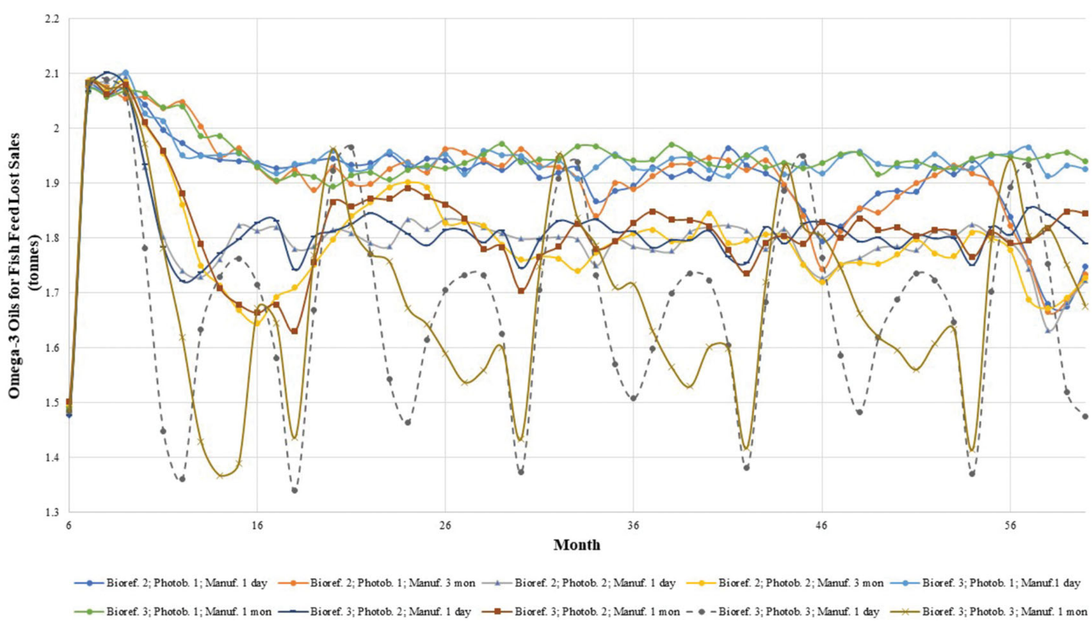

Figure 10. Dynamic behaviour of omega-3 oils for fish feed lost sales.

manage. Furthermore, the lead time for the production of omega-3 oils only slightly appears to affect the inventory development time by about two or three months. From a circular supply network design perspective, low-volume high-value products like omega-3 oils can benefit from digital and continuous manufacturing by enabling distributed production near to markets and via allowing flexible production and inventory control, based on the demand patterns and availability of the renewable feedstock. Digital technologies allow the just-in-time response to demand while contemporarily adjusting production intensity to minimise inventory costs.

Additionally, Figure 9 presents the dynamic behaviour of the system in terms of '*Biofertilizer Lost Sales*'. The increased demand for biofertilisers leads to the same trend in lost sales for all scenarios. Utilising digital-enabled large-scale manufacturing facilities for such high-volume products, particularly considering the seasonality of crops and associated needs for fertilisers, requires significant continuous manufacturing capacity in the future.

Moreover, Figure 10 depicts the dynamic behaviour of the system in terms of '*Omega-3 Oils for Fish Feed Lost Sales*'. The implementation of three production facilities reduces lost sales with the greater lead time smoothing the observed fluctuations. From a supply network design perspective, low-volume high-value products might imply the use of multiple digital micro-factories to limit lost sales and outperform operating costs through sales and profits (Grima et al. 2003). The fluctuations in lost sales further reflect the seasonal availability of algal blooms, which are considered the renewable feedstock source. In terms of the impact of 'green' market behaviour of environmentally sensitive consumers, the initialisation of the Circular Economy 4.0 operations triggers the environmental sensitivity of the market thus abruptly

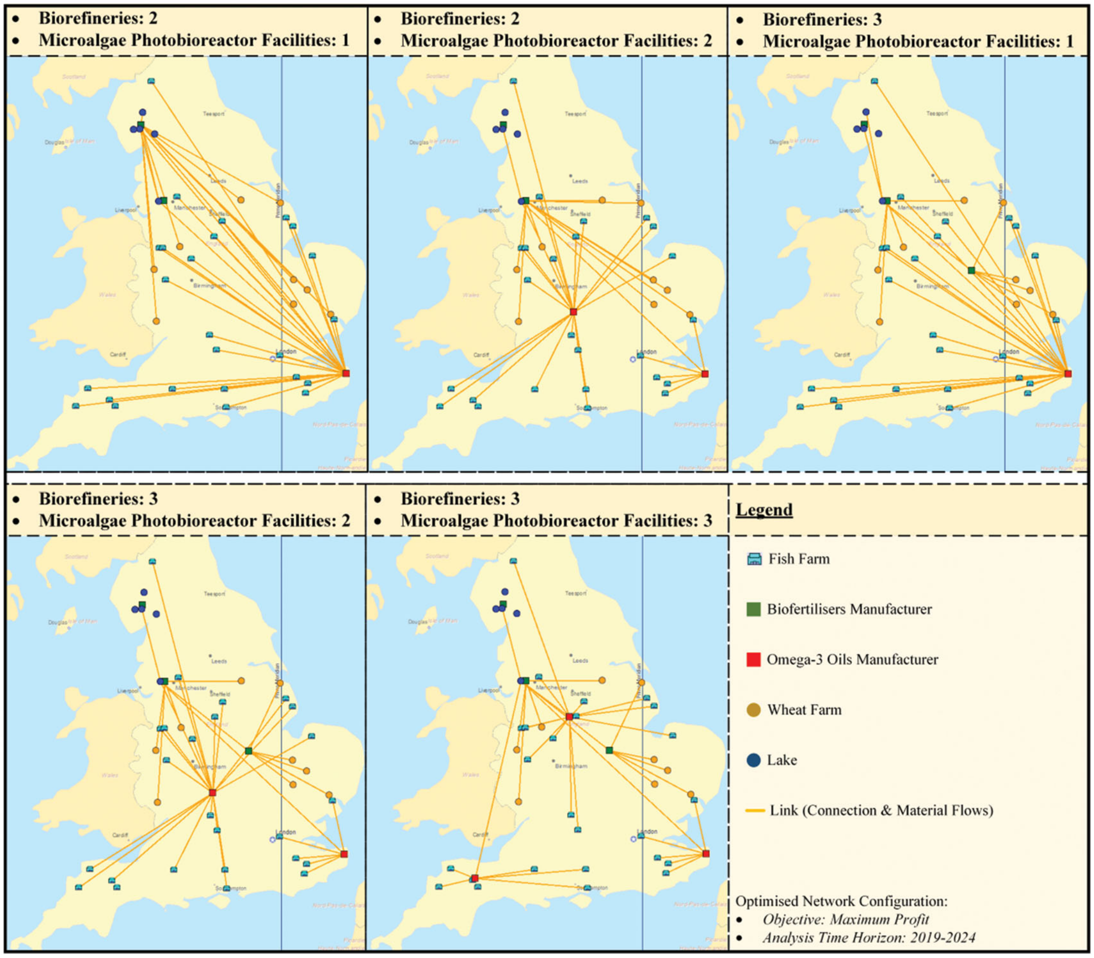

Figure 11. Optimised circular supply network configuration by digital scenario.

increasing demand and subsequent lost sales, subject to the considered capacity constraints.

6.2.2. Network and unit operations modelling (meso- and micro-levels)

The optimised network configurations for the examined scenarios, objective function (maximise profit) and time horizon (5-year period) are illustrated in Figure 11. The optimised network configurations demonstrate the balance needed between the availability of renewable feedstock, number of manufacturing facilities, and transportation requirements.

On the one hand, in the first scenario (i.e., 'Biorefineries: 2; Microalgae Photobioreactor Facilities: 1') most markets are remote, hence requiring intensive distribution operations. The use of a few large-scale manufacturing facilities typically increases lead time to markets along with requirements for transportation assets and associated costs. Such a centralised configuration serves standardised products that are manufactured in batches and are typically of low value. On the other hand, in the last scenario (i.e., 'Biorefineries: 3; Microalgae Photobioreactor Facilities: 3') manufacturing facilities are distributed and located closer to markets, thus requiring less transportation but more capital expenditure that needs to be balanced by meticulously planning the installed production capacity. Such a decentralised configuration is appropriate for high-value products that could be manufactured in a continuous mode and might require customised/personalised attributes. Additionally, in the last scenario (i.e., 'Biorefineries: 3; Microalgae Photobioreactor Facilities: 3') the increased production capacity reduces the '*Microalgae Biomass for Omega-3 Oils*' inventory by more than 90%, hence eliminating inventory costs.

Digitalisation is appropriate for enabling decentralised and distributed manufacturing for serving high-value markets and providing enhanced customisation/personalisation. Considering the use of renewable feedstocks and the possible degradation of its physico-chemical properties, primary processing facilities should be placed adjacent to the feedstock supply sources. This affinity further provides the circular supply network with resilience and flexibility to respond to both supply and demand fluctuations.

Finally, the optimised routing of the drone for signalling the initialisation of manufacturing operations, from the biofertilisers manufacturing sites to the targeted lakes, is presented in Figure 12. The routing of the drone assists in monitoring the availability of the renewable feedstock, hence informing manufacturing operations by adjusting production scheduling and rates accordingly. This interplay between Circular Economy and Industry 4.0 enables the design and management of manufacturing supply network operations from the feedstock perspective (Srai et al. 2018).

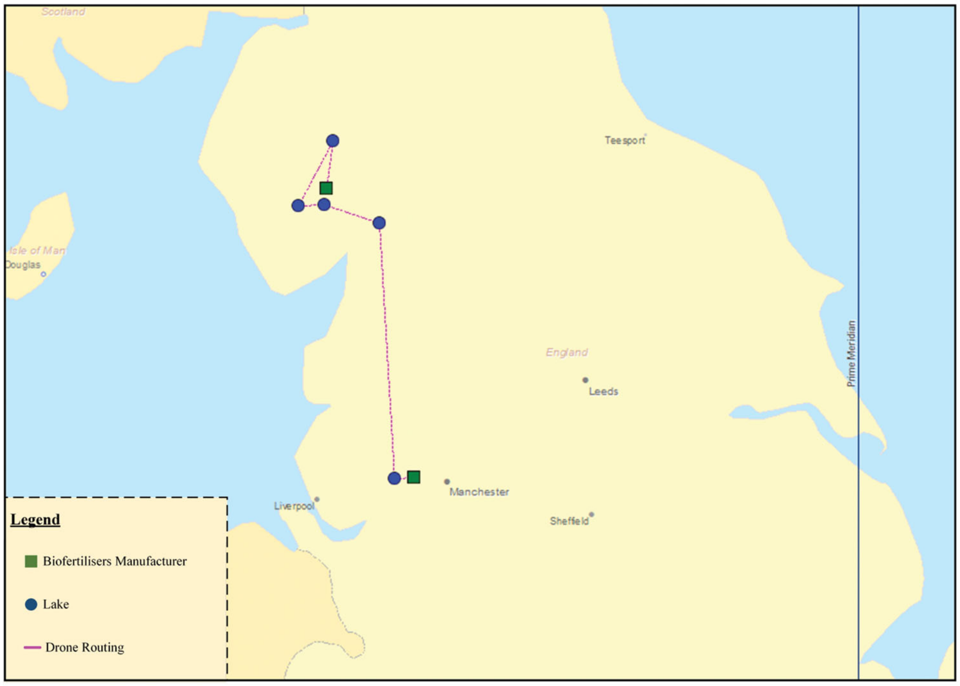

Figure 12. Drone routing for renewable feedstock monitoring.

Table 4. Hierarchical decision-making framework.

Strategic decisions
- Adopt a life-cycle corporate thinking and suitable industrial processes
- Establish information sharing interfaces to allow data exchange, ensure confidentiality and enable performance assessment
- Enable post-consumption tracking and tracing for exploring valuable waste feedstocks
- Identify human-technology synergy
- Understand stakeholders' expectations over the sustainability output of circular operations enabled by Industry 4.0

Tactical and operational decisions
- Monitor the flows and 'digital' life-cycle of materials and end-products
- Monitor consumer-data and assess end-user service level
- Monitor suppliers
- Identify and assess sustainability performance indicators
- Identify existing and required data sources, architectures and uncertainties
- Identify operations to automate
- Enable product upgradability
- Monitor production status and condition
- Monitor resources appropriation and waste generation
- Apply real-time monitoring systems for product status and maintenance requirements

6.3. Digital-enabled circular supply network design principles

The findings of this research, enabled through a mixed-methods approach, led to the articulation of four principles on the design of circular supply networks enabled by Industry 4.0 applications, as summarised in Table 5. In a Circular Economy context, Industry 4.0 applications can impact the configurational design of the respective supply chains, e.g., centralised – semi-centralised – decentralised, particularly in terms of the utilised feedstock valorisation and intermediate/end-products manufacturing sites, and manufacturing throughput time. The operational ramifications of the emerging configurational designs are mainly associated with transportation distance, inventory position per site, and lost sales.

7. Conclusions

The interplay between Circular Economy and Industry 4.0 triggers the emergence of unique types of digital supply network configurational designs which could be characterised by decentralisation, enhanced resources' utilisation efficiency, and market responsiveness. However, current perspectives in this emerging research domain – we refer to this space as 'Circular Economy 4.0' – are limited and largely descriptive. As a consequence, these are also limited in terms of practical relevance. To this end, this research studied the interplay between circular supply chains and Industry 4.0, proposing: (i) a framework capturing the interplay between Circular Economy and Industry 4.0 towards sustainable supply chains; (ii) an inclusive hierarchical decision-making process applicable to all stakeholders involved in the design and management of digital-enabled circular networks; and (iii) a multi-level simulation modelling and optimisation approach for the configuration and performance assessment of circular supply systems enabled by Industry 4.0 technologies.

Exploring key gaps and themes in the academic and practice literature led to the formulation of three questions of research interest. In approaching RQ#1, a framework was developed that captures the interplay between Circular Economy and Industry 4.0 concepts via a synthesis of pertinent research evidence. In terms of RQ#2, a critical taxonomy of the extant literature was conducted that resulted in an integrated hierarchical decision-support process for the design and management of digital-enabled sustainable supply network operations. In terms of RQ#3, a multi-level simulation modelling and optimisation approach was applied that investigated alternative network designs in the context of integrating circularity of materials, operations efficiency, product quality and customer satisfaction.

Table 5. Design principles on circular supply networks enabled by Industry 4.0 applications.

Network Design Principle		Industry 4.0 Technology	Circular Economy and Industry 4.0 Interplay Evidence
#1	In circular supply networks enabled by Industry 4.0 technologies, a decoupling point on the configurational design between upstream and downstream echelons of operations should exist.	Micro-factories & Piezoelectric Transducers for Continuous Processing	• Macro-level (i.e., system) simulation of the circular supply network system with regard to inventory and lost sales (for both biofertilisers and omega-3 oils for fish feed) demonstrates that feedstock valorisation should be decentralised, close to the material sources, while intermediate or end-products manufacturing should be semi-centralised, adjacent to clusters of markets to enable short lead times and customer centricity.
#2	In fully decentralised circular supply chains enabled by Industry 4.0 processing technologies, the manufacturing throughput time greatly affects downstream inventory and lost sales.	Piezoelectric Transducers for Continuous Processing	• Macro-level (i.e., system) simulation of the circular supply network system with regard to inventory and lost sales (for both biofertilisers and omega-3 oils for fish feed) indicates that continuous manufacturing (i.e., short manufacturing throughput time) creates large fluctuations in terms of inventory and lost sales for the same degree of decentralisation in a given network design.
#3	Circular supply networks enabled by digital manufacturing technologies and processes need to pursue a semi-centralised configuration, depending on constraints in: (i) feedstock supply; (ii) production capacity; and (iii) market demand.	Micro-factories & Piezoelectric Transducers for Continuous Processing	• Meso-level (i.e., network) optimisation depicts the benefits of semi-centralised designs (dependent on operational constraints) with regard to: (i) balanced distance from feedstock supply and intermediate or end-products demand sites; (ii) stable inventory level per manufacturing site; and (iii) stable lost sales.
#4	Monitoring the renewable feedstock supply to ensure availability and quality is essential for the scheduling of downstream operations in circular networks.	Intelligent Autonomous Vehicles	• Literature taxonomy supports the need to monitor the availability of renewable materials, both in terms of natural or processing output supply and waste generation in circular manufacturing operations enabled by Industry 4.0 applications. • Unit operations (i.e., drone equipped with sensors) routing optimisation over the targeted feedstock sources indicates the benefits of monitoring the progression of natural phenomena and signal the timely initiation of sustainable manufacturing operations.

7.1. Theoretical contributions

This research demonstrates that to realise the interplay between Circular Economy and Industry 4.0 within a supply chain context, the incorporation of selected digital technologies is required at network and unit operations levels to enable system integration, collaboration and resource productivity. This aligns with the theoretical findings of Fatorachian and Kazemi (2018). Specifically, this research proposed a research framework that captures the interplay between Circular Economy and Industry 4.0 towards sustainable supply chains. Furthermore, this study provided a critical taxonomy of the extant literature; the taxonomy findings confirmed the observation of Tseng et al. (2018) who stressed the limited number of peer-reviewed scientific publications investigating the interplay between Circular Economy and Industry 4.0. In addition, this research applied a multi-level simulation modelling and optimisation approach to demonstrate the implications of renewable feedstocks in the design of circular supply networks via investigating a real-world case. Therefore, this research contributes to the second stage of the roadmap developed by de Sousa Jabbour, Jabbour, Filho, et al. (2018) in terms of providing a methodological approach to assess Industry 4.0 technologies within a Circular Economy context so as to inform decisions valid to sustainable operations management.

Theoretical and modelling outputs of this research could be used to address the performance assessment challenge that governs sustainable supply networks (Bhattacharya et al. 2014). Furthermore, the decision-making approach outlined in this research can be used to differentiate pre-/post-implementation criteria to enable evaluation and re-evaluation phases, e.g., linking theoretical performance of solutions in the design stage with real-world performance in post-implementation stages for use cases. The richness of data demonstrated here may enable more informed correlations and, therefore, improvements in quality of evaluation criteria in Circular Economy solution designs.

7.2. Managerial and social implications

Based on our discussions with key stakeholders (i.e., industrialists, policy-makers, entrepreneurs and academics), we argue that many Circular Economy 4.0-type operational initiatives will fail to proceed to the implementation stage because the supply network benefits accruing may not be effectively (or correctly) evaluated from an end-to-end perspective. Hence, a key goal is that the proposed decision-making approach developed here be utilised by managers to obtain better estimates on end-to-end system performance for promising circular supply network designs enabled by Industry 4.0 implementations. In summary, this research provides practical guidance for organisations on Circular Economy 4.0 principles that can be used in designing their next-generation 'digitalised' supply networks. Through a conceptual framework development and its application using a real-world demonstrator, this study contributes in a number of ways, for example:

- While previous studies and modelling efforts have largely focussed at production and plant levels, they often lack a formal end-to-end network assessment. This research now provides industrialists with a better understanding of the various challenges/barriers for the successful transition to the circular economy era, from digital supply network design and configuration perspectives.
- From a managerial perspective, this research demonstrates an indicative Industry 4.0 operational structure within a Circular Economy context. Here, outputs from implementation of the in-depth demonstrator case provide valuable supporting decision-making evidence in terms of business context/viability, social impact, and supply network (re)configuration opportunities. Furthermore, this enables supply network designers and technology developers/providers to better understand alternative scenarios from a societal needs and end-to-end supply network perspectives, and to then pursue appropriate business models.
- As well as enabling operations managers to evaluate performance implications of alternative service offerings – driven by the adoption of the 'Circular Economy 4.0' principles – the applied multi-level modelling approach can be utilised to provide differentiation between pre-/post-implementation criteria as per Section 7.1. This decision-making capability enables evaluation and re-evaluation at different stages, i.e., linking performance of a solution in the design stage, with real-world performance in post-implementation stages of an initiative.
- In enabling this correlation at various stages, the applied multi-level modelling approach may be used as an investigational tool through use of its strategic, operational and tactical decision-making variables. As well as promoting evaluation quality in design and redesign stages, the proposed design principles provide managers with a basis for future benchmarking of network activities enabled by Industry 4.0 applications. Here, current state configurations may be evaluated against future desired state(s) in terms of, e.g., resource utilisation and market dynamics.

7.3. Limitations

This research may serve as a starting point for informing supply network designers, technology developers, manufacturers and service providers in their development of the next generation of sustainable supply networks (i.e., flexible, agile, adaptive and efficient). However, in short, there are two primary limitations to this study. First, the determinants of successful transition in Circular Economy-Industry 4.0 network contexts were explored through the use of one case study. Hence, additional validation with a more extensive set of 'Circular Economy 4.0'-specific cases would be beneficial. Secondly, this research did not focus on the exhaustive quantification of all the Industry 4.0 related challenges, as suggested by Luthra and Mangla (2018); however, this presents extensive and interesting opportunities for future research. Specifically, this quantification will serve to inform selection criteria in identifying follow-on studies, e.g., in targeting cases around digitalisation, personalisation, and localisation (as per Kumar et al. 2020).

7.4. Future research

In the future, with reference to the United Nations Sustainable Development Goals (e.g., Sustainable Development Goal 6 – 'Clean Water and Sanitation'), we envisage the development of models leveraging the interplay between Circular Economy and Industry 4.0 to provide insights to policy-makers and entrepreneurs on the valorisation of wasted renewable feedstocks (Mangla, Bhattacharya, and Luthra 2018). Particularly, in order to increase the generalisability of our research, we aim to expand our modelling focus to the case of terpenes, a class of naturally occurring chemical compounds with unexplored potential for the fine chemicals industry, through leveraging extant efforts on mapping the sector (Tsolakis et al. 2019). In addition, future studies will examine social (e.g., ecological health) as well as economic impacts and how digital technologies and societal needs may influence future operating philosophies.

Moreover, we aim to explore policies that may facilitate a region's ability to adapt and transition towards a 'Circular Economy 4.0' context. In an industrial context, we expect to inform distributed manufacturing strategies (Kumar et al. 2020) so firms leverage existing renewable feedstocks, available as untreated/unexploited waste in particular sectors, to establish circular supply network operations in other value-added fields.

Disclosure statement

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Appendix I.

System and network description

System modelling (Macro-level)

The '*Total Lake Area*' of the water bodies defines the '*Algae Biomass Supply Rate*', under the assumptions of stable algae growth rate and seasonality of the blue-green algae bloom phenomenon. An inspection drone transmits a '*Drone Blue-Green Algae Bloom Phenomenon Signal*' that informs both the growth of the phenomenon and the initiation of circular supply network operations. The accumulated '*Algae Biomass Inventory*' then provides the volumes of renewable feedstock.

On one end, the '*Biofertilizer Production Rate*' is dictated by the '*Number of Biorefineries*' and the '*Biofertilizer Production Capacity per Biorefinery*'. '*Biofertilizer Sales*' are defined by the '*Biofertilizer Inventory*' and the '*UK Demand for Algae as Biofertilizer Component*' which is further dictated by the '*Consumer Awareness Factor*'. The '*Consumer Awareness Factor*' is affected by the '*Algae Removal Ratio – Environmental and Social Perception*' of the consumers about the removal efficiency of blue-green algae from the considered water bodies and expresses the ratio of '*Algae Biomass Requirements*' to '*Algae Biomass Inventory*'. This perception is inspired by Mangla, Luthra, Rich, et al. (2018), who recognised consumers' awareness as an enabler of sustainability, and is mathematically captured via the Green Image Factor function used by Aivazidou et al. (2018). The '*Consumer Awareness Factor*' is expressed as an S-curve

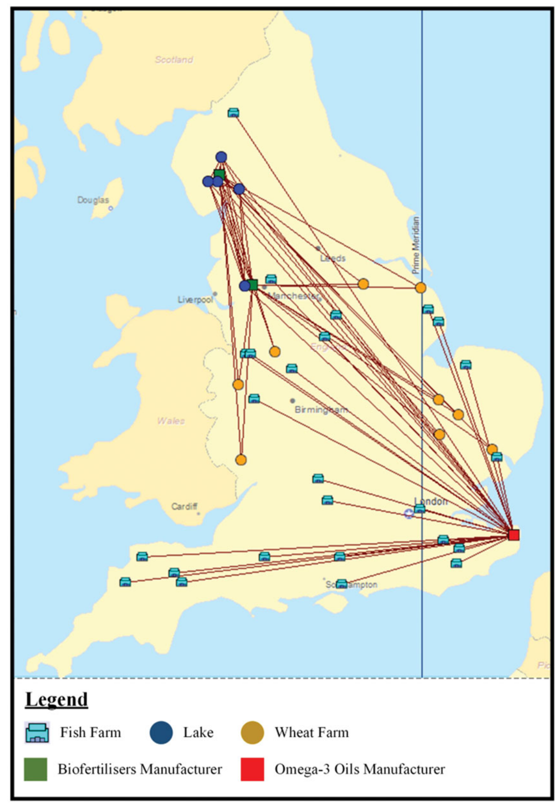

Figure A2. Circular network structure for the supply of biofertilizer and omega-3 oils for fish feed, enabled by algae feedstock, in the UK.

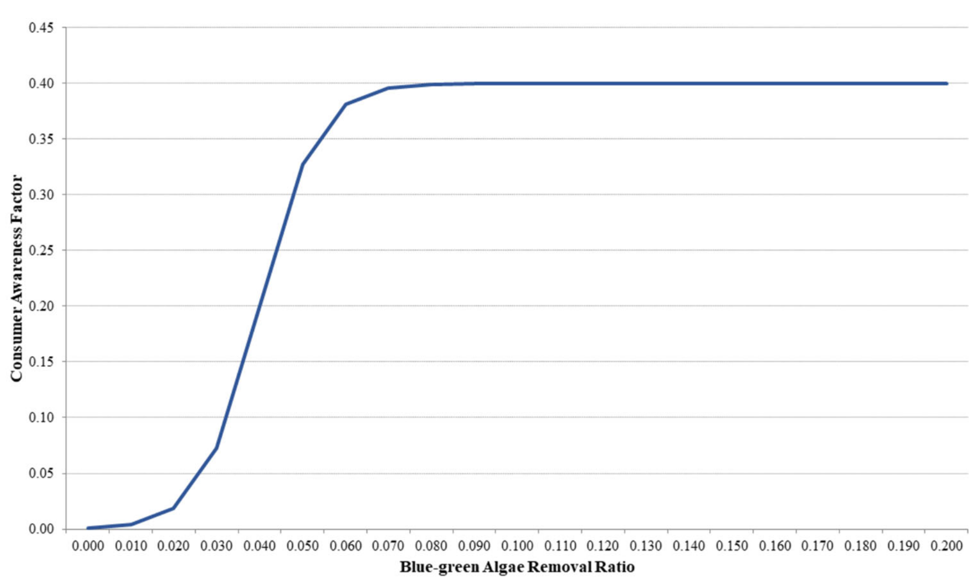

Figure A1. Consumer environmental awareness sigmoid function.

function of the blue-green algae removal efficiency (Figure A1). Actually, a higher blue-green algae removal ratio results in a higher '*Consumer Awareness Factor*' and vice versa. Processing time, depending on the used continuous manufacturing technologies, and market edge are considered key variables in the recovery process in sustainable supply chains (Mangla, Madaan, and Chan 2013).

On the other end, the '*High Quality Microalgae Harvesting Rate*' is defined by the '*Number of Microalgae Photobioreactor Facilities*' and the '*Microalgae Photobioreactor Harvester Capacity*'. Thereafter, the accumulated '*Microalgae Inventory*' along with the '*Omega-3 Oils Extraction Time*' define the '*Piezoelectric Extraction of Omega-3 Oils Rate*' which in turn affects the '*Omega-3 Oils for Fish Feed Inventory*'. In particular, the '*Omega-3 Oils Extraction Time*' depends on the elaborated piezoelectric transducers which comprise a representative Industry 4.0 application as they allow the continuous acoustic harvesting and extraction of omega-3 oils from microalgae biomass. Furthermore, the '*Omega-3 Oils for Fish Feed Sales*' are dictated by the '*Omega-3 Oils for Fish Feed Demand*' which is also being affected by the '*Consumer Awareness Factor*' as in the case of biofertilisers. The required '*Omega-3 Oils for Fish Feed Safety Stock*' impacts the '*Omega-3 Oils for Fish Feed Discrepancy*' which further affects the '*Omega-3 Oils for Fish Feed Orders*'.

Network modelling (Meso-level)

A network-level investigation allows the identification of sites and customers, along with a more granular analysis of each individual node in the network in terms of inventory cost. Figure A2 illustrates the network system in the UK where connections are depicted among all appropriate nodes, in line with the underpinning sourcing and transportation policies of intermediate or end-products.

Appendix II.

Systems model development

Table A1 summarises all feedback loops of the circular supply system under study. In addition, Table A2 includes the parameters, type of variables, units of measurement and mathematical expressions of the variables governing the circular supply network enabled by algae feedstock. Moreover, Table A3 provides a summary of the System Dynamics simulation results.

Table A1. Structure of feedback loops of the System Dynamics model.

Feedback Loop	Causal Effect Sequence
R1	Biofertilizer Production Rate → Algae Biomass Requirements → Algae Removal Ratio – Environmental and Social Perception → Consumer Awareness Factor → UK Demand for Algae as Biofertilizer Component → Biofertilizer Sales → Biofertilizer Inventory → Algae as Biofertilizer Component Discrepancy → Algae as Biofertilizer Component Orders → Biofertilizer Production Rate
R2	Biofertilizer Production Rate → Algae Biomass Requirements → Algae Removal Ratio – Environmental and Social Perception → Consumer Awareness Factor → UK Demand for Algae as Biofertilizer Component → Average UK Demand for Algae as Biofertilizer Component → Algae as Biofertilizer Component Safety Stock → Algae as Biofertilizer Component Discrepancy → Algae as Biofertilizer Component Orders → Biofertilizer Production Rate
R3	Biofertilizer Production Rate → Algae Biomass Requirements → Algae Biomass Inventory → Algae Removal Ratio – Environmental and Social Perception → Consumer Awareness Factor → UK Demand for Algae as Biofertilizer Component → Biofertilizer Sales → Biofertilizer Inventory → Algae as Biofertilizer Component Discrepancy → Algae as Biofertilizer Component Orders → Biofertilizer Production Rate
R4	Biofertilizer Production Rate → Algae Biomass Requirements → Algae Biomass Inventory → Algae Removal Ratio – Environmental and Social Perception → Consumer Awareness Factor → UK Demand for Algae as Biofertilizer Component → Average UK Demand for Algae as Biofertilizer Component → Algae as Biofertilizer Component Safety Stock → Algae as Biofertilizer Component Discrepancy → Algae as Biofertilizer Component Orders → Biofertilizer Production Rate
R5	Algae Removal Ratio – Environmental and Social Perception → Consumer Awareness Factor → Omega-3 Oils for Fish Feed Demand → Omega-3 Oils for Fish Feed Sales → Omega-3 Oils for Fish Feed Inventory → Omega-3 Oils for Fish Feed Discrepancy → Omega-3 Oils for Fish Feed Orders → High Quality Microalgae Harvesting Rate → Algae Biomass Requirements → Algae Removal Ratio – Environmental and Social Perception
R6	Algae Removal Ratio – Environmental and Social Perception → Consumer Awareness Factor → Omega-3 Oils for Fish Feed Demand → Omega-3 Oils for Fish Feed Average Demand → Omega-3 Oils for Fish Feed Safety Stock → Omega-3 Oils for Fish Feed Discrepancy → Omega-3 Oils for Fish Feed Orders → High Quality Microalgae Harvesting Rate → Algae Biomass Requirements → Algae Removal Ratio – Environmental and Social Perception
B1	Biofertilizer Production Rate → Biofertilizer Inventory → Algae as Biofertilizer Component Discrepancy → Algae as Biofertilizer Component Orders → Biofertilizer Production Rate
B2	Biofertilizer Sales → Biofertilizer Inventory → Biofertilizer Sales
B3	Algae Removal Ratio – Environmental and Social Perception → Consumer Awareness Factor → Omega-3 Oils for Fish Feed Demand → Omega-3 Oils for Fish Feed Sales → Omega-3 Oils for Fish Feed Inventory → Omega-3 Oils for Fish Feed Discrepancy → Omega-3 Oils for Fish Feed Orders → High Quality Microalgae Harvesting Rate → Algae Biomass Requirements → Algae Biomass Inventory → Algae Removal Ratio – Environmental and Social Perception
B4	Algae Removal Ratio – Environmental and Social Perception → Consumer Awareness Factor → Omega-3 Oils for Fish Feed Demand → Omega-3 Oils for Fish Feed Average Demand → Omega-3 Oils for Fish Feed Safety Stock → Omega-3 Oils for Fish Feed Discrepancy → Omega-3 Oils for Fish Feed Orders → High Quality Microalgae Harvesting Rate → Algae Biomass Requirements → Algae Biomass Inventory → Algae Removal Ratio – Environmental and Social Perception
B5	Piezoelectric Extraction of Omega-3 Oils Rate → Microalgae Inventory → Piezoelectric Extraction of Omega-3 Oils Rate
B6	Piezoelectric Extraction of Omega-3 Oils Rate → Omega-3 Oils for Fish Feed Inventory → Omega-3 Oils for Fish Feed Discrepancy → Omega-3 Oils for Fish Feed Orders → High Quality Microalgae Harvesting Rate → Microalgae Inventory → Piezoelectric Extraction of Omega-3 Oils Rate
B7	Omega-3 Oils for Fish Feed Sales → Omega-3 Oils for Fish Feed Inventory → Omega-3 Oils for Fish Feed Sales
B8	Algae Biomass Inventory → Algae Biomass Requirements → Algae Biomass Inventory

Table A2. Mathematical formulation of the System Dynamics model.

Name	Variable Type	Unit	Definition
Algae as Biofertilizer Component Desired Safety Stock	Auxiliary	tonnes/month	('Average UK Demand for Algae as Biofertilizer Component'*'Biofertilizer Safety Stock Time')/TIMESTEP
Algae as Biofertilizer Component Discrepancy	Auxiliary	tonnes/month	'Algae as Biofertilizer Component Desired Safety Stock'-'Biofertilizer Inventory'/TIMESTEP
Algae as Biofertilizer Component Orders	Auxiliary	tonnes/month	DELAYINF('Algae as Biofertilizer Component Discrepancy','Visibility Time')
Algae as Biofertilizer Component Pending Orders	Level	tonnes	0≪tonnes≫
Algae Biomass Inventory	level	tonnes	0≪tonnes≫
Algae Biomass Requirements	Auxiliary	tonnes/month	ABS('Biofertilizer Production Rate'+'High Quality Microalgae Harvesting Rate')
Algae Biomass Supply Rate	Auxiliary	tonnes/month	IF('Blue-Green Algae Bloom Seasonality'>0,'Exploitable Blue-Green Algae Biomass',0≪tonnes≫/TIMESTEP)
Algae Removal Ratio – Environmental and Social Perception	Auxiliary		IF('Algae Biomass Inventory'=0≪tonnes≫,0,'Algae Biomass Requirements'/('Algae Biomass Inventory'/TIMESTEP))
Average Blue-Green Algae Biomass per ha	Auxiliary	tonnes/ha	NORMAL(0.007692308≪tonnes/ha≫,0.0007692308≪tonnes/ha≫)
Average UK Demand for Algae as Biofertilizer Component	Auxiliary	tonnes/month	DELAYINF('UK Demand for Algae as Biofertilizer Component','Biofertilizer Demand Smoothing Time')
Biofertilizer Demand Smoothing Time	Constant	month	0.5≪months≫
Biofertilizer Inventory	Level	tonnes	0≪tonnes≫
Biofertilizer Lost Sales	Auxiliary	tonnes/month	'UK Demand for Algae as Biofertilizer Component'-'Biofertilizer Sales'
Biofertilizer Production Rate	Auxiliary	tonnes/month	MIN('Algae Biomass Inventory'/TIMESTEP*'Market Balance Factor',DELAYMTR('Algae as Biofertilizer Component Pending Orders'*'Microalgae Content of Biofertilizers Factor','Fertiliser-level Microalgae Extraction Time',1)/TIMESTEP,'Number of Biorefineries'*'Biofertlizer Production Capacity per Biorefinery')
Biofertilizer Safety Stock Time	Constant	month	2≪months≫
Biofertilizer Sales	Auxiliary	tonnes/month	MIN('Biofertilizer Inventory'/TIMESTEP,'UK Demand for Algae as Biofertilizer Component')
Biofertlizer Production Capacity per Biorefinery	Auxiliary	tonnes/month	'Biorefinery Utilisation Rate'*((18/12)*1≪tonnes≫)/TIMESTEP
Biorefinery Utilisation Rate	Auxiliary	%	NORMAL(80%,2%)
Blue-Green Algae Bloom Seasonality	Auxiliary		IF((TIME> =6≪@month≫ AND TIME< =9≪@month≫) OR (TIME> =18≪@month≫ AND TIME< =21≪@month≫) OR (TIME> =30≪@month≫ AND TIME< =33≪@month≫) OR (TIME> =42≪@month≫ AND TIME< =45≪@month≫) OR (TIME> =54≪@month≫ AND TIME< =57≪@month≫) OR (TIME> =66≪@month≫ AND TIME< =69≪@month≫) OR (TIME> =78≪@month≫ AND TIME< =81≪@month≫) OR (TIME> =90≪@month≫ AND TIME< =93≪@month≫) OR (TIME> =102≪@month≫ AND TIME< =105≪@month≫) OR (TIME> =114≪@month≫ AND TIME< =117≪@month≫) OR (TIME> =126≪@month≫ AND TIME< =129≪@month≫) OR (TIME> =138≪@month≫ AND TIME< =141≪@month≫) OR (TIME> =150≪@month≫ AND TIME< =153≪@month≫) OR (TIME> =162≪@month≫ AND TIME< =165≪@month≫) OR (TIME> =174≪@month≫ AND TIME< =177≪@month≫) OR (TIME> =186≪@month≫ AND TIME< =189≪@month≫) OR (TIME> =198≪@month≫ AND TIME< =201≪@month≫) OR (TIME> =210≪@month≫ AND TIME< =213≪@month≫) OR

(*continued*)

Table A2. Continued.

Name	Variable Type	Unit	Definition
			(TIME> =222≪@month≫ AND TIME< =225≪@month≫) OR (TIME> =234≪@month≫ AND TIME< =237≪@month≫) OR (TIME> =246≪@month≫ AND TIME< =249≪@month≫) OR (TIME> =258≪@month≫ AND TIME< =261≪@month≫) OR (TIME> =270≪@month≫ AND TIME< =273≪@month≫) OR (TIME> =282≪@month≫ AND TIME< =285≪@month≫) OR (TIME> =294≪@month≫ AND TIME< =297≪@month≫) OR (TIME> =306≪@month≫ AND TIME< =309≪@month≫) OR (TIME> =318≪@month≫ AND TIME< =321≪@month≫) OR (TIME> =330≪@month≫ AND TIME< =333≪@month≫)OR (TIME> =342≪@month≫ AND TIME< =345≪@month≫) OR (TIME> =354≪@month≫ AND TIME< =357≪@month≫), 1, 0)
Blue-Green Algae Drying Time	Auxiliary	month	1≪month≫/4
Coniston Water	Constant	ha	470≪ha≫
Consumer Awareness Factor	Auxiliary		IF('Algae Removal Ratio – Environmental and Social Perception'< =0.1,GRAPHCURVE('Algae Removal Ratio – Environmental and Social Perception',0,0.01,'Logistic Function'),0.4)
Dried Algae Biomass Volatile Matter Factor	Auxiliary	%	NORMAL(70.13%,5%)
Drone Blue-Green Algae Bloom Phenomenon Signal	Auxiliary	tonnes/month	DELAYINF(('Total Lake Area'*'Average Blue-Green Algae Biomass per ha'*'Dried Algae Biomass Volatile Matter Factor'),(1≪month≫/30))/TIMESTEP
Exploitable Blue-Green Algae Biomass	Auxiliary	tonnes/month	DELAYMTR('Drone Blue-Green Algae Bloom Phenomenon Signal'*'Exploitable Blue-Green Algae Biomass Factor','Blue-Green Algae Drying Time')
Exploitable Blue-Green Algae Biomass Factor	Auxiliary	%	NORMAL(60%,5%)
Fertiliser-level Microalgae Extraction Time	Constant	month	(1/5)*TIMESTEP
High Quality Microalgae Harvesting Rate	Auxiliary	tonnes/month	MIN('Algae Biomass Inventory'/TIMESTEP*(1-'Market Balance Factor'),DELAYINF('Omega-3 Oils for Fish Feed Pending Orders','Omega-3-level Microalgae Harvesting Time',1)/TIMESTEP,'Microalgae Photobioreactor Harvester Capacity'*'Number of Microalgae Photobioreactor Facilities')
Industrial Algae Farming	Auxiliary	tonnes/month	'Algae Biomass Supply Rate'-'Drone Blue-Green Algae Bloom Phenomenon Signal'
Killington Reservoir	Constant	ha	57≪ha≫
Logistic Function	Auxiliary		XLDATA("C:/Users/Naoum K. Tsolakis/Desktop/./S-Curve.xls", "Sheet1", "R14C2:R34C2")
Market Balance Factor	Constant	%	50%
Microalgae Content of Biofertilizers Factor	auxiliary		RANDOM(0.25,0.30)
Microalgae Inventory	Level	tonnes	0≪tonnes≫
Microalgae Photobioreactor Harvester Capacity	Auxiliary	tonnes/month	0.0052≪tonnes≫/((TIMESTEP/26))
Number of Biorefineries	Constant		1
Number of Microalgae Photobioreactor Facilities	Constant		1
Omega-3 Oils Extraction Factor	Constant	%	25%
Omega-3 Oils Extraction Time	Constant	month	(1/26)*TIMESTEP
Omega-3 Oils for Fish Average Demand	Auxiliary	tonnes/month	DELAYINF('Omega-3 Oils for Fish Feed Demand','Omega-3 Oils for Fish Feed Demand Smoothing Time')
Omega-3 Oils for Fish Feed Demand	Auxiliary	tonnes/month	(1+'Consumer Awareness Factor')*('Target Omega-3 Oils for Fish Feed Market Share'*'Omega-3 Oils for Fish Feed Replacement Ratio'*NORMAL(('UK Imports of Fish Meals and Flours'/12), 0.01*'UK Imports of Fish Meals and Flours'))
Omega-3 Oils for Fish Feed Demand Smoothing Time	Constant	month	0.5≪months≫
	Auxiliary	tonnes/month	

(*continued*)

Table A2. Continued.

Name	Variable Type	Unit	Definition
Omega-3 Oils for Fish Feed Desired Safety Stock			('Omega-3 Oils for Fish Average Demand'*'Omega-3 Oils for Fish Feed Safety Stock Time')/TIMESTEP
Omega-3 Oils for Fish Feed Discrepancy	Auxiliary	tonnes/month	'Omega-3 Oils for Fish Feed Desired Safety Stock'-'Omega-3 Oils for Fish Feed Inventory'/TIMESTEP
Omega-3 Oils for Fish Feed Inventory	Level	tonnes	0≪tonnes≫
Omega-3 Oils for Fish Feed Lost Sales	auxiliary	tonnes/month	IF('Omega-3 Oils for Fish Feed Demand'>'Omega-3 Oils for Fish Feed Sales','Omega-3 Oils for Fish Feed Demand'-'Omega-3 Oils for Fish Feed Sales',0≪tonnes≫/TIMESTEP)
Omega-3 Oils for Fish Feed Orders	auxiliary	tonnes/month	DELAYINF('Omega-3 Oils for Fish Feed Discrepancy','Visibility Time')
Omega-3 Oils for Fish Feed Pending Orders	Level	tonnes	0≪tonnes≫
Omega-3 Oils for Fish Feed Replacement Ratio	Constant	%	6%
Omega-3 Oils for Fish Feed Safety Stock Time	Constant	month	2≪months≫
Omega-3 Oils for Fish Feed Sales	Auxiliary	tonnes/month	MIN('Omega-3 Oils for Fish Feed Inventory'/TIMESTEP,'Omega-3 Oils for Fish Feed Demand')
Omega-3-level Microalgae Harvesting Time	Constant	month	(1/26)*TIMESTEP
Pennington Flash	Constant	ha	70≪ha≫
Piezoelectric Extraction of Omega-3 Oils Rate	Auxiliary	tonnes/month	MIN('Microalgae Inventory'/TIMESTEP,DELAYMTR('Microalgae Inventory'/TIMESTEP*'Omega-3 Oils Extraction Factor'*'Number of Microalgae Photobioreactor Facilities','Omega-3 Oils Extraction Time',1))
Target Biofertilizers Market Share	Constant	%	5%
Target Omega-3 Oils for Fish Feed Market Share	Constant	%	5%
Total Lake Area	Auxiliary	ha	'Coniston Water'+'Killington Reservoir'+'Pennington Flash'+Ullswater + Windermere
UK Algae-based Biofertilizers Market Share	Constant	%	10%
UK Demand for Algae as Biofertilizer Component	Auxiliary	tonnes/month	(1+'Consumer Awareness Factor')*('UK Demand for Nitrogen as Fertiliser Nutrient'*'UK Algae-based Biofertilizers Market Share'*'Target Biofertilizers Market Share')
UK Demand for Nitrogen as Fertiliser Nutrient	Auxiliary	tonnes/month	COMPOSITESERIES(1026000≪tonnes≫/12/TIMESTEP,PREV()+ PREV()*2.3%)
UK Imports of Fish Meals and Flours	Auxiliary	tonnes/month	NORMAL(71085.35≪tonnes≫,13962.8444≪tonnes≫)/12≪months≫
Ullswater	Constant	ha	890≪ha≫
Visibility Time	Constant	month	4≪month≫
Windermere	Constant	ha	1472≪ha≫

Table A3. Summary of System Dynamics simulation results.

Scenario	Number of biorefineries [number]	Number of microalgae photobioreactor facilities [number]	Unit omega-3 oils extraction time [months]	Omega-3 oils for fish feed lost sales [tonnes]	Biofertilizer lost sales [tonnes]	Omega-3 oils for fish feed sales [tonnes]	Biofertilizer sales [tonnes]	Omega-3 oils for fish feed inventory [tonnes]	Biofertilizer inventory [tonnes]
#1	2	1	1/26	1.862	1,227.199	0.109	2.085	0.109	2.085
#2	2	1	78/26	1.862	1,226.441	0.109	2.085	0.109	2.085
#3	2	2	1/26	1.767	1,245.519	0.226	2.084	0.226	2.084
#4	2	2	78/26	1.766	1,245.943	0.226	2.084	0.226	2.084
#5	3	1	1/26	1.895	1,257.479	0.108	2.691	0.108	2.691
#6	3	1	78/26	1.898	1,257.462	0.108	2.696	0.108	2.696
#7	3	2	1/26	1.780	1,255.016	0.220	2.600	0.220	2.600
#8	3	2	78/26	1.783	1,254.877	0.220	2.599	0.220	2.599
#9	3	3	1/26	1.665	1,245.075	0.319	2.510	0.319	2.510
#10	3	3	78/26	1.672	1,245.455	0.315	2.517	0.315	2.517

ARTICLES FOR FACULTY MEMBERS

CIRCULAR ECONOMY AND BLUE ECONOMY INITIATIVE

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How to Deal With Seafloor Marine Litter: An Overview of the State-of-the-Art and Future Perspectives

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Marine litter is a significant and growing pollutant in the oceans. In recent years, the number of studies and initiatives trying to assess and tackle the global threat of marine litter has grown exponentially. Most of these studies, when considering macro-litter, focus on floating or stranded litter, whereas there is less information available about marine litter on the seabed. The aim of this article is to give an overview of the current state-of-the-art methods to address the issue of seafloor macro-litter pollution. The overview includes the following topics: the monitoring of macro-litter on the seafloor, the identification of possible litter accumulation hot spots on the seafloor through numerical models, and seafloor litter management approaches (from removal protocols to recycling processes). The article briefly analyzes the different approaches to involve stakeholders, since the marine litter topic is strongly related to the societal engagement. Finally, attempting to answer to all the critical aspects highlighted in the overview, the article highlights the need of innovative multi-level solutions to induce a change toward sustainable practices, transforming a problem into a real circular economy opportunity.

Keywords: marine litter, seafloor litter, derelict fishing gear, marine litter mapping, numerical modeling, pyrolysis, circular economy, stakeholder engagement

INTRODUCTION

Marine debris is a growing problem with plastics making up 60–80% of marine litter worldwide (Derraik, 2002). Plastic enters in the sea as macro- (>0.5 cm) and micro- (<0.5 cm) litter. In the marine environment several chemical and physical processes affect its shape, density, and composition (Zhang, 2017; Guo and Wang, 2019; Schwarz et al., 2019). The global amount of plastic entering the oceans each year is estimated to be between 4 and 12 million metric tons (Jambeck et al., 2015). The five ocean gyres, i.e., North and South Pacific, North and South Atlantic, and Indian have been identified as the largest accumulation zones together with highly populated, shallow, and enclosed waters, such as the Mediterranean Sea (Cózar et al., 2015; Suaria et al., 2016).

Marine litter can be found throughout the marine environment, i.e., the beach, sea surface, water column, seafloor as well as on and in marine biota. Much of the research on distribution, accumulation zones, and concentrations of marine litter have focused on beach and floating litter, while studies on benthic litter are more problematic due to the less accessible environment

(Galgani, 2015; Schneider et al., 2018; Schwarz et al., 2019). However, investigating the seafloor is of fundamental importance, as it is estimated that about 70% of marine debris sinks to the seabed with unknown consequences (UNEP, 2005). Even low density polymers can lose buoyancy under the weight of bio-fouling. Deposition rates on the seabed depend on many factors, such as the size and density of plastic objects, depth, currents, wave motion, and the topography of the seabed.

Marine litter has physical, chemical, and biological implications, as well as economical ones (McIlgorm et al., 2011; Raynaud, 2014; Brouwer et al., 2015; Newman et al., 2015; Watkins et al., 2015; Vlachogianni, 2017). Impacts of marine litter on marine organisms were reported on 557 species, showing the deleterious effects and consequences of entanglement, consumption, and smothering (Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel—GEF, 2012). Although marine birds, turtles, and mammals have received most attention, the effects on other organisms, such as fish and invertebrates, are becoming more evident. Ingestion of floating waste and entanglement in discarded or lost fishing gear and ropes might have consequences on survival capability of an individual, often causing direct mortality (Kühn et al., 2015). Yet, there are also sub-lethal effects on organisms that result in reduced energy intake, which may influence fecundity rates. Plastics contain and adsorb persistent organic pollutants (POPs) (Rios et al., 2007). POPs not only pose a problem for the marine environment but can bio-accumulate through the food web and affect human health (Gobas et al., 2009). Recently, plastic pollution has become so pervasive that new mixtures of melted plastic and natural sediments or rocks (the so-called plastiglomerates and plasticrusts) have been discovered (Corcoran et al., 2014; Gestoso et al., 2019).

The sources of marine litter can be grouped in two broad categories: land-based and marine-based sources. Land-based sources include landfills and littering of beaches and coastal areas (tourism), rivers and floodwaters, industrial emissions, discharge from storm water drains and untreated municipal sewerage (UNEP, 2009). It is estimated that land-based sources contribute substantially to the marine litter problem, about 80% of the total (STAP, 2011). Marine-based sources include cargo and passenger shipping, recreational boating, military navigation, fishing and aquaculture facilities, and the energy industry, as well as legal and illegal dumping (Čulin and Bielić, 2016). The importance of marine-based sources can greatly vary in different regions: in the Northeast Atlantic, maritime activities such as shipping, fishing, and offshore installations, together with coastal tourism activities, are the predominant sources (OSPAR, 2009). Not all sectors produce the same amount of marine litter. For instance, tourist ships have been identified as one of the principal pollution sources of marine eco-systems with cruisers being a particular problem (Allsopp et al., 2005; Jeftic et al., 2005).

Fisheries and aquaculture related activities are another marine-based sector that produces marine litter. Abandoned, lost or otherwise discarded fishing gear (ALDFG) is thought to contribute approximately 10% of the marine litter deposited at sea per year (Macfadyen et al., 2009; Pham et al., 2014). However, this amount can greatly vary depending on the importance of local fishing and aquaculture activities and on specific hydrological and geomorphological conditions (Pham et al., 2014). In the Pacific garbage patch, ALDFG is considered to contribute nearly half of the tonnage found in the region (Lebreton et al., 2018; Richardson et al., 2019). Similarly, derelict fishing gear was the prevalent type of litter on the seafloor of the upper São Vicente submarine canyon (SW Portugal), representing 89% of total debris (Oliveira et al., 2015). Within the Mediterranean Sea, Angiolillo et al. (2015) reported that, in the deep seafloor of 26 areas off the coast of three Italian regions in the Tyrrhenian Sea, the dominant type of debris (89%) was represented by fishing gears (mainly lines). The most abundant quantities were observed on rocky banks in Sicily and Campania, which are characterized by intense recreational and professional fishing activities. The durability and morphology of ALDFG imply that when it sinks, it often snags on reefs and on other underwater obstacles causing significant damage to benthic habitats, impacting ecosystems and fisheries through "ghost fishing" and acting as a navigational hazard (Richardson et al., 2019).

Information on the characterization, quantification, and location of the amounts of marine litter also represents the background for the development of the management strategies to reduce marine litter and to verify their effectiveness. The management measures proposed and then adopted to tackle the environmental problems related to marine litter are divided into three categories: (a) preventive measures to avoid the occurrence by reducing the sources (e.g., waste reuse and recycling, waste conversion into energy, enforcement of port reception facilities, gear marking); (b) mitigating measures to reduce the presence and the impacts through debris disposal and dumping regulations; (c) curative measures to remove litter from the marine environment through clean up campaigns and retrieval programs (Chen, 2015). Measures to raise awareness are also essential to lead to behavioral changes in citizens and stakeholders. These management measures are contained in a number of policy instruments (e.g., conventions, regulations, and strategies) proposed at global, regional, and European Union (EU) levels, both compulsory and voluntary. The legislative framework refers to two main sectors: the protection of the sea and its resources, including the fishery sector, and the waste management (**Table 1**).

The most important global conventions were negotiated under the United Nations Environment Program (UNEP) and the Agency for the Safety, Security and Environmental Performance of International Shipping (International Maritime Organization, IMO). According to their different nature, these instruments were explicitly transposed into regional or EU legislation or served as guidelines for the states to take coordinated actions to tackle the marine litter issue. The EU has recently developed a European Strategy for Plastics and the follow-up legislation to reduce the negative effects on the environment of some single use plastic items and derelict fishing gear. In 2019, the EU adopted the long-awaited Directive 2019/904/EU on the reduction of the impact of certain plastic products on the environment, which introduces several bans and restrictions on different uses and materials. This

TABLE 1 | List of the main strategies and regulations developed to address marine litter issue at international, regional, and EU levels.

Level	Main sector	Instruments	Provisions related to marine litter and derelict fishing gear
Global instruments	Environment protection	United Nations Convention on the Law of the Sea (UNCLOS, 1982)	Sets the adoption of all the necessary measures to prevent, reduce and control any type of pollution in order to protect and preserve the marine environment
		UN Fish Stocks Agreement, 1995	Promotes the development of environmentally safe fishing gear and techniques to protect fish stock and to minimize impacts by lost or abandoned fishing gear
	Fishery	Code of Conduct for Responsible Fishing, 1995	Sets universal standards and principles to guide governments and private actors for a sustainable use of aquatic resources and for responsible fishing practices, directly referring also to ALDFG
	Waste management	The International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), 1973-1978	Annex V sets measures to eliminate or reduce the amount of garbage and solid waste produced by ships and discharged into the sea, and sets the absolute prohibition of the disposal of plastic waste into the sea
		London Convention and 1996 Protocol	Sets the complete stop of waste dumping at sea, represents a decisive change in the approach to the question of the use of the sea as a deposit of waste materials and introduces the so-called "precautionary approach" and the "polluter-pays principle".
Mediterranean Region instruments	Environment protection	Barcelona Convention 1976 and Protocols	Aims to protect the Mediterranean Sea against pollution. Dumping protocol: prevention and elimination of pollution by dumping from ships and aircraft or incineration at sea. LBS Protocol: protection against pollution from land-based sources and activities
		Barcelona Convention: Regional Plan on Marine Litter Management in the Mediterranean (2014)	Aims to prevent and reduce to the minimum marine litter pollution in the Mediterranean and its impact on ecosystem services, habitats, species (in particular the endangered species), public health and safety and to remove to the extent possible already existent marine litter. The plan also intends to implement the « fishing for litter » system.
		MEDPOL program (1996): Strategic Action Program for the management of marine litter in the Mediterranean, 2011	Aims to minimize and further eliminate, to the fullest possible extent, marine litter in the Mediterranean Region through regional and national activities. The Strategy highlights that marine litter represents a local, national as well as trans-boundary problem needing specific measures at each level and across all levels,
European instruments	Environment protection	Marine Strategy Framework Directive (Directive 2008/56/CE) and the subsequent Commission Decisions (2010/477/EC and 2017/848/EC)	Descriptor 10: Properties and quantities of marine litter (macro and micro) do not cause harm to the coastal and marine environment, also including marine organisms, in particular referring to ingestion of and entanglement in litter and derelict fishing gear
	Environment protection	The European Strategy for the Adriatic and Ionian Region (EUSAIR), 2014	Specific objective within the Pillar 3 "Environmental quality" is to improve waste management by reducing waste flows to the sea. The foreseen actions to contrast pollution at sea include to joint efforts to deal with entire life cycle of marine litter.
	Fishery	Regulation (EC) 1224/2009 for a Community control system and its Commission Implementing Regulation (EC) 404/2011	Specifies mandatory measures to the marking and identification of fishing vessels and of fishing gear used in community waters and the correct behavior to adopt when fishing gear is lost during fishing operations, emphasizing the obligation of a timely retrieval or, if the lost gear cannot be retrieved, of a detailed notification to the competent authorities
		Regulation (EC) 1005/2008 establishing a Community system to prevent, deter and eliminate illegal, unreported and unregulated fishing	Illegal fishing is recognized as one of the most serious threat to the sustainable exploitation of aquatic resources and to marine biodiversity. As well as one of the causes that led to the abandonment of fishing gear at sea.
	Waste Management	Waste Framework Directive (Directive 2008/98/EC)	Although not directly related to the management of ship-generated or fishing waste or to marine litter, the Directive offers a modernized framework and establishes a five-step waste hierarchy approach where prevention is the best option, followed by re-use, recycling and other forms of recovery, with disposal such as landfill as the last option.
		Directive (EU) 2018/851 amending the Directive 2008/98/EC	Specifically refers to marine litter recognized as a particularly pressing problem, and states that measures should be taken to halt the generation of marine litter particular from land-based activities
		Directive (EU) 2019/883 on port reception facilities for the delivery of waste from ships, repealing the Directive 2000/59/EC	Introduces some important novelties: the inclusion, among the waste from ships covered by the Directive, also of "passively fished waste", defined as waste collected in nets during fishing operations; encourages the use of 'fishing for litter schemes' and provides that the costs of collection and treatment of passively fished waste are not borne exclusively by port users
		Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment	Introduces several bans and restrictions on different uses and materials. This initiative focused on the ten most found single use plastics and on fishing gear containing plastic and set limits on the use of single use plastics through a national reduction in consumption, design and labeling requirements, and waste management/clean-up obligations for producers are also specified

initiative focused on the ten most found single use plastics and on fishing gear containing plastic.

The purpose of this paper is to give an overview of the most recent advances with regards to seafloor macro-litter pollution, from monitoring and assessment to prevention and mitigation. The review covers the following topics: (**Figure 1**): (1) the assessment of macro-litter on the seafloor including the monitoring and the identification of possible

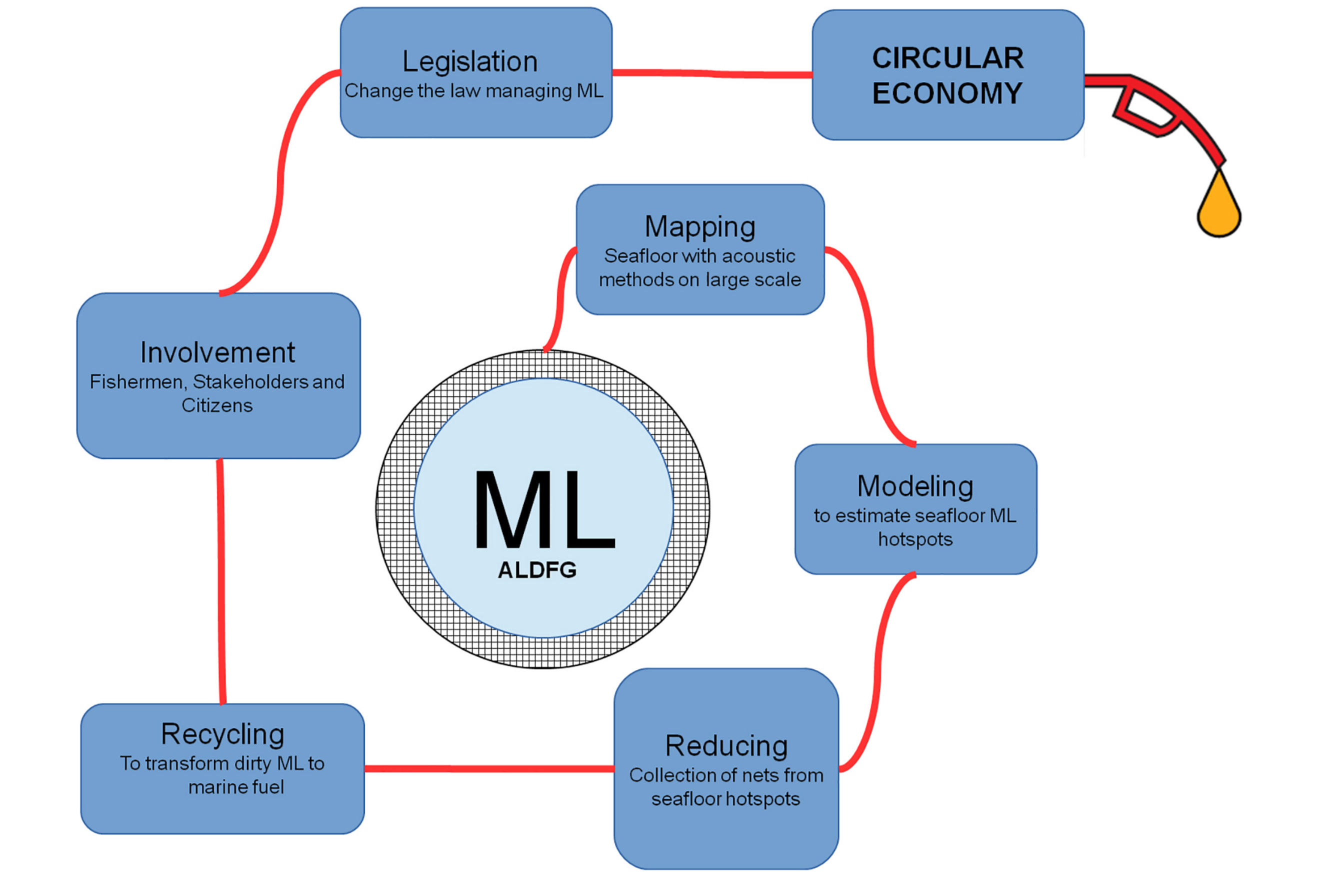

FIGURE 1 | Conceptual model illustrating the main actions needed to tackle the marine litter issue.

litter accumulation hot spots through numerical models; (2) the management of seafloor marine litter, including the removal and recycling procedures, and the strategies for stakeholder and citizen engagement.

Finally, attempting to answer all the critical aspects highlighted in the overview, in the future perspectives we suggest a holistic approach, combining actions to tackle the phenomenon of marine litter at all phases, from reduction and prevention, through the monitoring and quantification up to the removal and recycling. This multidisciplinary approach aims to avoid, prevent, or mitigate environmental, economic, and social losses derived from poor marine litter management practices.

ASSESSMENT OF MACRO-LITTER ON THE SEAFLOOR

Monitoring the Presence of Macro-Litter on the Seafloor

The detection and characterization of marine litter on the seafloor relies mainly on three different approaches (or sometimes a combination of them): litter collection with bottom trawlers, optical mapping, and, more recently, acoustic mapping of the seafloor.

Trawling for scientific purposes allowed extensive investigation of large areas of the seafloor and monitoring of marine litter over long periods of time. For example, Maes et al. (2018), present the results of a long term monitoring of the North West European seas investigating a wide inshore (within 12 nm of land) and offshore (>12 nm) area of the Celtic and Greater North Seas (2461 trawls). Gerigny et al. (2019) analyses a 24-year time series of data based on trawling for fish stock assessment of the MEDITS project in a large area of the French Mediterranean continental shelf. A similar approach has been recently adopted for other parts of the Mediterranean Sea (e.g., Galgani et al., 2013; Pasquini et al., 2016; Fortibuoni et al., 2019; Spedicato et al., 2019). However, bottom trawlers present several limitations: (1) they are invasive for the seafloor; (2) they cannot operate on rocky bottom where litter (such as ALDFG) is likely to accumulate; and (3) they do not give precise information about the spatial distribution of the litter on the seafloor.

Optical methods are based on videos and images collected either by divers in shallow coastal and/or coral reef environments (e.g., Donohue et al., 2001; Bauer et al., 2008) or by high resolution cameras installed on Remoted Operated Vehicles (ROVs) (i.e., Oliveira et al., 2015; Gerigny et al., 2019;

Pierdomenico et al., 2019), manned submersibles (Galgani et al., 2000; Watters et al., 2010) or unmanned platforms such as Unmanned Surface Vehicles (USVs) or Autonomous Underwater Vehicles (AUVs) (Wynn et al., 2014; Huvenne et al., 2018) (**Table 2**). Photographic transects were collected also using a towed camera over different years (since 2002) in the HAUSGARTEN observatory in the Fram Strait (Bergmann and Klages, 2012; Tekman et al., 2017) and on the continental shelf or in the deep sea in the Bay of Fundy, Canada (Goodman et al., 2020). These methods are commonly used for quantifying marine litter on the seafloor (e.g., Angiolillo et al., 2015 for a review and the more recent works by Melli et al., 2017; Consoli et al., 2018; and Pierdomenico et al., 2019 in the coastal areas of the Mediterranean Sea) and its increasing presence over time (Tekman et al., 2017).

The advantage of the optical methods is that they are non-invasive, they provide quantitative data and they can be applied to all types of seafloor including complex rocky substrata. From the collected images it is possible to obtain photomosaics of the seafloor combining different video frames. In some cases, thanks to photogrammetry, the images can be used to interpret the 3D morphology of objects in the pictures (see, e.g., Drap et al., 2015 and Price et al., 2019 for photogrammetry applications to corals and archeological remains in deep sea, respectively). This can be achieved either using stereophotographic cameras or combining sufficient overlapping consecutive photographs from a single moving camera (Huvenne et al., 2018). Moreover, the images can also provide useful information about the benthic habitats. Typically, high resolution cameras allow the identification of litter larger than 5 cm.

However, the use of cameras can be limited by the visibility or the hydrodynamic conditions and can only cover points or transects. For example, Angiolillo et al. (2015) used a ROV to cover an area of 6.03 km^2 over 4 months, with an average mapping rate of, i.e., 0.002 km^2/h in average. Melli et al. (2017) mapped some rocky outcrops in the Northern Adriatic Sea using ROV transects covering a total area of 0.039 km^2 with a mapping rate of about 0.0014 km^2/h. With a drifting drop frame camera, Goodman et al. (2020) covered an average area of about 0.002 km^2/h.

More recently, also underwater hyperspectral imaging (UHI) has shown a strong potential of detecting small objects and it has been shown that UHI can be used as a non-invasive, *in situ* taxonomic tool for benthic megafauna with sizes on a sub-cm scale (down to 0.8 cm) with an increased detection rate for small (<2 cm) objects having a resolution of 1 mm/pixel (Dumke et al., 2018; Foglini et al., 2019).

Acoustic methods have considerably improved their efficacy since the first review of the different methods applied for benthic marine litter detection by Spengler and Costa (2008). The use of acoustic methods for waste detection on the seafloor dates back to the early 1990s. Karl et al. (1994) made use of side scan sonar (SSS) and video recording to identify barrels and other containers of low-level radioactive waste dumped on the

TABLE 2 | Examples of different underwater optical and acoustic methodologies reported in recent studies. The mapping rate and the detectable target dimension were estimated, where possible, from the data available in the different studies.

Method		Estimated mapping rate (km^2/h)	Detectable target dimension (m)	Depth (m)	Bottom type	Geographical area	Source
Optical methods	Divers	0.006	<1 m	10 m	Coral reef	Northwestern Hawaiian Islands	Donohue et al., 2001
		0.001-0.004	< 1 m	10–20	Rocky outcrop	North Adriatic Sea	Fiorin, R. (from GHOST project experience)
	Camera mounted on ROV	0.002	<1 cm	30–300	Rocky bottom	Tyrrhenian Sea	Angiolillo et al., 2015
		0.0014	<1 cm	20–30	Rocky outcrop	Northern Adriatic Sea	Melli et al., 2017
	Drifting drop frame	0.002	<10 cm	10–100	From muddy and sandy flat seafloor to bedrock and till	Bay of Fundy, Canada	Goodman et al., 2020
	UHI	0.0001	<0.8	4200	Manganese nodule field	Peru Basin (SE Pacific Ocean)	Dumke et al., 2018
		0.001	<0.8	200–400	Muddy and rocky seafloor	Bari Canyon, Adriatic Sea	Foglini et al., 2019
Acoustical methods	SSS	-	≤10 m	100–2500	-	San Francisco Bay	Chavez and Karl, 1995
		0.125	≤2 m	100–150	Soft mud seafloor	Chiniak Bay, Kodiak Island, Alaska	Stevens et al., 2000
	MBES	0.097–0.728	≤1 m (depending on the distance from seafloor)	2–20	Mostly muddy - sandy mud and rocky outcrops	North Adriatic Sea	marGnet survey - Madricardo et al., 2019
	HRSS	0.012	5 cm	10–20	Rocky outcrop and sandy seafloor	North Adriatic Sea	Fiorin, R. (from GHOST project experience)
	SAS	-	1 cm	-	Various types of seafloor	Extensive survey in different locations-	Williams, 2014
		2.25	4 cm	-	-	Southern Ionian Sea	Zwolak et al., 2020
	FLS	-	<1 cm	-	Sandy seafloor	Tank experiment	Valdenegro-Toro (2016)

continental margin off San Francisco Bay between 1946 and 1970. Chavez and Karl (1995) applied a spatial variability analysis and other digital processing procedures to the SSS images (with 1 m pixel resolution) to automatically detect and map the location of barrels a few meters long on the seafloor. Stevens et al. (2000) employed SSS to locate lost crab pots off Kodiak, Alaska, making use of submersible and ROV to confirm the remote observation.

Identification of the location of mines on the seabed has driven a large number of studies dedicated to underwater target detection using acoustic data and specific dedicated algorithms. Synthetic aperture sonar (SAS) imaging can reach up to 1 cm/pixel resolution and has proven particularly useful for the detection of proud mines on the seabed (Williams, 2014). Recent development of the interferometric SAS mounted on an AUV allowed to reach a specified image resolution better than 5 cm and a mapping rate of 2 km^2/h (Zwolak et al., 2020). SAS data acquired with AUV systems in deep waters in the Norwegian Sea within the MAREANO (Marine areal database for Norwegian waters) program in Norway, demonstrated the effectiveness of mapping also individual coral blocks indicating that this technology could be successfully applied for marine litter surveys (Thorsnes et al., 2020).

The recent development of multibeam echosounder systems (MBES) (Hughes Clarke, 2018) has made it possible to collect georeferenced co-located bathymetry and backscatter intensity data for the mapping of objects with very high spatial resolution. Hughes Clarke et al. (1999) showed the effectiveness of the combined use of side scan sonar imagery and MBES data in the search for aircraft debris after the crash of Swiss Air Flight 111, off Nova Scotia, Canada. Mayer et al. (2007) conducted specific experiments showing that the resolution of multibeam sonar combined with 3D visualization techniques provided realistic looking images of mines and mine-like objects that were dimensionally correct and enabled unambiguous identification on a sandy seafloor. More recently, Madricardo et al. (2019) used high resolution MBES data (up to 5 cm resolution to map objects larger than 0.8 m) to assess the mean abundance of marine macro-litter in a large area of the Venice Lagoon and to identify marine litter hot spots (see **Figure 2a**). The average area *per diem* covered was 0.68 km^2/day with a mapping rate of 0.097 km^2/h (Madricardo et al., 2017).

Valdenegro-Toro (2016) proposed the combined use of Forward-Looking Sonar (FLS), frequently used by AUVs as obstacle avoidance sensor, to detect submerged marine debris and the Convolutional Neural Networks (CNNs) showing the promising results of a tank experiment.

Moschino et al. (2019) present the results of acoustic surveys that were carried out on biogenic rocky outcrops (Northern Adriatic Sea) during the Life GHOST project using a High-Resolution Scanning Sonar head – HRSS. The HRSS provided very detailed images of the seabed near the sonar head (up to 100 m) (**Figure 2b**), highlighting the presence of ALDFG.

The main limitation of the acoustic methods in comparison with images or videos is still resolution which is dependent on the sonar characteristics and the distance from the target.

To overcome the specific limitations of the non-invasive optical and acoustic methods (i.e., limited coverage and resolution, respectively), the solution seems to be the systematic combination of the two approaches. This will be more readily feasible in light of the rapid development of autonomous vehicles, such as USV and AUV, that are likely to be the future of the marine litter surveys for shallow and deep waters, respectively. We can expect that new levels of autonomy will allow a fleet of USV or AUVs to be launched to survey a specific area. The autonomous vehicles will communicate and co-operate to survey the area in an efficient and safe manner and use machine learning algorithms to compute and analyze high-resolution acoustic data on-the-fly. Then, it will be possible to perform a close-to-bottom photographic survey after identifying key targets for in-depth study (Sture et al., 2018; Thorsnes et al., 2020). This approach is also highlighted by the future integrated marine debris observing system (IMDOS) which has to provide long-term monitoring of the state of anthropogenic pollution and support operational activities to mitigate impacts on the ecosystem and on the safety of maritime activity (Maximenko et al., 2019).

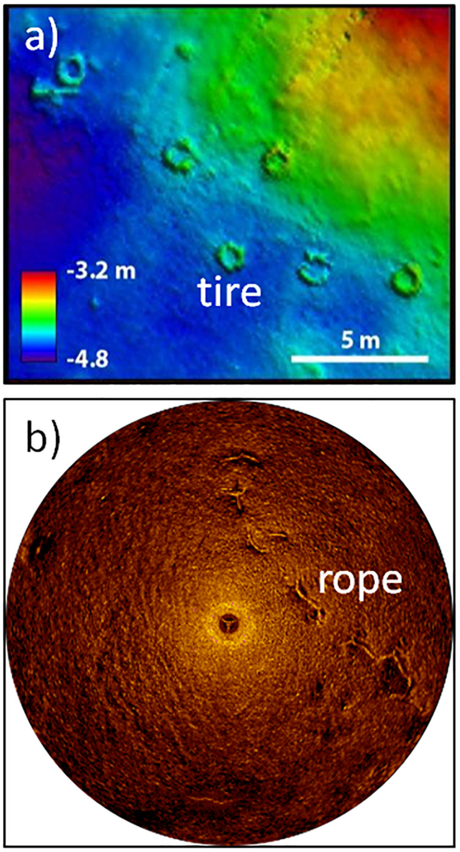

FIGURE 2 | (a) Example of tires on the Venice Lagoon seafloor mapped with a high-resolution MBES (modified from Madricardo et al., 2019). **(b)** Example of rope fragments on the seafloor mapped with HRSS during the "GHOST" project.

Modeling Litter Dispersion and Fate

Numerical models can be used to predict the fate of litter in the sea and its effect on marine organisms; however, we are still some distance away from developing a fully multi-disciplinary approach, and there are still several gaps in knowledge and model development. Numerical models can integrate and account for the most relevant physical, bio-geochemical, and physiological processes and consider multiple stressors, feedbacks, and accumulation effects. Different model setups can produce a range of scenarios shedding light on the global impact of each process on short-, medium-, and long-term scales. The MODEL plastic workshop identified the water-sediment plastic interaction process as one of the three main knowledge gaps (Martins et al., 2019). The other two are the quantification of point and diffuse sources of plastic and the identification of hot spots of plastic accumulation.

Several studies focus on modeling floating litter at the global (Lebreton et al., 2012; van Sebille et al., 2015; Corral, 2017), Mediterranean and Adriatic scale (Mansui et al., 2015; Liubartseva et al., 2016, 2018; Carlson et al., 2017). Numerical models often estimate the distribution and convergence of floating litter by tracking the particle movement due to currents, wind and waves interacting sometimes with the shoreline. The wind drift routines are often derived from already existing oil spill codes. Some authors developed models with no particle sinking (Yoon et al., 2010; Critchell et al., 2015) or considered the wash ashore effect when particles enter grid cells with a model shoreline (Maximenko et al., 2012). Only a few studies investigate the fate of marine litter taking into account loss by degradation, fragmentation, sinking, ingestion, and bio-fouling. These processes influence the size and the density of the particles changing their pathways in the marine environment. However, these processes are difficult to parameterize accurately.

Only a limited number of studies explicitly focus on macro-litter. Corral (2017) developed a simple routine for degradation/sinking process parameterization. Their model evaluated the global 'plastic cycle', indicating the areas where litter can accumulate with time. The study showed that sinking can occur at multiple sites along shores on the pathway to and from the gyre in the Pacific.

In other cases (Liubartseva et al., 2016), sinking is computed in a statistical way taking into account the age of particles while neglecting particle change of buoyancy and subsurface transport by a 3D current field (Liubartseva et al., 2018). Critchell and Lambrechts (2016) developed a plastic fate model: plastic particles enter the sea as macro-plastic and are directly affected by the wind. Later particles can go through beaching and re-floating, settling, degradation into micro-plastic, and burial in the sediment. No seafloor re-suspension and no return flow from open boundaries are considered. The mathematical treatment of the sinking plastic is the same for both micro and macro plastic using different settling rate coefficients. The sensitivity analysis of the tool offers a useful guide to set-up processes in other models highlighting the overall relevance of the input data in the definition of litter sources.

Jalón-Rojas et al. (2019) developed a numerical model for micro-plastic debris to include all these processes. In addition, they presented a sensitivity analysis of the tools to assess which variables influence the sinking of particles. Their results indicate that plastic density and biofilm thickness and density have the biggest effect on the transport, followed by turbulent dispersion and washing-off.

What is still missing is a description of the relationship between micro- and macro-litter and the water column and seafloor. This aspect is poorly understood and has been neglected for a long time in marine litter modeling. Some studies are starting to consider this aspect (Gutow et al., 2018; Palatinus et al., 2019). Recent results indicate the possible existence of micro-litter fiber carpets on the ocean floor (Woodall et al., 2014; Hardesty et al., 2017) and the relevance of the near-bottom transport for the seafloor litter distribution (Pham et al., 2014).

Gutow et al. (2018) collected floating and seabed macro-litter and investigated their relationship using numerical models without sinking processes and statistical analysis. Their results highlight the relevance of biofouling and of near bottom transport. Palatinus et al. (2019) collected field data of floating macro- and micro-litter and seafloor micro-litter in the Adriatic Sea, along a part of the Croatian coastline. No clear correlation was found between floating macro- and micro-litter or between floating and seabed micro-litter data. This study, together with others in the Mediterranean area (Suaria and Aliani, 2014; Carlson et al., 2017; Fossi et al., 2017), points to the need of an improved understanding of processes and further modeling. To be compared with field data, model results need to be calculated on the basis of a 3D hydrodynamic model with high spatial and temporal resolution. At the same time, the particle tracking model has to take into account the wind drift effect, particle sinking and the subsurface and near bottom transport.

A crucial point in all the numerical approaches is to define the input characteristics in terms of how often, how much and what kind of litter enters in the model. The main sources of litter in the ocean are from land (Hardesty et al., 2017). Several studies estimate the amount and kind of litter on beaches (Vlachogianni et al., 2018) and seabed (Strafella et al., 2015). Lebreton et al. (2012) and Liubartseva et al. (2016) estimate the quantity of floating litter from the main cities, rivers and from shipping lines. Missing in these previous works is the amount of litter deriving from fishing activities and from aquaculture plants.

Another relevant point is that sinking particles are represented as spherical particles with neutral buoyancy. In more complicated studies, particles with asymmetrical length and width sink differently depending on the angle between object and current direction. For this purpose, the paper of Gabitto and Tsouris (2008) looks at the sinking velocity for a cylindrical shaped object, which, one could imagine, approximates the shape of a discarded net if it is rolled up. The results are corroborated with field data and experiments which are in good agreement with the equation in the case of small objects.

MANAGEMENT OF SEAFLOOR MARINE LITTER

Removal of Seafloor Marine Litter

Since marine litter has become a global threat, an increasing number of videos, photos and direct witnesses have showed to the world that fish and benthic organisms were not the only inhabitants of the seafloor. Many removal activities have been planned and implemented all over the world to restore marine habitats and save untold millions of marine organisms (Donohue et al., 2001; Cho, 2011; Szulc et al., 2015; Sahlin and Tjensvoll, 2018; Vlachogianni et al., 2018; Williams and Rangel-Buitrago, 2019). Removal activities may be subdivided into two main categories, retrieval performed by trawling or removal performed through diving surveys. The choice between the two methods depends on the water depth and the substrate characteristics (coherent, as rock or incoherent as mud or sand). On deep soft seafloors, fishing vessels equipped with trawling nets, chains, and chains armed with hooks are used, while on shallow rocky seafloors the scuba and/or snorkel divers are employed. Considering that the two methods are not interchangeable, i.e., fishing vessels cannot trawl on hard bottom and scuba divers cannot reach in safe operative conditions depths below 50 m, they lead to different results, in terms of retrieved material, costs and used technologies. Moreover, removal activities must be carried out only if the resulting environmental benefits exceed the disturbance or damage inevitably caused during removal operations, and only if operations can be performed in a safe and cost-effective way (Da Ros et al., 2016).

Fishermen, as key stakeholders, have been shown to play an important role for the collection of marine litter through the implementation of Fishing for Litter (FfL) activities. These are clean-up actions aimed both at removing litter from the seafloor using fishing vessels and at increasing the awareness of the fishery sector toward the marine litter issue (Ronchi et al., 2019). These FfL schemes are so important that the legislation supports them explicitly (see **Table 1**). FfL activities are commonly divided into two types of practices: active when the removal practices are performed by fishermen during specific funded clean-up campaigns; passive when the litter removal is carried out by fishermen during their normal fishing activities without any financial compensation (KIMO, 2014). The first pilot FfL projects was started in Scotland (UK) in 2005 and was coordinated by KIMO, an association of coastal local authorities whose goal is to eliminate pollution from the Northern Seas (KIMO, 2014). Later on, other FfL campaigns were organized in other Northern European Countries (Sweden, the Netherlands, Denmark. Norway, and Germany), South Korea, the North East Atlantic (OSPAR region), and the Baltic Sea (Ronchi et al., 2019). In the Mediterranean region a number of FfL initiatives were carried out in the framework of EU funded projects such as: DeFishGear[1], ML Repair[2], Plastic Busters[3], and Clean Sea LIFE[4].

Trawling activities, however, are not selective methods, both litters and organisms being collected from the seafloor. Only after the trawls have been completed is it possible to release the caught organisms back into the sea. Most of them, can be damaged and eventually die due to the trawling activity itself. Removal activities carried out by scuba divers may be more accurate, since operations can be performed manually or using scissors and cutters thus preserving marine organisms. However, only a limited amount of materials can be retrieved. Operative depths, visibility, and currents are the main issues for scuba or snorkel divers. Moreover, human safety must be considered in these types of activities. Retrieval activities performed by scuba or snorkel divers may be cheaper in terms of fuel consumption and technologies used and are, without doubt, more respectful of the environment. However, they are more expensive in terms of man hours (Riccato et al., 2016).

A removal protocol for divers, specifically designed for ALDFG entangled on rocky outcrops, was implemented during LIFE GHOST project[5]. The protocol was conceived and developed to be applied in a simply and univocal way, helping the researches step by step considering dichotomous choices. It considers human safety, biota safeguarding, with particular interest on protected species and habitats, and environmental pollution. Two subsequent schemes illustrate the procedure to be followed (**Figure 3**): the first scheme aims to identify the type of ALDFG and materials (**Figure 3A**). The second scheme leads the decision-makers to the final choice of removing or not removing the identified nets (**Figure 3B**) (Da Ros et al., 2016; Moschino et al., 2019).

The newest research approaches focus on implementing automatic or remotely controlled wireless devices capable of collecting plastics and other marine litter in order to conjugate accuracy and sustainability of clean-up interventions also in deep environments[6].

Removal strategies are curative measures and have always to be considered less effective than avoiding debris dispersal into the marine environment. The long-term efficacy of clean-up campaigns is not always guaranteed by the lack of legislative, economic, and infrastructural tools (Ronchi et al., 2019). However, the information they provide on marine litter sources, amounts, and impacts can be used to develop preventive measures (Richardson et al., 2019).

Recycling of Marine Litter

According to the “waste hierarchy” implemented within EU Directive 2008/98 (summarized in **Table 1**), proper management strategies for plastic waste should include recycling (mechanical and chemical) and energy recovery technologies. Landfill disposal, the cheapest but also less sustainable method for the environment and human health, should therefore be the last option to consider[7].

Mechanical recycling includes a series of steps: collection, sorting, washing, grinding, and extruding of the plastic waste, which is transformed into raw materials or secondary products without a substantial change in its chemical structure. Chemical recycling, instead, converts plastics into monomers, oligomers, and higher hydrocarbons using specific solvents (solvolysis), or thermic methods (pyrolysis), with the final aim of obtaining fuels and no-fossil alternative molecules (Ragaert et al., 2017). Waste-to-energy technologies allow to turning non-recycled plastic

[1]http://www.defishgear.net/
[2]http://www.ml-repair.eu/it
[3]http://plasticbusters.unisi.it/
[4]https://cleansealife.it/
[5]www.life-ghost.eu
[6]http://rozaliaproject.org/about/technology/
[7]https://ec.europa.eu/environment/waste/framework/

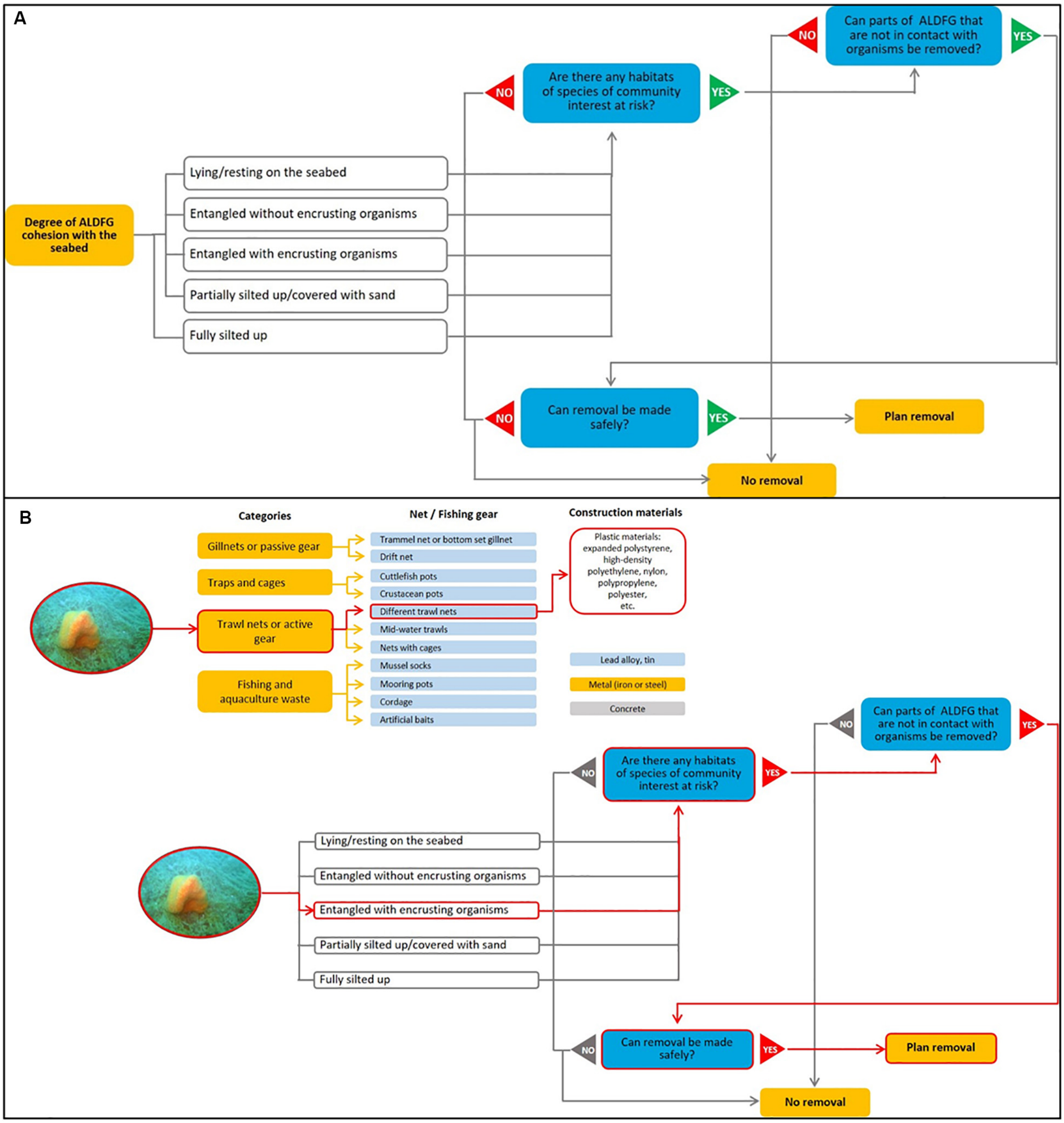

FIGURE 3 | (A) Decision flowchart for assessing the degree of entanglement and removability of ALDFG detected on the seabed. **(B)** Example of application with a bottom trawl to be removed, on which encrusting organism had grown (from Da Ros et al., 2016).

to oil, which can be used to power homes and businesses (Eriksson and Finnveden, 2009).

Worldwide consolidated entrepreneurial experiences were implemented in recent years in the management of plastic materials, especially those aimed at recycling disused nylon 6 fishing nets. Through mechanical recycling processes these materials are converted in various types of products such as accessories, sportswear, textile flooring which have contributed to the economic and image success of many companies (Charter et al., 2018).

However, considering marine litter, standard mechanical recycling methods are ineffective and uneconomical because plastics debris is mixed, contaminated by salts and incrusted with organic matter. From previous experience on marine litter management, it was found that incineration is the method most widely employed to treat marine debris (Iñiguez et al., 2016). Despite some examples where marine litter has been used to manufacture new objects, the magnitude of the marine litter problem requires similar magnitude solutions. Besides, the new objects manufactured from reclaimed marine litter will end up again as waste again sooner or later. If incineration and landfill are the most frequent options for marine litter once recovered from the seas and oceans, then there is little value in recovering it. Yet, there is increasing attention directed toward the synthesis of liquid fuels and chemicals from waste streams in order to reduce the carbon footprint of transportation sectors within a circular economy concept.

Pyrolysis of plastic waste generates a liquid oil (pyrolysis oil) which is composed of several hydrocarbon families, ranging from C7 to C30 + , similar to those of fossil crude oil (Buekens, 2006). Huge amounts of fuel are used globally every year for marine transportation: 207 Mton in 2017 (Fuels Europe, 2019), and huge amount of plastics waste is stranded in landfills and dispersed in the oceans. Therefore, recycling marine litter to produce liquid fuels for marine transportation seems an ideal solution to the problem.

Numerous papers have been published on the pyrolysis of plastic, where the pyrolysis oil can be used as a fossil fuel substitute or as a crude oil replacement (e.g., Buekens and Huang, 1998; Aguado et al., 2006; Blazsó, 2006). Few cases of large-scale applications are documented in the literature and none where marine litter is the feedstock. However, previous works have shown that it is possible to manufacture fuels meeting international ISO 8217 standards for marine fuels by mean of pyrolysis of post-consumer plastic waste (Faussone, 2018) at a relatively large scale of 10 ton/day range. Even ultra-low sulfur fuels can be produced from waste plastics for terrestrial transportation by pyrolysis and hydrogenation as upgrading step (Bezergianni et al., 2017).

Planning Stakeholder Engagement Tools

Effective solutions to prevent or mitigate the presence and the impacts of marine litter require a transition toward a more sustainable way of producing and consuming. With this aim, coordinated actions must be undertaken by several stakeholders involved in different sectors (Lohr et al., 2017; European Commission, 2019). This implies the active involvement of consumers, producers, policy makers, managers, citizens, tourists, fishery industries, companies, and many others. The stakeholder engagement requires a series of actions aimed at designing and organizing the most appropriate participatory process for each category (Walton et al., 2013). The final aim is to promote their participation and active involvement in the decision-making process. In this way, the possible conflicts between the different actors may be solved and the definition of operational solutions is obtained thanks to the contribution of all the actors, leading to a more willing attitude to use the newly implemented systems (Hartley et al., 2015a). Specific involvement strategies were implemented to achieve long-term improving results for marine environment (**Table 3**).

The fishing community naturally finds itself on the frontline of the fight against marine litter. Most of professional fishermen are aware that litter can impact the marine environment by damaging ecosystems and marine animals, including commercial species. They are also conscious that a significant portion of marine litter derives from fishing activities (Wyles et al., 2019).

Therefore, promoting the participation and the active involvement of both fishermen and aquaculture farmers in the fishing waste management process is a prerequisite not only for the long-term prevention of ghost nets and other marine litter but also for optimizing the recovery of discarded fishing nets and the other marine waste (Ronchi et al., 2019).

Policy makers, waste management companies and industries may play a crucial role in outlining a virtuous management system for marine litter, identifying appropriate options for their recovery, disposal and recycling according to the Circular Economy model and the waste hierarchy, with a view to maximizing the environmental benefits. Regular collaborative

TABLE 3 | Management actions to induce a change in the perceptions and attitudes of the different stakeholder groups.

Stakeholder categories	Actions	Examples	Measure
Fishermen and aquaculture farmers	Signing voluntary agreements of responsible fishing	Adopting national codes of practice or guidance, delivering the FAO Code of Conduct for Responsible Fisheries	Preventive
	Improvement of waste management practices	Installing waste containers in fishing vessels to dispose waste generated on board or collected during the fishing activity.	Preventive
	Participation in fishing for litter campaigns	Fishing for Litter scheme: -fishermen collect marine litter during their fishing activity without any financial incentive -fishermen collect marine debris during organized and funded campaigns at sea	Curative
	Participation in education program	Training programs to raise awareness of the impacts of fishing activities on marine biodiversity Training programs for the protection of cetaceans, marine turtles and seabirds.	Preventive
Local and national authorities, Waste companies	Improvement of waste management practices.	Enforcement of disposal collection points for civil wastes and fishing related materials (number and periodicity of collection).	Preventive
Industries	Implement new production chains.	Setting up of mechanical and/or chemical recycling process using marine litter.	Curative
Citizens, students, teachers	Increase awareness on marine litter issue and induce habit change.	Organization of seminars, events	Preventive
		Realization of informative materials	
		Implement specific education programs for students	
		Implement Arts and Science programs	
		Participation in clean up campaigns	Curative
	Support to scientific research activities.	Participation in citizen science programs	Preventive

partnerships between fishers, scientists and managers constitute the most effective way to access local ecological knowledge in fisheries assessment and management (Orensanz et al., 2015; Barnett et al., 2016). At European level, cooperation with fishery sector has allowed decision makers to put in place specific practical solutions aimed at removing marine litter from the sea, improving the waste management practices on-board and port disposal mechanisms with the final aim being to increase recycling process (NOWPAP MERRAC, 2015; Mengo, 2017).

Finally, also citizens may play an important role in triggering processes which may be effective in the fight against marine litter by: paying attention to a proper waste disposal, choosing sustainable certified products, reducing the amount of disposable waste and avoiding the excess of packaging and plastics. To achieve these goals, specific involvement strategies have been applied in order to educate citizens on the importance of the ocean following the Ocean Literacy principles (Santoro et al., 2017), to develop specific education programs for children and students (Hartley et al., 2015b), organizing clean up campaigns or participating in citizen science programs (Hidalgo-Ruz and Thiel, 2015). Art can also give a crucial contribution, reworking the information in the light of the artist sensitivity and creativity. Evocative art works can capture the attention of people and induce them to question their un-sustainable habits (Ellison et al., 2018).

FUTURE PERSPECTIVE: THE IMPLEMENTATION OF THE MULTI-LEVEL SOLUTION APPROACH

This work has given an overview of various strategies proposed for the monitoring and management of seafloor marine litter. This section of the article presents a multi-level solution to overcome some of the bottle necks highlighted in the overview:

- A combined underwater acoustic and video remote sensing approach should be adopted to efficiently map wide areas of the seafloor to identify marine litter hot spots. In these hot spots, video footage of the seafloor should be collected either by ROVs, drop frame camera or by divers to ground truth the acoustic data and to increase resolution where needed. Field experiments have been specifically designed to extract the acoustic signature of the various types of marine litter, both in the water column (**Figure 4**) and on different types of seafloor, with focus on

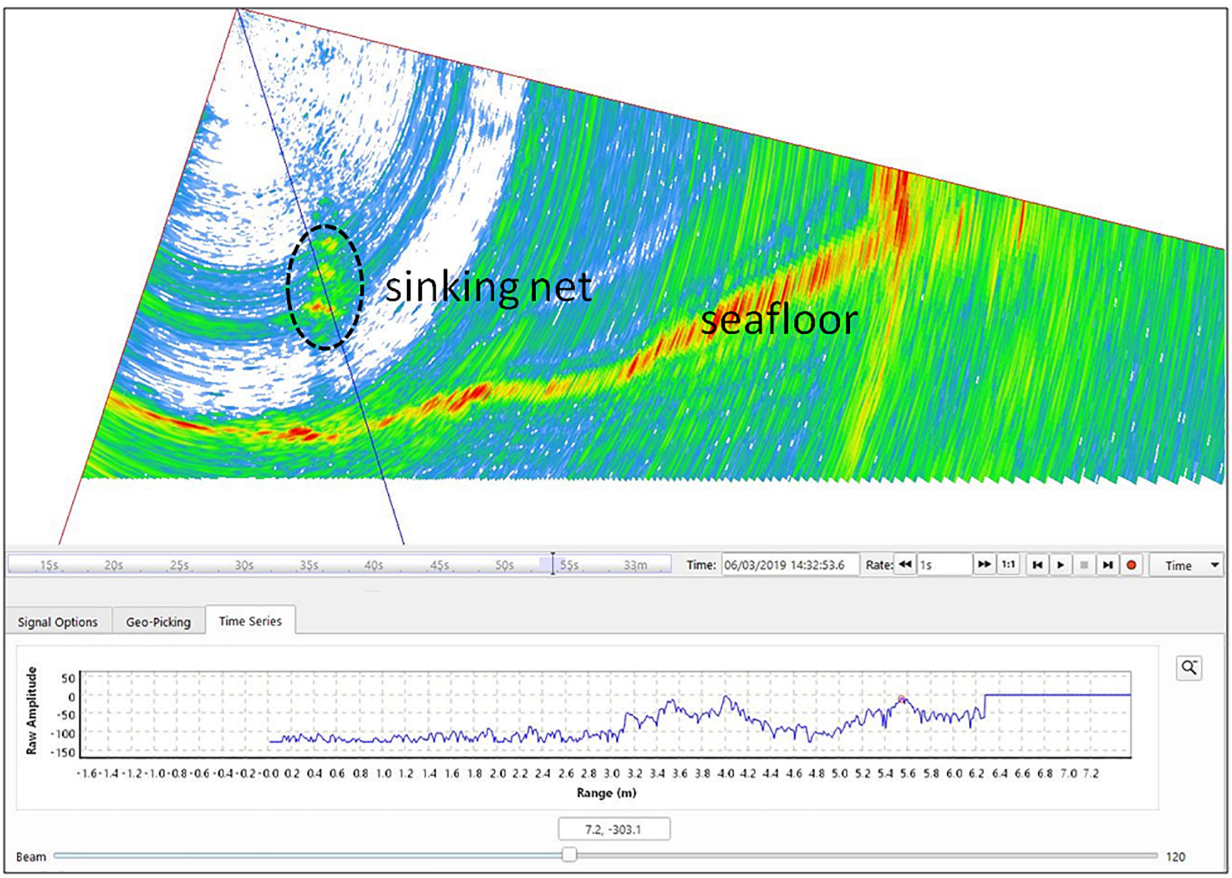

FIGURE 4 | MBES water column data collected to measure the marine litter sinking velocity and acoustic signature and echogram of signal extracted in correspondence of the blue line to identify the sinking net.

ghost nets. Also, the sinking velocities of different marine litter types can be measured to provide a parameter for the numerical modeling. Dedicated target identification algorithms need to be implemented to map and recognize as many categories of benthic marine litter as possible.

- A state-of-the-art Lagrangian model, taking into account sinking speeds based on previous works (Takagi et al., 2007; Gabitto and Tsouris, 2008; Monroy et al., 2017; Tang et al., 2018) should be further developed. The model will have to use input velocities provided from simulations performed using a regional ocean model. Moreover, specific parameterizations need to be developed to represent the sinking process of various types of litter and discarded fishing nets. The aim would be to estimate the trajectories of marine litter and thus identify potential hot spots to be incorporated in coastal zone management and maritime spatial planning strategies.
- The protocols developed during the GHOST project need to be improved and adapted to different geographical locations and substrates. The environmental benefits obtained from the removal actions need to be verified taking into consideration the characteristics of the specific species of fauna and flora populating the investigated areas. Finally, the removal of gear associated with different types of fishing techniques need to be incorporated into the removal protocols, such as long-line gear (100 m of nylon armed nets with hooks lost or discarded on the seafloor).
- Besides the monitoring and removing of the marine litter on the seafloor, there is a strong need to find new solutions to recycling it, giving the limitations of mechanical recycling, or dumping. In this sense the use of marine litter to synthetize liquid fuels for marine transportation seems to be an ideal solution to the problem. New research is ongoing to design fully portable prototypes based on a pyrolysis reactor with a total condensation system and a distillation apparatus that replicate the process of fuel synthesis employed in larger industrial units. Several conditions will have to be fulfilled: (a) fuel quality must comply with technological standards; (b) environmental impact must be in line with regulations; and (c) the equipment must be easy to operate in any context. Use of low temperature pyrolysis for the synthesis of marine fuels will motivate marine litter removal and collection.
- Demonstration days could be organized, targeting fisheries and aquaculture operators and local administrators engaged in the management of marine litter. These public events will show the advantage of collecting marine litter to be transformed into marine fuels to raise awareness and engage fishermen, aquaculture operators and local authorities in a real circular economy process.

CONCLUSION

This article presents an overview of the state of the art methods to deal with seafloor macro-litter pollution which include the monitoring of its presence on the seafloor, modeling its dispersion and fate, and the management strategies to prevent and mitigate its impact. The overview aims to provide a holistic framework to deal with this global challenge while identifying current gaps in the knowledge and presenting future perspectives.

In light of this approach, we believe that a multi-level solution need to be employed which puts in place a chain of actions dealing with the sea-floor litter from the assessment of its distribution, mapping hotspots, to its removal and finally to its transformation into an energy source. This means of obtaining viable marine fuel will then encourage fishermen and citizens to collect and deliver marine litter creating a circular economy process. This way, the proposed solution will transform a problem into an opportunity which could ultimately lead to a change in the perception and the behavior of stakeholders and a change in the legislation concerning marine litter.

AUTHOR CONTRIBUTIONS

FM collected the contributions from the different authors, prepared the section "Monitoring the Presence of Macro-Litter on the Seafloor," **Table 2** and **Figure 2**, and overviewed and edited the full document. MG wrote most of the section "Modeling Litter Dispersion and Fate" together with WM and FD, and prepared **Figure 1**. NN wrote the section "Planning Stakeholder Engagement Tools" and prepared **Table 3**. RF and FR wrote the section "Removal of Seafloor Marine Litter" together with NN and contributed to **Figure 3**. GF wrote the section "Recycling of Marine Litter." PM contributed to the section "Introduction." JB contributed to write the section "Planning Stakeholder Engagement Tools." AK and AP contributed to write the section "Monitoring the Presence of Macro-Litter on the Seafloor" and to produce **Figure 4**. VM wrote the section "Introduction," produced **Table 1**, and contributed to the overview of the manuscript. All authors contributed to the sections "Future Perspective: The Implementation of the Multi-Level Solution Approach" and "Conclusion." All authors contributed to the article and approved the submitted version.

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ARTICLES FOR FACULTY MEMBERS

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Implications of developing a tool for sustainability screening of circular economy initiatives

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Abstract

Circular economy seems to offer abounding opportunities for companies that are seeking to optimize their business practices while reducing the environmental burden. Circular economy therefore is often seen as a stepping-stone towards sustainability. However, to ensure the transition from linear to circular economy in a sustainable way, a shift requires implementation of not only financially beneficial circular strategies, but also environmentally and socially valuable ones. The challenge for companies is to understand how a particular circular initiative in their business context contributes to sustainability and what elements of sustainability have to be assessed prior to the initiative implementation. This paper illustrates how an indicator-based sustainability screening tool for circular economy initiatives can guide companies in their decision making towards a more sustainable circular initiative choice. In addition, the paper highlights challenges of measuring sustainability in a circular economy context.

Keywords: sustainability screening; circular economy; indicators for sustainability; micro-level; business processes; life cycle thinking

1. Introduction

Sustainable development has never been as high on the global agenda as nowadays. Since the development and adoption of the Sustainable Development Goals (SDGs) by the United Nations Development Programme, an enhanced awareness of the need to combat global challenges and work on improving environmental and social well-being and sustaining economic resilience can be observed across continents, countries, corporations and citizens [1]. It is also more evident that businesses are now embracing other ways of addressing sustainability, going from "internal" sustainability considerations, i.e. focusing mostly on internal benefits by creating value for shareholders, to the "external" sustainability considerations, by creating value for customers, societies and other stakeholders [2]. Circular economy (CE) is a new economic and industrial paradigm that offers a myriad of strategies that focus on rethinking businesses, products and systems with main goal of generating economic and social benefits by optimizing and retaining value of resources [3,4]. CE initiatives can be adopted at a product level (by designing products to allow for their longer use or by facilitating reuse, repair, remanufacture or recycling of products, parts and materials at the end of life) [5]; at production level (by focusing on material and energy efficiency of processes and by using renewable and non-toxic materials) [3,4,6], and at strategic level (by fostering innovative circular business models and circular supply chain configurations [7,8]). Therefore, many authors see CE as a tool for sustainable development that is expected to lead to new employment opportunities, maximized resource efficiency and development of new innovative markets for business growth [4,9–12].

Despite numerous benefits that CE potentially could bring, it is, however, important to note, that not all CE approaches are intrinsically sustainable and not necessarily better than "non-circular" solutions [13–16]. For example, product leasing is not automatically 'greener'[17], as it might inspire more frequent product replacement, therefore leading to an increased

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production. Also, there is a risk of "burden shift" as a reduced impact in one stage of a product's life cycle can induce increased impact in another (e.g. due to excessive use of energy and transport) [14]. For instance, using a mixture of recycled and virgin feedstock in product manufacture can contribute to lower virgin resource consumption in the beginning of product's life; however, it could make recycling at the end of life complicated or impossible, possibly leading to higher energy use and larger fraction of waste generated in the recycling process. It becomes evident that due to the abundance of conceptualizations of CE, the dominant focus on recycling and lack of focus on consumers, supply chain and novel business models as enablers of CE [6,20,56], industrial practitioners are struggling to understand CE and are not aware that CE should be approached from a systems perspective, often requiring fundamental changes [20,23]. Furthermore, many academics try to contrast CE and sustainability, highlighting that CE stays unclear on its contribution to sustainability, particularly to social well-being [3,57]. Authors as Sauve et al., [58] explain that CE can be defined as a "bottom-up" approach, while sustainability is a "top-down" approach, reckoning that they ever overlap.

Therefore, in order to ensure a more sustainable transition from linear to CE, micro-level actors (industrial practitioners) need to be supported in the assessment of how particular CE initiatives they are considering will contribute to sustainability.

This paper presents the implications of conceptualizing and developing a tool to assess the potential sustainability impact of CE initiatives implementation across a number of business processes in manufacturing companies. The ultimate goal of the sustainability screening tool is to support decision-making process and allow for comparison of different CE initiatives and other improvement initiatives across business processes in their potential contribution to economic resilience, environmental integrity and social well-being prior to actual implementation. The sustainability screening tool employs an indicator-based approach, allowing for the assessment from all the three main angles of sustainability and providing early warning information for decision makers [18,19]. The sustainability screening tool comprises of the database of sustainability-related key performance indicators (KPIs) charted according to the selected criteria, such as business processes and circular economy strategies, and the corresponding guidelines for KPIs selection. This paper is designated to the development of the KPIs database as one of the main components of the sustainability screening tool for the assessment of circular economy initiative implementation.

This paper is structured in the following way. Firstly, it provides the theoretical background that has influenced the development of the sustainability screening tool and its contextual application (section 2), secondly, it explains the research methodology used to extract indicators to be used as a foundation for the tool (section 3), thirdly, it elaborates on the foreground of the sustainability screening tool, namely identification and classification of key performance indicators (KPIs) (section 4), followed by a discussion on main gaps and particularities of making sustainability assessment in a CE context. Lastly, suggestions for further development and improvements are discussed in the conclusion (section 5).

2. Theoretical background

2.1. Circular Economy initiatives and Business processes

There are more than 100 definitions of CE [20], that are being suggested and widely used by both academia and governmental and industrial actors around the world. Many authors call CE as a business or economic model [3,9,20], others refer to CE as an industrial system [21], however most agree that CE aims at fostering economic prosperity and boosting growth by preserving and regenerating environmental quality. CE relies on principles of regenerative and restorative design [21], industrial ecology [6], cradle to cradle approach, eco-efficiency and eco-effectiveness, performance economy and the extended producers responsibility [9,22], and involves systemic thinking [21,23], thus can be understood as a paradigm that creates a relation between pre-existing independent concepts (an umbrella concept) [24].

The authors of this paper have adopted one of the CE definitions, provided by Ellen MacArthur Foundation, where CE is defined as "… is an economy that provides multiple value creation mechanisms, which are decoupled from the consumption of finite resources" [19].

CE principles are viewed by majority of authors as "how to" for CE and are sometimes referred to as "initiatives", "strategies" [25], "resource efficiency strategies" [26] or RE-strategies (e.g. reuse, recycle, recover, remanufacture, etc) [27–29]. In this research, the model for CE strategies proposed by Potting et al., 2017 has been adopted and slightly restructured. The modified model gives a good overview of major existing CE initiatives, gives definitions of each initiative and examples of implementation.

Business processes (BP) are structured activities or tasks that need to be managed to produce a specific valuable outcome (e.g. service or product) [30]. BPs can be seen as a "playground" for delivering the CE initiatives, meaning that CE initiatives can be embedded into different BP to bring desired improvements and potentially contribute to sustainability.

2.2. Sustainability assessment

Sustainability assessment (SA) is a process that directs the planning and decision-making towards sustainability [31]. There are different types of sustainability assessment, for example, ex-ante, which helps assessing sustainability impact of current or future actions or initiatives, and post-evaluation, which evaluates the consequences of actions taken [32]. This research presents a SA of an ex-ante type, aiming at "predicting" potential contribution of particular actions to sustainability. Moreover, its purpose is to assess actions' contribution to social well-being, economic prosperity and environmental integrity rather than simply "direction to target", thus enabling decision-makers to determine which actions should or should not be taken [33]. SA of CE initiatives contributes to better understanding of sustainability within CE context, as CE can be seen as a means towards achieving desired sustainability, however, whether CE brings desired effects has to be carefully predicted, monitored and evaluated. The tool to SA in this research is called sustainability screening and is built on an indicator-based approach. The indicator-based approach for sustainability screening provides a solid, traceable and measurable ground for identifying future consequences of proposed or current CE actions in relation to the economic, environmental and social benefits. Sustainability screening allows companies to apply their data to calculate suitable indicators, thus making a screening of proposed CE actions on their potential sustainability impacts. According to Waas et al., [33] “an indicator is the operational representation of an attribute (quality, characteristic, property) of a given system, by a quantitative or qualitative variable (parameter, measure)…”. Indicators enable detection, monitoring, quantification, assessment and interpretation of the systems’ status in terms of sustainable progress. In addition, indicators allow comparison of alternatives and highlight potentials for optimization; then can help internal and external benchmarking and be used as a tool to communicate and promote sustainability [33–35].

3. Research methodology

In order to develop an indicator-based sustainability screening tool, a systematic literature review was executed. The main goal of the systematic literature was to identify leading key performance indicators that will form a base for the sustainability screening of CE strategies across different BP. The systematic literature review followed the procedure proposed by [36] consisting of: (1) review planning; (2) review execution and (3) results analysis. The review focused on identification, selection and systematization of leading sustainability related KPIs.

A literature search was performed in the databases Scopus and ISI Web of Knowledge, due to availability of advanced web search mechanisms, high volume of indexed papers and proven relevance in the fields of research [37–39]. Search strings (title, abstract and keywords) were composed of the main keywords and their synonyms, as follows (“key performance indicator*” OR “metric” OR “index” OR “indices” OR “measure*” OR “indicator*” OR “evaluation”) AND ("sustainab*" OR "triple bottom line") AND ("social" OR "environment*" OR "econom*") AND (“business model" OR "product dev*" OR "end of life" OR “supply chain"). The initial set of found literature consisted of 892 documents. The results were further refined by choosing relevant scientific area (engineering, environmental science, economics and social science), so the second set consisted of 665 documents.

The next step was to gradually select relevant literature by screening the title, abstract and keywords, and when reading the introduction and conclusion applying the inclusion criteria. Inclusion criteria the studies must meet are following: a) contain proposition, application or review of a leading indicator for sustainability assessment; b) focus on manufacturing companies or at micro-level (product, process, industry). The final set consisted of 52 publications that also included articles used from the “snowballing technique”, i.e. using references’ references to develop the search out to all relevant studies. This allowed retrieving around 400 leading sustainability related KPIs. The KPIs were then charted according to such criteria as business processes, circular economy initiatives, and sustainability dimensions and were all registered in an excel database. The characterization was done based on the literature the KPIs were extracted from. For example, product related KPIs were assigned to BP of pre-manufacturing, manufacturing and end of life stages, i.e. following the usual life cycle approach. Supply chain related KPIs were assigned to supply chain BP, business model KPIs were assigned to business model BP. Furthermore, the retrieved KPIs were classified according to CE initiatives and sustainability dimensions. Additional information about each KPI was collected and registered, including name of the KPI, symbol, detailed description of the KPI, how to measure it and unit of measure.

4. Conceptualizing and developing an indicator-based sustainability screening tool

The KPIs retrieved from the literature are quantitative and leading, or proactive, indicators. The advantage of using leading indicators is that they provide warning in advance and give a good estimation of the potential sustainability impact of the proposed actions [40–42]. At the same time, lagging, or reactive, indicators help measuring the effect of actions approved and undertaken by the company. Many authors [40,41] advice using leading indicators for corporate performance measurements, as they provide insight into the organization’s potential impact and indicate about future performance, thus assist decision makers with information to introduce improvements in the early stages of decision making. One of the challenges of working with leading KPIs, however, is the level of uncertainty of data needed to calculate the KPIs. Since the decision needs to be taken early in the process, data may not always be accurate or available. Nevertheless, leading KPIs can be used throughout the implementation of the initiative to monitor its performance and to indicate future improvements.

In terms of representation of KPIs according to the three dimensions of sustainability, the largest fraction (about 65 %) of all KPIs retrieved from literature belongs to the environmental dimension, which is also confirmed by other authors working with sustainability indicators [43,44]. At the same time, the social dimension is “underrepresented” by KPIs, also confirmed by literature [45,46]. In terms of KPIs distribution according to BP, most of the KPIs are related to the pre-manufacturing stage, which includes inbound logistics and product design and development. The “end of life” BP has also a very good KPIs coverage. This can be explained by the fact that aspects related to the life cycle of a product are very well researched and KPIs are developed, again, with a large focus on environmental part. In terms of business model, many KPIs belong to the economic dimension and only few relate to social and environmental, which several authors had expressed their concern about [2,47]. Regarding the supply chain BP, many KPIs are available and are very aligned with indicators related to product development, manufacturing, and end of life, however with a gap in social indicators [48]. Despite many KPIs being available for supply chain measurements, literature reports difficulties when it comes to KPI application. Many companies do not have bilateral agreements with all the suppliers in different tiers, thus have no accessibility to their data [48,49].

To develop the indicator-based sustainability screening tool, the identified KPIs were classified according to different categories. The classification categories were: the BP, the CE initiatives, and sustainability dimensions.

CE initiatives included in the sustainability screening tool are: reinvent; rethink; reduce impact in raw material, sourcing and product design; reduce impact in manufacturing and logistics; reduce impact in product use and operation; recirculate products and parts by providing: upgrade, repair and maintenance, reuse, refurbish, remanufacture, repurpose options; recirculate materials by providing: recycle, cascade and recover options. BP, included in the sustainability screening tool, are encompassing primary activities, mainly related to life cycle of a product and related services, i.e. product development, manufacturing, closing the loop (end of life), but also business model and supply chain.

An example of a BP that can encompass specific CE is given in figure 1. Important to emphasize, that CE often requires several configurations of CE initiatives to be introduced in business in sequence or parallel (for example, a business model for leasing or renting a product to give access to more customers, may involve redesign of a product to make it more durable and easier to reassemble in case repair is needed). Some authors [24] stress that implementation and assessment of CE initiatives should shift from singular towards different CE configurations.

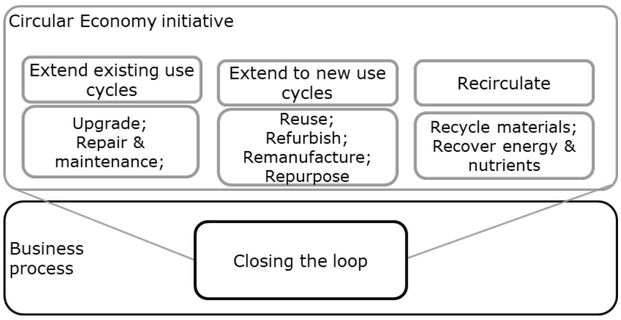

Fig. 1. A business process and corresponding circular economy initiatives.

Sustainability dimensions, the KPIs are also classified according to, are defined as economic resilience, environmental integrity and social well-being, each comprising several categories, which align with international standards and frameworks as shown in the table 1.

These sustainability categories were then unfolded to aspects, allowing to be analyzed by the KPIs, assigned to them. An aspect is defined as an element of an organization's activities, products or services that interacts with the environment, society and other stakeholders (partners, suppliers, employees) [53]. An aspect may trigger a change (impact) in the economy, society or environment, therefore has to be managed responsibly. For instance, "supply chain category" under social well-being dimension has one of the aspects "relationships", which can be assessed with help of several KPIs assigned to it, one is them being "suppliers that affirmed business code of conduct and ethical policy" [54]. Similarly, category "product composure" under environmental integrity dimension has one of the aspects "product circulation", which can be assessed by calculating assigned to it KPI, "product degree of utilization" [55].

Table 1. Sustainability dimensions with corresponding categories and occurrence in international standards and frameworks.

Sustainability dimension	Categories	Alignment with
Social well-being	supply chain, employees, customers, local community	S-LCA [50] IChemE [51] GRI [52]
Economic resilience	value creation, value distribution investment, product information	GRI IChemE
Environmental integrity	material, energy, transport, product composure, packaging, waste, water, land, air	ISO 14031[53] GRI IChemE

Such hierarchical model (i.e. sustainability dimension – category – aspect – KPIs) allows decision makers detect and understand what a specific value of a calculated KPI can signal about in relation to the management of a specific organizational sustainability aspect.

In addition to the classification categories, more information was added to help understanding and interpreting each KPI. Additional information indicates name of the KPI, symbol, detailed description of the KPI, how to measure it and unit of measure. Furthermore, each KPIs is supplemented with an elaborated explanation of the purpose of measuring it and what its measured value can potentially signal about. Also, more information is provided about what benefits a company can potentially achieve by managing a certain aspect, hence improving the value of a certain KPI.

In order to select KPIs, it is important to define the scope for the sustainability screening. The scope can be defined by prioritizing the business process and /or CE initiative that the company wants to introduce and make screening for. Such prioritization allows filtering suitable KPIs for the chosen scope. The filtered set of proposed KPIs can then be reviewed and customized depending on the particularities of the organizational business processes. Despite all the indicators in the tool being referred to as key performance indicators, only the final set of indicators chosen will consist of KPIs that are key for the screening of a particular CE initiative by a particular company. At the same time, other indicators in the tool will not be taken into account, although can still become key indicators if the company decides to change the scope of the screening and select different combination of CE and BP.

An example of the set of KPIs that can be obtained from the screening tool is given in the table 2. In order to arrive at the given set of KPIs, a specific combination of BP and CE strategies was selected. In the example from the table 2 it was assumed that the company wants to introduce remanufacturing of its used products as a part of its business model. Therefore, the business processes "business model" and "end of life management" as well as the CE strategy "remanufacturing" were selected as the scope for the screening that allowed filtering the suitable set of KPIs. Notably, the set of KPIs aims at screening the CE initiative on its potential sustainability impact, but not at assessing the internal business suitability to undertake CE.

Table. 2. Example of the set of KPIs that were obtained from the tool by limiting the screening scope to "business model", "end of life management" and "remanufacturing". The KPIs are also charted according to sustainability dimensions.

Business Processes*		Circular Economy Strategies*	Sustainability dimension			KPI
Business Model	End of life Management	Remanuf	Env	Soc	Econ	
x	x	x			x	Revenues from remanufactured products
x	x	x			x	Take back cost
x	x	x		x		Number of customers with take-back contract
x	x	x			x	Cost of remanufacturing
x	x	x	x			Useful Life of a product
x	x	x	x			Distance traveled in reverse supply chain

**Greyed BP and CE in the table are taken as an example, as there are more BP and CE strategies available in the screening tool.*

5. Conclusion and future work

This research is a first attempt to conceptualize and develop a sustainability screening tool to enable assessment of potential sustainability impact of future or current CE initiatives across a number of business processes in manufacturing companies. It is evident that due to the abundance of conceptualizations of CE and various implementation strategies, it becomes challenging for decision makers from industry to identify which initiative would bring more benefits to them and their stakeholders. Moreover, the main goal of many industries is to contribute to sustainable development by introducing improvements into their business processes, including CE initiatives. Therefore, the sustainability screening tool is intended to support industrial practitioners to assess CE strategies before implementation and possibly guide them towards choosing and improving the initiatives that are to benefit to environmental integrity, social well-being and economic resilience.

The main objective of the screening tool is to support decision makers from industry in: selecting suitable KPIs according to the CE initiative or the improvement in a BP that they consider introducing; providing guidelines how to calculate suitable KPIs and then how to interpret their values for sustainability assessment and comparison of different initiatives. Since the sustainability screening tool is under development, there are several considerations to be made in order to improve it. First, most of the retrieved KPIs cover environmental dimension of sustainability, whereas social dimension is underrepresented by KPIs in most CE initiatives and BP. The screening tool can be enhanced by making suggestions of new social KPIs. Second, despite the environmental dimension being most covered, a variety of KPIs need to be redefined with the purpose of addressing the particularities of circular systems and products (for example, the product's lifetime can be lower than industrial average, however the intensity of its use is higher, allowing it to deliver its function many more times than an industrial average). Also, system models for each CE strategy have to be understood and explained to support companies in the selection of suitable KPIs for their CE strategy or BP (for example, system model of remanufacturing process clearly showing when does the process of remanufacturing start and finish and what operations it involves). Third, the KPIs have to be critically analyzed and clarified to allow for transparent and effective interpretation of KPIs and their calculated values (for instance, having a KPI addressing number of locally purchased goods can bias companies to make more focus on local supplies, which are not necessarily "better" than non-local). Fourth, the tool has to be validated by testing it in manufacturing companies. Application of the sustainability screening tool in industry will serve to assess the usefulness of both, the KPIs the screening database comprises of (relevancy and applicability of KPIs) and the screening tool itself (accuracy of delimitation from the database of KPIs).

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ARTICLES FOR FACULTY MEMBERS

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Innovative financing mechanism for blue economy projects

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ABSTRACT

Investments flowing into blue economy projects are estimated to be much lesser than the requirements, for achieving the targets set out in the UN Sustainable Development Goals. Blue economy projects are typically financed through conventional means of public and development finance. However, the nature and characteristics of blue economy projects transcend the need to extend beyond the conventional financing options of multilateral/bilateral aid. The objective of this article is to assess if the existing blue economy initiatives are adequate to the sectoral investment needs and to develop contours of a framework that could accelerate the blue economy investments. The research finds that the current initiatives such as blue bonds are relatively small and accelerating investments requires access to additional financing instruments and a transformative change in participating stakeholders. Using a Theory of Change approach, contours of a framework that pools in low-cost funds from a diverse set of investors to be deployed for either public sector promoted large impact projects or individual blue economy projects through market-based instruments are suggested. The findings contribute to the ongoing debate on how to improve the financial capability of various blue economy stakeholders and enable them to configure more sustainable financing mechanisms.

1. Introduction

Oceans make life possible and support the livelihoods of billions of people. The importance of marine life is emphasized through Sustainable Development Goal 14 that deals with life below water. The concept of sustainable oceans' economy relies on maintaining a balance between ecological and economic imperatives. The blue economy refers to the use of ocean and associated resources sustainably for economic development while protecting the ecosystem. and is defined as "… practical ocean-based economic model using green infrastructure and technologies, innovative financing mechanisms, and proactive institutional arrangements for meeting the twin goals of protecting our oceans and coasts and enhancing their potential contribution to sustainable development, including improving human well-being, and reducing environmental risks and ecological scarcities" [1]. Clean technology and renewable energy sources provide necessary tools for the blue economy to achieve social and economic stability characterized by inclusiveness, stakeholder participation, and transparent and accountable processes [2]. The market value of coastal, marine resources, and related industries is an estimated USD 3 trillion to USD 5 trillion, which is nearly 5% of global GDP [3]. In some East Asian countries, the ocean economy accounts for 15%–20% of GDP [4]. Better management of blue economy assets can enhance productivity, improve operational efficiency, and provide attractive returns for stakeholders. Yet, such an important resource has been misused and improperly managed, causing irreversible negative effects to the environment and marine life in particular, and the livelihoods of many communities along the coastline.

Human activities are impacting the earth's natural landscapes at an alarming pace. The health of oceans, earth's largest natural system, is rapidly deteriorating. Dumping of chemicals and trash generated from land sources into oceans is a significant source of marine pollution [5]. This type of pollution severely impacts the environment, poses adverse health risks to all organisms, and is a threat to economies. Additionally, the oceans are impacted by climate change, environmental pollution, unsustainable fishing, and unregulated coastal development, which present a grave threat to marine life and the productivity of oceans. Nearly 50% of coral reefs were lost in the last three decades and at this pace, it is estimated that about 90% of this unique ecosystem would perish by 2050 [6]. The largest negative impact on marine ecosystems in the last 50 years has been through overfishing and land/sea-use change

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[7]. Besides, eight million tons of plastic enter the ocean annually, mostly from Asia, along with huge volumes of agricultural pollutants and untreated wastewater. Population growth in cities, rising economies in Asia, along with declining fish stocks, pollution, water crisis, and climate change, necessitate an urgent need and incentives for promoting the blue economy.

Human activities on land that result in various forms of pollutants are responsible for almost 80% of marine pollution [2]. Waste in the form of plastics is the biggest threat, followed by sewage, pesticides, industrial chemicals, and other solid waste. China, Indonesia, the Philippines, Thailand, and Vietnam contribute to approximately 60% of the plastic waste entering the oceans [5]. Plastic bags, fishing nets, and other debris that find their way into the sea as waste dump directly affect marine life. These are the cause of unnatural death for a large number of seabirds and sea turtles every year. Through the seafood chain, these constituents enter the food chain and pose serious health hazards when consumed by humans. About two-thirds of marine lives are under threat from the daily use of chemicals, including household cleaners. Nearly half of the total of 120 million tonnes of nitrogen used for crops end up flowing to oceans [8]. Ocean acidification by the shipping industry due to nitrogen oxides and sulfur oxides that are emitted, caused by burning of marine fuels, ballast water, greywater, and other cleaning material is on the rise [9]. The rise in seawater is estimated to be 0.13 inches per annum over the last two decades, which is almost double the rate at which sea level rose in the previous 80 years [10]. Expected consequences of seawater rise are frequent wetland flooding, increased erosion, and farmland contamination and more importantly a serious threat to marine life. The quantum of hazardous waste dumped into water bodies by mining companies every year is estimated to be 220 million tonnes [11].

Many countries have indicated their intention to curtail the ocean pollution, evident through their articulation of nationally determined contributions under the Paris Agreement and the Aichi targets (part of the Convention on Biological Diversity). The conventional funding sources that underpin the commitments include the official development assistance and public budgets [12,13]. Newer sources have emerged in the recent past that includes philanthropic grants [14–16]. The avenues available under green finance are sought to be utilized for funding the blue economy, however, the past trends of green finance indicate that water-related sectors did not manage to raise substantial sums [17].

The financial constraints include a lack of fiscal measures and declining development assistance and funding from private investors through foreign direct investments, in addition to some countries also facing huge burdens of external debt. The other challenges for attracting investments into blue sectors arise from weak enabling frameworks, which include institutional, regulatory, governance, legislative and human resources that are required for establishing strong intersectoral and transboundary partnerships [18].

A survey conducted by Responsible Investor, reached out to 328 institutional investors in 34 countries to assess their interest in financing the ocean economy [19]. The results indicate that nine out of 10 investors are interested in investing in sustainable blue economy projects and a third of the respondents regard the sector to be an important one in 20The survey highlights that public pension funds, charitable organizations, wealthy families, and individuals are more interested in blue finance. The reasons cited are positive financial gains in addition to advancing SDG 14 to make a difference to society and the environment. The key sectors identified by investors include climate change mitigation and adaptation through marine renewables, marine plastic pollution, sustainable fisheries, and aquaculture. To reduce the risk in investments, the respondents opined that strengthening enabling conditions and developing innovative finance approaches was a necessity [19].

From the time Robert Costanza estimated the annual value of natural capital [20] there have been numerous attempts at valuing the ocean economy [5,12,15,21–23]. It is estimated that the ocean economy if treated as a country, would be the 7th largest economy in the world [2]. The contribution of marine fisheries to the global GDP is estimated to be more than US$270 billion per year [24] and result in benefits of nearly USD 2.5 trillion per annum to humanity [23]. However, the investments that go into managing this precious resource have not kept pace [16].

The approach to developing a blue economy hinges on balancing the twin objectives of economic growth and environmental sustainability. Growing the blue economy provides a unique potential for expanding a range of interdependent sectors and services, predominantly tourism, fisheries, and aquaculture, and ocean renewable energy. This expansion requires access to long-term financing options, that provide the scale and flexibility for different stakeholders.

The trends witnessed in financing and investments in the blue economy have been more significant in coastal and ocean-related sectors, through various blue financing instruments. Limited success was seen in developing new and innovative financing mechanisms to attract financing for other blue economy sectors[12]. For sectors to transition to the blue economy and gain from the potential these sectors have to offer, developing a range of scalable financing instruments is one of the most pressing challenges that countries are facing.

A key challenge that remains includes an assessment of the adequacy of the current blue economy investment products in relation to the investment needs of various stakeholders, and what should be contours of a blue finance mechanism that could accelerate investments from diverse stakeholder groups. Theory of Change (ToC), an approach that is outcome focussed while systematically assessing the context of the system [25], is adopted as a framework for configuring various interventions that are needed to promote increased investments into the blue economy.

Within this context, the research investigates the following questions:

- How do the recent blue investment instruments (in particular, blue bonds) compare with the investment needs of the blue economy?
- What are the contours of a financing mechanism that could be used by developing countries for accelerating blue economy investments?

The article is structured in the following manner. The conceptual framework of the method adopted is set out in Section 2. The current understanding of the blue economy financing landscape is set out in Section 3. Section 4 discusses the inputs, interventions, and imperatives for accelerating the blue investments and Section 5 presents the findings and conclusions.

2. Methodology: theory of change approach to reach intended outcomes

While the blue economy sectors are evidencing increased interest by the impact investor community, the scale and terms of investment are not in tune with the requirements [26]. There is a growing consensus on the outcomes of the blue economy financing landscape, and the stakeholders including the government agencies, development finance institutions, impact investor community is willing to make requisite interventions. The theory of change framework is widely used in impact investing as a steering tool to effectively measure and manage investments that garner positive change [27]. The process starts with the end goal of creating a sustainable impact and details out the steps that translate this intention to specific actions and result areas. ToC involves mapping the steps commencing from the current context to the desired transformation through various changes/initiatives. In essence, ToC comprises an interactive, iterative process used to develop a description of why and how a series of activities can lead the transformation in a particular context. ToC has been utilized across many disciplines including development research and social impact investing. The ToC approach encourages deliberations amongst various stakeholder groups on why certain activities would lead to expected outcomes, thereby building the confidence of prior initiatives [28]. ToC sets out the path from the initial state to the desired outcomes of a program or a project by setting out the logic, assumptions, influences, and causal linkages.

This research, therefore, adopts the Theory of Change (ToC) to analyze and evaluate economic and development initiatives [25], predominantly from an impact investment perspective. ToC as a concept and process is useful in investigating why and how a certain sequence of activities leads to a specific transformation in a given context. An intervention strategy based on ToC is reflective of a transformative change, from a current suboptimal situation to a more desirable high-performance ambience. In the international development context, it is seen as an outcome-based approach leading from the design, implementation, monitoring, and evaluation of schemes aimed at transforming the current context [27].

ToC typically comprises the following elements: a diagnostic of the current status (including the stakeholders involved who are part of the problem, and who could be the part of the solution), the long term transformation that is desired, series of change activities/events, assumptions for the same and transformation narrative summary (usually depicted as a schematic) [25]. The process of developing the ToC transforming the financing ecosystem for blue economy projects is based on literature review, perusing the summary notes of conferences on green and blue finance, and the program documents on the blue economy by the multilateral and bilateral agencies. The process is depicted in Fig. 1 below.

In the blue economy financing landscape, the current context relates to how the blue economy sectors are structured, the strengths and weaknesses, the motivations of various stakeholders who influence the conduct of the blue economy. There is an increasing consensus on the long term transformation that is desired (more investments and sustainable practices), based on the anticipated external and internal factors affecting the growth of the blue economy [12]. The requirements for such a long term transformation, the actions that would need to be undertaken, and the outputs of such actions which lead to the desired change, need to be based on the way the financing mechanism is likely to evolve for the blue sectors.

In this research, ToC is used ex-ante to systematically generate a picture of transformation through a series of change initiatives (goals and principles). These initiatives can be applied at different levels in the region based on the needs, local context, and exigencies. One of the main constituents for achieving the SDGs is to provide appropriate financing resources. This would involve providing adequate quantum, in a timely fashion, through appropriate instruments, and at an equitable cost. This vision could be achieved through a series of initiatives to be undertaken over the period. ToC approach can have substantial benefits that match the requirements, expectations, and challenges for achieving the financing needs of blue economy projects. Obtaining robust evidence would further enhance the theoretical understanding needed for achieving this transformation.

3. Diagnosis of blue economy financing landscape

Human actions have been adversely affecting the marine life through a myriad of activities including the discharge of urban pollution, overfishing, habitat destruction [29,30], leading to a severe drop in the ocean health, and consequently impacting the livelihoods of local communities on one end to the global trade and economy at the other extreme [31,32]. The 21st Conference of the Parties of the United Nations Conference on Climate Change included "Ocean" in the Paris Agreement and resulted in subsequent Global Climate Action Agenda. The Paris Agreement mandates the stakeholders to make their best efforts through "Nationally Determined Contributions" in responding to the threat of climate change. The stakeholders need to report parodically on their pollution levels and implementation plans. UNFCCC has a system in place for measuring, transparency, and verification. The Ocean and Climate Initiatives Alliance (OCIA) emphasizes the importance of cooperation and cohesiveness in achieving a greater impact on Ocean and Climate Action. To mitigate the declining ocean health, numerous commitments and initiatives have been taken by nations, within the Rio +20 outcome document, and through their nationally determined contributions. Multilateral and development agencies have also launched initiatives to protect the blue economy including the following ones listed in Table 1 below.

Despite these efforts, the lack of uniformity and alignment in the participating nations is apparent. As part of the Ocean Conference and the nationally determined contributions, nearly 1400 voluntary commitments have been made [12], about 70% of those had marine-related aspects [33]. However, the importance ascribed to SDG 14 is relatively lower [34], while the official development assistance to the marine sector has reduced more than 30% between 2010 and 2015 [35]. The inadequacy of conservation funding is widely prevalent [36] partly due to the reason that the project revenue models for most of the marine conservation projects depend on the monetization of economic rewards and capture of enforcement fees and penalties [37].

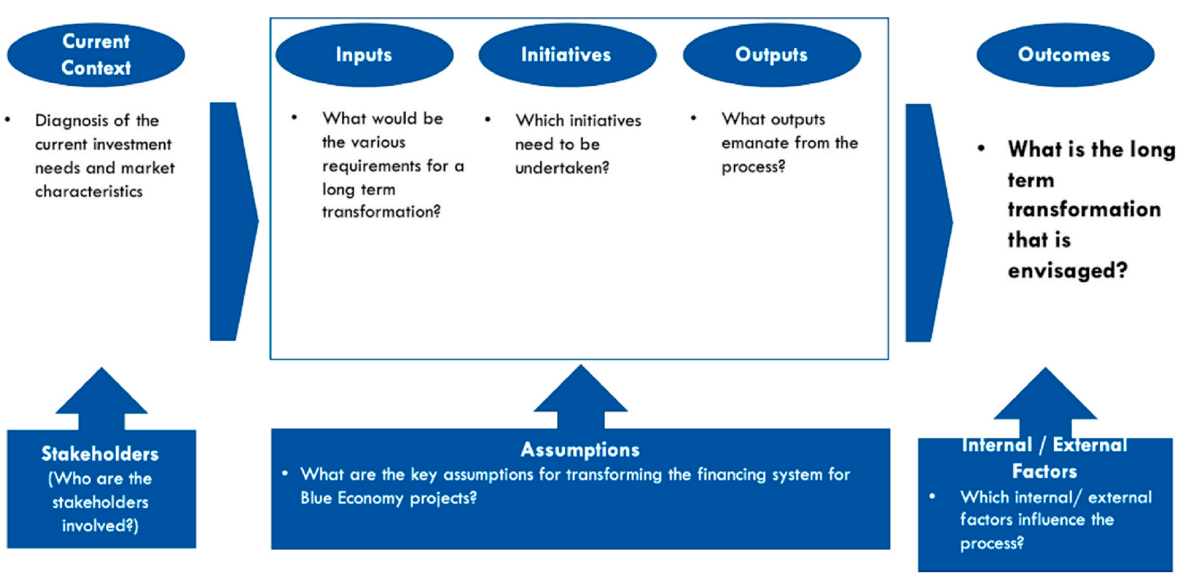

Fig. 1. ToC steps.

Table 1
Initiatives by Multilateral Agencies. Source: Authors Compilation from respective organizations' websites and press releases.

S No.	Entity	Blue Economy Initiative
1	Asian Development Bank (ADB)	ADB announced the "Action Plan for Healthy Oceans and Sustainable Blue Economies for the Asia and Pacific region" in May 2019, indicating a financial and technical assistance of USD 5 billion.
2	The World Bank	The World Bank's Blue Economy Program, PROBLUE was launched in September 2018, to support integrated and sustainable economic development in healthy oceans. This program addresses themes related to ocean pollution prevention, sustainable economic development of marine economy, developing institutional capacities of government and other stakeholders.
3	United Nations Environment Programme (UNEP)	UNEP drafted a "Marine and Coastal Strategy of UN Environment Programme for 2020–2030". The strategy sets out the guiding principles for sustainable ocean actions and emphasizes development of knowledge base relating to marine economy, promote circularity, encourage policies for sustainable utilization of coastal system resources and encourage adoption of innovative financing instruments.
4	United Nations Conference on Trade and Development (UNCTAD)	UNCTAD provides support for policy development, preparation of project pipelines, assist in developing regulation and dissemination of best practices in blue economy sectors.
5	European Union (EU)	The EU proposed a "Blue Growth" strategy in 2012 as a core approach for policies regarding Europe's large water bodies. The Strategy provides framework for cooperation between various stakeholders with the objective of ensuring the sustainability of the marine environment. The report on the "Blue Growth Strategy Toward More Sustainable Growth and Jobs in the Blue Economy" prepared by the EU in 2017, sets out their thrust areas including push for growth in blue energy, aquaculture, coastal and maritime tourism, blue biotechnology, sea bed mineral resources; use data analytics, spatial planning, and maritime surveillance.

The discourse on marine sustainability and urban pollution have been treated separately, though the integration is increasingly visible in the urban settlements [38,39], leading to the development of interrelated project ideas, such as urban runoff and sustainable drainage systems [40].

The estimates for ocean conservation funding are based on the United Nations Convention of Biological Diversity target of 20% of the ocean in the marine protected areas and are estimated to be of the order of USD 4 billion to USD 8 billion per annum [41]. The same was subsequently revised to USD 3 billion to USD 8 billion per annum for 10% of MPA coverage [42]. Under UNFCCC, USD 100 billion per annum by 2020, was committed by developed countries. Of the major funds established namely Least Developed Countries Fund, the Special Climate Change Fund, the Adaptation Fund, and the Green Climate Fund, an estimate by Guggisberg, indicates that only 6% is in marine or coastal initiatives [15].

Conservation of the ocean economy is being funded through a variety of sources, the most common ones being official development assistance and grants [36]. The funding availability is constrained by many factors including business and revenue uncertainties faced by the investors, legal and regulatory challenges (relating to property rights, policy certainty over the project life) [16]. The gap in conservation funding is quite significant and needs a combination of different sources to bridge the same. While the study by McKinsey estimates the gap in financing to be the order of USD 300 billion [43], various researchers have estimated the same at a much higher magnitude of approximately USD 7 trillion [14,36,44]. The blue economy projects have received a very marginal share of available conventional and green sources [16]. There have been arguments to enhance the share of private capital markets and the adoption of more innovative financial instruments [12]. Bonds specifically for ocean-related activities have been launched in the recent past. The deployment of such funds is sought across a diverse range of marine economy initiatives such as stakeholder capacity building and infrastructure projects [45].

The frameworks available under the Clean Development Mechanism (under the Kyoto Protocol for managing the greenhouse gas emissions) have been sought to fund the blue economy projects. The market for green bonds has been in existence for more than a decade and that provides some cues for the future of blue bonds. The cumulative issuances of green bonds since 2007 are of the order of USD 521 billion. The five largest countries in terms of gross issuances in 2018 are the USA (USD 34 billion), China (USD 31 billion), France (USD 14 billion), Germany (USD 7.6 billion), and Netherlands (USD 7.4 billion). Developed economies with well-developed capital markets have largely been accountable for the majority of green bond issuances. The contribution of emerging and developing economies to green bond issuance has been small. Among those emerging and developing economies who issued green bonds, South Africa led the pack with a share of 0.2% of global issuances. The share of Asia Pacific (excluding China, India, South Korea, and Singapore) is relatively small [17]. Most of the bond finance has been channeled towards energy-efficient conventional technologies and sectors. Recently issued bonds pertain to renewable energy, energy efficiency, and transport sectors. Green bonds targeted for renewable energy have been funding established technologies, such as hydro, wind, and solar, and projects where environmental and emissions characteristics are conventional. In the transport sector, almost 90% of the green bonds outstanding are financing rail infrastructure (primarily in China). The share of finance for energy-efficient vehicles and bus systems has been small [17]. The green bonds market is estimated to reach USD 250 billion in sales by the end of 2019, according to the Climate Bond Initiative, or an almost 50% increase from 2018 [46]. The green bond market is characterized by established systems to ensure that the use of proceeds is tracked and reported; this, however, comes at a significant cost of administration and monitoring, effectively resulting in the deployment of more than 80% of funds in energy efficiency sector. Funding generated from the capital markets is not flowing toward ocean health and conservation efforts. There has been limited use of these funds by other sectors, namely, water, waste, pollution, agriculture, and forestry.

The prominent blue bond that has caught worldwide attention is the one issued by the Republic of Seychelles. As the first sovereign Blue Bond issued in the world, it provided finance for private capital firms to invest in sustainable fisheries management. The bond was issued in February 2016 and originates from a debt buy-back of USD22 million with Paris Club creditors. The size of bond issuance was a nominal amount of USD 15 million with a maturity of 10 years. The World Bank, Global Environment Facility, and International Bank for Reconstruction and Development provided support of USD 20 million finance package, 5 million loan and a USD 5 million grant respectively to the bond to conserve its marine ecosystem and promote the value chain of the seafood industry. Additionally, IBRD provided a guarantee of EUR 5 million and GEF provided a credit of USD 5 million as a Non-Grant Instrument. These credit enhancement mechanisms were intended to reduce risk to investors, increased credit rating thereby lowering the interest rate to between 2% and 3%. The blue bond will provide grants and loans. Grants are meant for fisheries management planning activities and loans are meant to channelize local public and private investment in sustainable fishing management activities. The disbursement of blue bond proceeds will be through the Seychelles Conservation and Climate Adaptation Trust and the Development Bank of Seychelles [47].

In 2019, Nordic Investment Bank issued its first Nordic-Baltic Blue Bond with SEB bank as the lead manager. The 5-year USD 213 million bond is focused on financing projects in water pollution prevention, wastewater treatment, and water-related climate change adaption. The bond offering 0.375% coupon was oversubscribed more than two times. The details of these initiatives are set out in Table 2 below:

There has been increased activity of launching blue -economy themed impact funds that are focussed on marine and coastal based industries. The features of a few of the funds are as set out in Table 3 below:

While the announced initiatives have a large initiative size, all the initiatives that have been launched have a typical size under USD 50 million, with an investment horizon of about 10 years. The deal sizes of each project are expected to be an average of USD 2 million. The return expectations are typically commercial with the targeted projects in fisheries and circular economy. It is expected that the final beneficiary of most of these funds is a private sector developer. The funds are highly assisted/structured products, which makes replicability a concern. The funds while expected to benefit the direct users might fall short on the impact on the environment given these features and large investments needed.

Blue bonds on their own will not be able to scale blue finance in the coming years. Public sector involvement in conservation would still be necessary. Blue bonds would, however, support certain projects under some market conditions.

The diagnosis of the current context indicates that there is a huge requirement of funds to achieve the targets sets out under SDG 14, there is not enough information on the project pipelines across the globe that point towards an approach for tackling ocean pollution prevention, the funding continues to be with conventional sources including the government sources with multilateral/bilateral assistance, and with a large section of investors staying out of the blue economy investments. The initiatives that have been launched, though are very welcome, appear to be insufficient to address the gap. There is a need for mechanisms that would accelerate the investments required in the blue economy.

The stakeholders in the financing landscape of the blue economy are largely the governments and their agencies, development finance institutions, who traditionally have been providing necessary funds, policy, and institutional support. The needs, following from commitments to sustainable practices including SDG 14, have meant that their sources of funding are not adequate, and would need diversification to attract private sector and philanthropic sources. Though the private sector interest has increased, the participation is not mainstreamed as yet in relation to the requirements. The countries do not have adequate project pipelines to provide a regular stream of investment opportunities to the investors. The significant extent of discourse is from the non-government sector (often representing the beneficiaries), policy, and academic think tanks, who do not have a substantial financial stake in the blue economy.

Table 2
Blue bond initiatives.

Bond	Objective	Size/ Duration	Investors	Key Terms
Seychelles Blue Bond	Transition support to sustainable fisheries	USD 15mn; 10 years	World Bank; Private Placement: Calvert Impact Capital; Nuveen, and Prudential	The loan provided by GEF reduced interest rate for the government from 6.5% to 2.8%
Nordic-Baltic Blue Bond	Targeted towards water resource management and protection	USD 213mn; 5yrs	Capital Market	0.375% coupon

Source: Authors' compilation

4. Inputs, interventions, and outcomes

Various investment approaches and opportunities that are available (i.e., multilateral/bilateral sources, market-based approach, incentives, regulations, etc.). need to be dovetailed for a cohesive development framework of the blue economy [12]. The challenges faced for upscaling ocean economy investments include the lack of consistent source of concessional finance, limited capacity of the implementing authorities (to develop project pipelines and subsequently develop and implement in projects), bankability concerns of the blue sector projects and nascent customized instruments.

The blue economy assessment is focused on the economic perspective of the ocean economy and the natural oceanic capital while meeting the goals of healthy oceans and a more inclusive, sustainable development. The financing strategy needs to be in tandem with the sub-sector characteristics influencing the choice of instruments and structures. The following Table 4 indicates the revenue models prevalent in blue economy sectors:

Most environmental sectors need public funding support for construction and O&M of infrastructure. The limited fiscal constraints of local authorities, the public sector proponents, and the private sector underscore the need for sustainable, long-term concessional and innovative financing structures [48,49]. There is a need to provide a substantial quantum of concessional finance across the spectrum of blue sectors to get the projects off the ground. While the projects that have sizeable revenue potential, would find the support of private investment, the challenge would be those projects that have large economic benefits but very limited existing cash flow streams. These projects also tend to be those with large impacts on the environment, usually promoted by the public sector. Assured access to concessional finance, particularly those regions (in Asia for instance), would significantly assist the launch and implementation of ocean conservation projects. The recent initiatives such as the ASEAN Catalytic Green Finance Facility have been able to substantially lower the cost of funds (below those offered by official development assistance). Similar bouquet of stakeholders, along with philanthropy sources can provide a sustainable source of low-cost funds for ocean finance. The funds can then be used to provide capital expenditure and operations and maintenance related expenses and could be used to underwrite or guarantee the issuance of bonds by the project entities.

Generating a healthy pipeline of blue economy projects is one of the most significant challenges that remain to be addressed [50]. Specifically, progress has been slow on building a pipeline of projects that: (i) support a country's sustainable development goals while also being (ii) well-structured and (iii) bankable (or having the potential to be bankable). Scaling up conservation and development efforts will be challenging in the absence of addressing the pipeline challenge. Much of this work needs to happen at a national level and will be a critical part of creating the systematic "transformation" required to fully realize a sustainable blue economy. Establishing routine processes in project evaluation is a way to increase efficiency in the selection process. A good due-diligence checklist is required to assist fund managers to identify credible projects early. Project templates will assist in the development and structuring of projects and help investors avoid risky projects.

The bankability of a project to investors and lenders is generally defined as one that generates sufficient cash flows to meet obligations created during the outlay of capital. Also, investors are looking for a project with a predictable revenue stream. Investors and lenders are often faced with a challenge of not enough bankable and investment-

Table 3
Recent blue economy related fund activity.

Fund	Objective	Size/Duration	Investors	Key Terms
RARE's Meloy Fund	Incentivize the development and adoption of sustainable fisheries	USD 22Mn; 10–12 projects in 10 years	GEF; FMO (Dutch Development Bank); Impact Investors; the Jeremy and Hannelore Grantham Environmental Trust; Bloomberg Philanthropies; JPMorgan Chase	Equity and Debt; Looking at effective IRR of near 6%; debt at 10%.
Encourage Capital	Investing for sustaining global fisheries	USD 100Mn (hypothetical assumptions) across 6 blueprints	Private investors; grant foundations; multilaterals	5–35% equity returns; around 10 years
Althelia's Sustainable Ocean Fund (SOF)	Making available growth capital for harnessing the ocean's natural capital	USD 100Mn across 10–15 investments	Conservation International; Environmental Defense Fund	Duration of 8–10 years with an annual coupon
Circulate Capital	Protecting South & Southeast Asia from plastic waste	Aim USD 5Bn • USD100mn equity commitments from private corporations • USD35mn guarantee secured from USAID	Coca-Cola; Dow; Danone; PepsiCo, Procter & Gamble;; Unilever	Unlock USD 5.5 bn in private financing

Source: Authors' compilation.

Table 4
Features of blue economy sectors.

Sector	Features	Revenue Model
Fisheries and Aquaculture	Mostly private initiatives – with many small and a few large players – across geographies	Sale of processed/ unprocessed produce. Incentives needed for sustainable fishing
Coastal and Marine Tourism	Cruises, hotels/resorts	User Charges/fees
Water Supply	Public Control	Not financially free standing. User fees cover a portion of costs. Significant funding support needed.
Environmental Protection	Public control Wastewater treatment Water Body Cleaning	Not financially free standing. The user fee only in FSM covers costs partially.
Shipbuilding	Private Sector	Manufacturing, services
Ecosystem Conservation (Mangrove, coral reef)	Public Sector	Economic benefits, avoided costs, blue carbon financing, conservation financing
Chemical/ Pharmaceuticals	Private sector	Sale of products
Ports and Shipping	Public/private sector	Sale of products/services
Offshore Oil and Gas	Private Sector	Sale of produce – usually policy support only
Energy (marine renewable + Coastal wind/solar/tidal)	Private Sector	Sale of power – incentives for the feed-in tariff

Source: Authors.

ready projects. Banks will be reluctant to finance such projects unless they are satisfied with the risk that they would be assuming by financing these projects. A credit enhancement mechanism could reduce the financial risk for banks, but it adds to the total cost of the project. Marsh and McLennan estimate that around 60% of infrastructure projects in emerging markets in Asia are not 'bankable' without support from public sources [51]. The scarcity of blue investments can mean that it is challenging to accumulate a portfolio of commercially viable blue assets.

A key challenge encountered by conservation finance is the lack of clear definitions and project selection criteria. Issuers and investors seek clear blue investment guidelines. In the absence of well-defined principles and a framework for "blue economy investing", investors will shy away from investing in this sector. The confidence of investors in the performance of their investments usually improves when the underlying features of the instruments namely transparent reporting, the system of independent verification are present [52]. Common standards coordinated and enforced by national and international bodies are critical to guiding investors to understand blue economy investing. In 2018, One of the initial frameworks for the sustainable blue economy is launched through a collaborative initiative of The European Commission, European Investment Bank, World Resources Institute, and World Wide Fund for Nature. The principles aim to promote the implementation and achievement of SDG 14 (life below water) and ensure that ocean-related investment delivers long-term value without negatively impacting marine ecosystems, carbon emission reductions, or the livelihoods of people who depend on the oceans and their resources[2]. However, much needs to be done to further develop and refine the framework to accelerate investments.

Fig. 2 below summarizes the elements that constitute the ToC for accelerating the blue economy investments.

The ToC process analyses the gaps in the existing financing landscape and establishes the need for a framework to accelerate blue economy investments that can accelerate the implementation of projects. The process of progressing from the current low investment, minimal participation by various stakeholders to the desired outcome of accelerated investments, and quicker implementation of projects would entail a series of actions by the stakeholders concerned, including the policymakers, administrators, investors, beneficiaries, and community groups.

The inputs required for the process of blue economy transformation include the development of project pipelines, having adequate capacity to implement the same, and generating a financing plan for sustainable project performance. generation of project investment roadmaps for achieving the commitments made by the respective governments. These roadmaps need to align with sustainable practices and with national SDG targets. The capacity of stakeholders needs to be substantially improved to configure various elements of the projects and to implement the projects in close collaboration with other stakeholders. While the technical, institutional, and governance elements need to be addressed, a clear financing plan that sets out the investments required, and the instruments likely to be deployed need to be developed. These instruments would need to reflect the revenue models of subsectors of the blue economy.

The project pipeline preparation would need to supported appropriate studies and investigations that would provide the necessary basis. These would also feed into the financing structures that are proposed to be developed. Requisite training and outreach programs need to be configured to build the capacity of the stakeholders concerned. The capacity building of the stakeholder groups is complemented by fostering engagement of the political and community members. The result of these initiatives is a set of objectives, tangible outputs that could be acted upon – a bankable project pipeline, enhanced capacity of the public, private and community stakeholders, and a generation of a bouquet of financial instruments that could be used as appropriate.

The transformation process needs to be premised on the

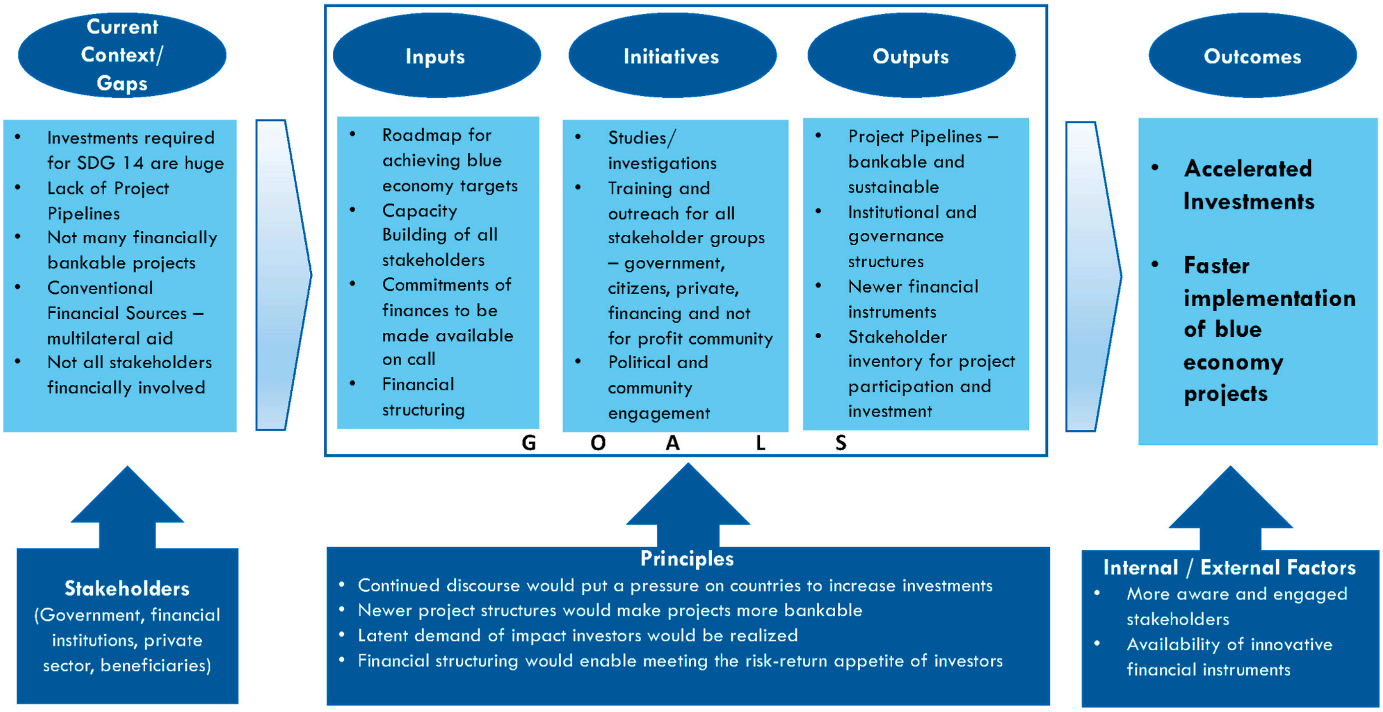

Fig. 2. ToC constituents for accelerating blue economy investments. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

transparency of activities, being open to considering newer project structures, proactive engagement with impact investors, and adoption of financial structures that match the risk-return appetite of the investors intending to participate in the process. The process would need to address the internal and external factors that affect the outcomes including awareness and continued engagement of the stakeholders, and market availability of the financial instruments configured.

The ToC approach as depicted in Fig. 2 provides a context of the current state of blue economy financing landscape, sets out a big picture transformation that is desired to be achieved by various stakeholders, inputs, interventions, and outcomes, and the assumptions for the transformation as intermediate process activities [25]. A synthesis of these elements is presented as a framework that proposes pathways for accelerating the investments in the blue economy. This mechanism is set out in Fig. 3 below.

The acceleration of blue economy investments are centered around a financing facility (termed as Ocean Financing Facility) that can act as an anchor for raising the required sources of funds, and to direct the same to the blue economy projects as required. This financing facility (with an appropriate institutional structure) could be established at a national or

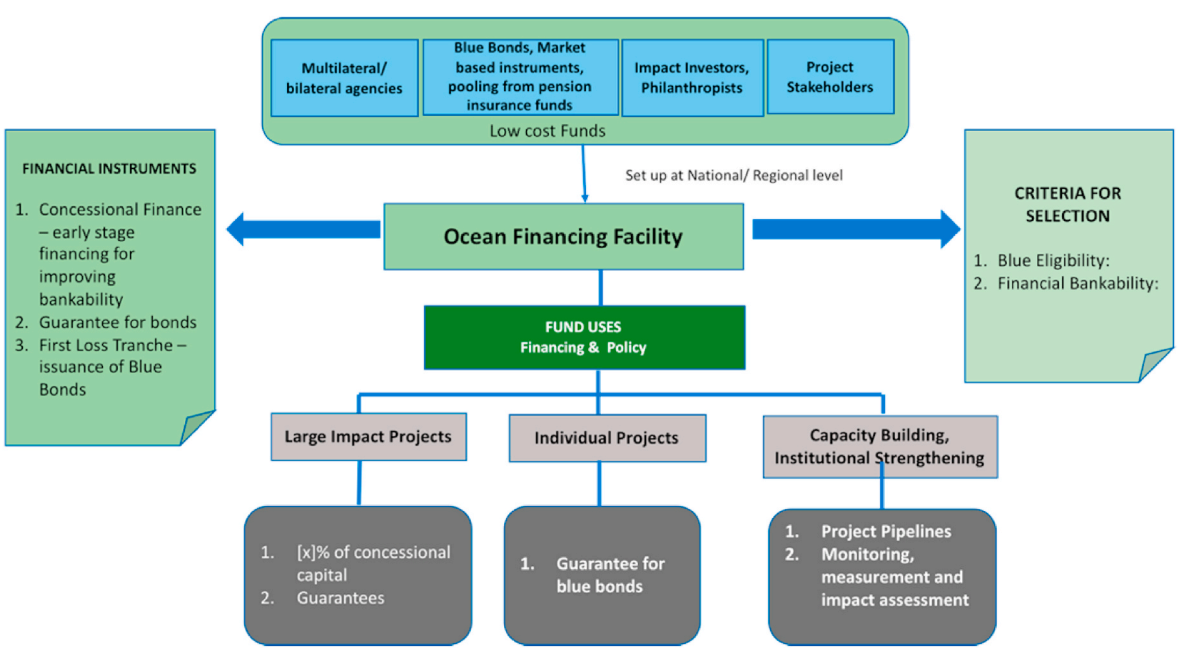

Fig. 3. Framework for accelerating blue economy investments. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

regional center and should be so organized to blend national, multilateral, impact investment, and philanthropic funds. The diversification of the funding sources (category of investors) needs to be so managed to obtain the as low cost of funds as possible. Assistance from multilateral agencies and philanthropic investors could be leveraged with investments from impact investors to raise a larger pool of funds. Financing structures as (blue) bonds and other market-based instruments can provide different tenors of funds as required for the diverse nature of blue economy sectors.

The low cost of funds provided by the investor group is contingent upon the funds being deployed for the projects that enable achievement of blue economy principles, similar to the practices observed in green sector projects. The projects that are eligible to attract funds from the investors need to follow the green principles developed by various agencies as International Capital Market Association or country-specific guidelines as issued by Indonesia, China, or India. Similarly, the blue economy principles are being developed by various international organizations such as the World Wide Fund, United Nations Environment Programme and the United Nations Development Programme. These principles relate to the association and impact of the sector or project on the blue economy. Blue Eligibility refers to projects that adhere to such principles. The investor groups also expect the projects to adequate bankability, usually maintain a minimum debt service coverage ratio, with or without credit enhancement. The pool of resources raised from the investor groups can be made available to eligible projects (generated from a project pipeline and meeting the "blue" criteria and the bankability assumptions).

A range of financial instruments that provide the credit to the blue sector projects could be developed including concessional loans (with varying structures of interest and payment), credit guarantee mechanisms, and first loss tranches. These markets based instruments could be configured for different projects based on their respective investment, cash flow, and risk profiles.

The facility can use the funds through two pathways. First, the large impact projects that the public sector proponents configure, which typically have very little revenue base, but have a significant environment, economic benefits. The facility can assist in raising concessional finance and provide guarantees for repayment of loans/monies raised for undertaking these projects. The facility can also substantially improve the financial outlook (by providing guarantees and participating through subscription to first loss tranches) and can attract a range of project stakeholders. The second pathway would be to provide credit enhancement support to the initiatives of the private sector (typically blue bonds) by providing credit enhancement through guarantees. Simultaneous capacity building and institutional strengthening of the proponents will foster healthy dialogue and could lead to a monitoring and feedback mechanism for continuous improvement of the system.

5. Findings and conclusions

The objective of the research is to assess if the current blue market instruments are adequate to meet the investment needs of the blue economy sector, and what could be the contours of a financing mechanism that can accelerate investments into the blue economy sectors. With the billions of dollars investment to support a sustainable healthy oceans economy, the blue instruments that have been announced are relatively small in comparison and are not capable of addressing the magnitude of financing needs [12]. The financing mechanism that could accelerate the investments could be in the form of a financing facility (with appropriate institutional structure) set up at a national or a regional level. The facility could pool in low-cost funds from a diverse pool of investors and can support projects that meet blue principles (to ensure that the use of proceeds is as stated) and the bankability criteria of inventors [50]. The facility can extend financial support to either large impact projects (typically configured by public sector agencies) or individual projects through a variety of market instruments that meet the project-specific requirements.

Establishing collaborations between stakeholders and getting influencers from the government to be at the forefront can help in developing a strong project pipeline in the blue economy. Private sector involvement in the blue economy is essential – from research to design, deployment, operation, and financing. The public and private partnership is important to move the blue economy forward. However, enabling conditions have to be put in place to ensure viability, and make such partnerships work [50]. The private sector is motivated largely by the enhanced profits generated for its stakeholders in relation to the risks they assume, which the blue economy sectors have failed to demonstrate to date. The role of development organizations (multilateral development banks in particular) becomes important in this context to set out frameworks, financial structures, encourage partnerships with all market stakeholders to shares risks and develop pockets for incubating projects that could be mainstreamed. Blended finance vehicles have a role to play, but more innovative structures like blue bonds, social impact bonds, as well as projects to tap regional capital markets need to be explored [53].

The appetite of institutional investors to assume risks in relation to the returns generated is not currently met by the blue economy projects in the current market [50]. Newer sources or financing or the structuring of assistance that promotes a steady flow of capital (and recurring operating expenditure), at attractive rates (blended with cheaper funding or philanthropic monies), setting out appropriate risk management to improving credit is required. This mechanism can include investors from foundations, multilateral development banks, impact investors, commercial investors, and governments. Such types of arrangements can distribute risk amongst the stakeholders and mobilize the needed private capital that would otherwise stay on the sidelines [54].

The various project phases will require different blending approaches. The typical project life cycle stages, as applied to blue economy sector projects, provide pointers for the type of financing support that is needed. The construction phase needs cheaper low-cost long term financing (with partial risk guarantees, first loss protection for a defined portion of assets), which then can be optimized with take-out financing instruments once the "risky" period has been completed. This would mean demarcating instruments based on the phase of the project and the underlying characteristics. The approach for accelerating the finance for the blue economy sector needs appropriate segmentation and targeting of investors and the respective financing instruments. Education, public awareness, and capacity development are crucial to have behavior change or lasting transformational change and the governance needed in the blue economy.

This research invites attention from government agencies, development finance institutions, and private investors to the challenges faced while considering investments in the blue economy sectors. The findings of this research provide contours of a financing framework that can optimize public and private capital for bridging the financing gap and strengthening the transition to a sustainable blue economy. The findings provide inputs to the government agencies to align the development of their SDG projects to the blue economy principles and suggest broad elements of a financing facility that they can set up to accelerate blue economy projects. The nature of the blue economy projects and characteristics of the same would mean that the development financing institutions could expect substantial credit enhancement support and different instruments that provide concessional financing. The structure of the facility, specific instruments designed, and credit enhancement offered provide a basis for private investors to assess their interest in participating in blue economy sector. These discussions contribute to the ongoing debate on how to improve the financial capability of various blue economy stakeholders and enable them to configure more sustainable financing mechanisms. The research is limited by the small number of initiatives (particularly relating to the issue of blue bonds) that have been undertaken so far. Further research into different blue economy sub-sectors and markets, the appetite of impact investors to look at geographies with significant blue economies, and institutional governance mechanisms will contribute to the acceleration of investments and quicker achievement of SDG.

CRediT authorship contribution statement

Raghu Dharmapuri Tirumala: Conceptualization, Methodology, Data curation, Writing - original draft, Visualization. **Piyush Tiwari:** Supervision, Validation, Writing - review & editing.

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Appendix A. Supplementary data

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Towards defining the Blue Economy: Practical lessons from pacific ocean governance

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ABSTRACT

Governments and regional agencies of the Pacific Islands are strengthening their commitment to sustainable oceans management through proactive policies and programs. The Blue Economy concept is increasingly being invoked, yet clarity on definitions and implementation steps remain vague. This paper reviews reports, academic literature and regional speeches to develop a Blue Economy conceptual framework which is then applied to three case studies from the fisheries sector – small scale fisheries, urban fish markets and onshore tuna processing. The cases illustrate an imbalance in attention paid to key components of the Blue Economy and missed opportunities for integration across scales, time and stakeholders with a few noteworthy exceptions. Issues of power, agency and gender remain weakly addressed even in the most recent initiatives. While clearly defining components of the Blue Economy provides a valuable tool for assessing coverage of key elements of sustainable ocean management, it is less obvious that the new label, Blue Economy, significantly advances practice beyond existing sustainable development frameworks. A proliferation in terms adds more complexity to an already challenging management space. Nevertheless, the conceptual framework is useful for structuring evaluations of practice, and helping to reveal missing ingredients necessary for the sustainable development of oceans.

1. Introduction

Oceans, and the valuable resources they contain, are integral to the lives and identities of Pacific Islanders. Hau'ofa [29] in his seminal article *Our Sea of Islands* argued that it is the oceans and people's relations with them that define Pacific Islanders. A decade later similar sentiments are still being expressed by leaders in the region. In 2015, speaking in her role as Pacific Ocean Commissioner, Dame Meg Taylor described the ocean as central to Pacific lives: “it is our culture, our livelihood, our economy and, for many, the ocean is the mother of all things” [66].

Regional and national policy attention to oceans governance in the South Pacific has sharpened in response to increasing anthropogenic threats, mainly from population growth, intensifying resource use and climate change (c.f. [24,72,49,61]). In response, political leaders are putting oceans on national and international agendas, eager to maximize revenues, sustain livelihoods and minimize coastal vulnerability and ecological degradation. Recently, the leaders of the Pacific island countries (PICs) were instrumental in pushing to have oceans as one goal of the 2030 Sustainable Development agenda [50,51].

Translating words into action, however, can be complex because of different interpretations of what sustainable oceans governance entails [57], the multiple jurisdictions in the region, and competing interests. In the South Pacific, twenty-two island states and territories share ocean resources with exclusive economic zones (EEZs) that cover an area roughly the size of Africa. Ocean resource management is complicated further by overlapping, and at times competing, institutional arrangements at national and regional levels. At the local level, national governments often fail to adequately resource the necessary governance and management frameworks. Few government agencies, at any level in the South Pacific, have the capacity to actively manage across their areas of responsibility [26].

Regionally and internationally, the PICs and their leaders have begun to invoke the Blue Economy concept (c.f. [44,65,69]) to capture the multi-sectoral and multi-scalar objectives of ocean governance. The Blue Economy aims to balance sustainable economic benefits with long-term ocean health [16,69], in a manner which is consistent with sustainable development and its commitment to intra- and inter-

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generational equity [35,75]. The term has also been used to give greater recognition to the many, though often not priced, ocean values ranging from cultural worth and village-based subsistence economies, to commercial and industrial commodities [30]. Under this definition not all ocean-based activities are consistent with the Blue Economy concept, because many ocean activities are not sustainable.

This paper examines the Blue Economy concept as an analytical frame for assessing initiatives aimed at achieving sustainable oceans development and management, with a particular focus on fisheries as an example of an important sector within a Blue Economy. Fisheries represent an essential economic sector for many PICs. Using existing literature, a Blue Economy conceptual framework is developed and then a case study approach used to assess its utility in analyzing fisheries management and development issues and opportunities. The case studies are drawn from Solomon Islands because of its heightened attention to fisheries and oceans policy in relation to other South Pacific countries. It has recently revised its fisheries legislation, is exploring the development of a national oceans policy, and has a vibrant fishery sector which involves multiple stakeholders operating at different scales. The policy implications of a rapidly evolving Blue Economy, across multiple sectors, are highlighted.

2. Study method

Despite the Blue Economy concept being increasingly invoked as an ideal, it is not well conceptualized with an explicit mapping of its key components, and hence its utility to date has been more conceptual or political, than practical. Literature, policy documents, and speeches by leaders in the South Pacific, are used to map out key components of the Blue Economy in a conceptual framework. The framework is not exhaustive, but rather indicative of the objectives and values of the Blue Economy as regionally defined. As a conceptual framework its utility is heuristic—a means to stimulate discussion that can enable researchers and practitioners to better understand, assess, evaluate and, if necessary, contextually modify, the Blue Economy concept and its implementation for the sustainable development of oceans.

A case study approach was considered most suitable to the exploratory nature of this research [17], and the research aim to examine contemporary approaches taking account of context [79]. Case studies also provide rich and nuanced insights into how policies and regulations are implemented, and the real world political-economy factors affecting practice [21]. This approach is also well suited to data poor areas of inquiry where more in-depth understanding is captured through a combination of observation, interviews and document analysis.

Three case studies were conducted, based on an “information-oriented selection approach” which aims to maximize the utility of information from a small selection of cases [22]. To achieve this, the case studies varied on one core element, scale. They include small-scale fisheries management (local), national fisheries markets (national, linking rural-urban areas), and industrial fisheries development (national – international)—these being priority areas for national development in Solomon Islands. The case studies are used to examine how linkages work across jurisdictions, across agencies (horizontal integration) and between levels of governance (vertical integration).

This article draws extensively on published literature and reports to analyse the cases using the Blue Economy framework. This was complemented by local insights. Two of the authors are well placed to observe the evolving ocean management processes in Solomon Islands, being employed in the local fisheries and environment sector. The authors also validated findings with local experts to gain further insights.

3. The Blue Economy conceptual framework

The term ‘Blue Economy’ first gained traction in PICs in 2011, largely as a complement to the ‘green economy’ concept — a discourse where ecosystems integrity is embraced as being fundamental to sustainable socio-economic resource use [57]. The Blue Economy, while a relatively new term, is reflected in regional initiatives aimed at sustainable oceans management. For example, the Pacific Islands Regional Ocean Policy [59] and the Framework for Pacific Oceanscape [49], never explicitly mention the Blue Economy, but do espouse some of its values, calling for improved oceans governance through the sustainable use of ocean resources, the better coordination of management across scales and time, and the protection of oceans’ cultural and natural integrity.

The specification of ‘blue’ makes explicit the focus on oceans, as opposed to land-based resources. For PICs, the Blue Economy refers to the sustainable management of ocean resources to support livelihoods, more equitable benefit-sharing, and ecosystem resilience in the face of climate change, destructive fishing practices, and pressures from sources external to the fisheries sector (Pacific SIDS 2011). The ideas are not new to the region, Pacific islanders have been implementing elements of coastal resource management for thousands of years through traditional practices like harvesting limitations, closed seasons, limited use rights, and the protection of ecologically and culturally significant sites [32,55].

In this context, the Blue Economy concept does not sit comfortably with conventional definitions of economy (c.f. [74]) with their focus on production and allocation processes. Instead, ecological economics definitions with their greater emphasis on scale, context and socio-ecological relations are better aligned:

> “... the interaction and co-evolution in time and space of human economics and the ecosystems in which human economics are embedded. It uncovers the links and feedbacks between human economies and ecosystems, and so provides a unified picture of ecology and economy” [78].

Using the ecological economics lens to better define the Blue Economy term makes it more compatible with sustainable development concepts promoted in the region and by UN agencies that strive to integrate ecological, social and economic systems (c.f. [70,75]).

The Blue Economy focus on the sustainability–food security–economic development nexus is relevant in the region where reliance on subsistence fisheries is high, and revenues from national fisheries can generate as much as 68% of GDP, for example Kiribati [31]. Fish make up 50–90% of the animal protein intake [7] in PICs and artisanal fishing provides the primary or secondary source of income for up to 50% of households [61]. As pressures mount from current and new economic activities, as well as changing demographics and climate, concerns about sustainable use of oceans are coming to the fore, with some pushing for better local access to the revenues from ocean based activities [28].

The examination of the Blue Economy presented here draws on many key policy framework documents from the South Pacific aimed at achieving more sustainable ocean management. A sectoral example includes a Regional Roadmap for Sustainable Pacific Fisheries produced by two regional agencies— the Pacific Islands Forum Fisheries Agency (FFA) and the Pacific Community (SPC) which outlines goals and indicators for sustaining fish stocks, livelihoods and food security, and is monitored through an annual fishery report card [62,63]. Multi-sectoral frameworks include the SAMOA Pathway (2014) which incorporates an oceans agenda in its broader sustainable development framework, calling for actions to sustain ecosystem services, livelihoods, economic development and food security. It promotes the importance of institutional integration across national, subregional and regional scales, and better, cost-effective monitoring and surveillance.

These themes are also strongly reflected in more targeted papers and strategies such as the regional technical paper for biodiversity beyond national jurisdiction [47], and the Noumea Strategy [61] for

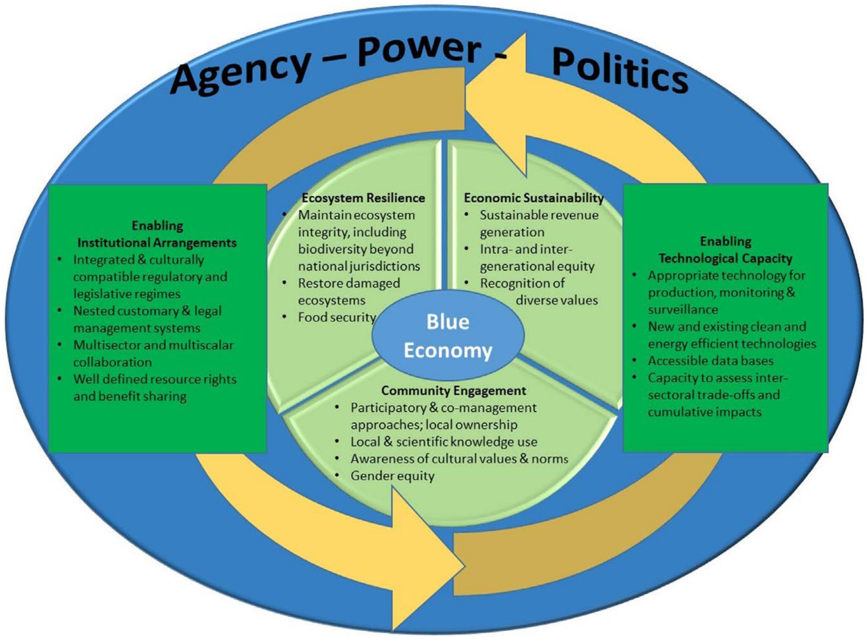

Fig. 1. Representation of the core components of the Blue Economy.

coastal fisheries with its desired outcomes relating to: sustainable livelihoods, empowered communities, knowledge sharing, integrated institutional arrangements across scales, and equitable benefit sharing.

Fig. 1 represents five components of the Blue Economy: ecosystem resilience, economic sustainability, community engagement, institutional integration and technical capacity. Ecosystem resilience, economic sustainability and community engagement are directly derived from the Blue Economy's roots in the sustainable development literature, referred to here as core components. Maintaining *ecosystem resilience* is key in the South Pacific where the carrying capacity of ocean ecosystems is under strain from stressors which span the local to global scales, and can lead to cumulative and cross–jurisdictional impacts. E*conomic sustainability* encompasses village livelihoods, as well as commercial activities which generate jobs and government revenue. Completing the core trio is *community engagement,* particularly vital given the lack of reach of central governance systems, the high proportion of rural populations dependent on marine ecosystems [39], and the pervasiveness of customary marine tenure [32].

Institutional arrangements and *technological capacity* are considered to be enabling components of the Blue Economy because they can facilitate the achievement of ecological, economic and social sustainability. Currently, institutional arrangements are failing to adequately manage the competing uses of ocean environments in PICs and to boost intra- and inter-generational equity [27]. Community-based management is often relied upon to sustain activities in the Blue Economy, but needs better integration between levels of management, and customary and formal arrangements [41–43]. Improved *technological capacity* can improve efficiency, knowledge generation and sharing, and monitoring and surveillance. In some cases, when combined with effective management, technological innovation enhances productivity, for example nearshore fish aggregating devices [2,7].

The five components, outlined above, sit within a wider political and cultural context. Relationships, agency and power dynamics among resource owners, users and elites, determine resource access and management capacity by shaping institutional arrangements (that is the rules, regulations and enforcement efficacy) and who exercises power. The resulting institutions can be formal (and legally enforceable), or informal with their roots in culture and tradition. Where management regimes are weak, powerful elites — political, non-governmental and commercial — can set resource exploitation agendas. When this occurs development outcomes depend not only on capacity, resources and performance, but also "critically on the balance of power between the classes and groups affected by that institution, that is on the political settlement" [33].

Drawn together and depicted in Fig. 1, it is clear that the Blue Economy concept is an extension of sustainable development frameworks, but with a stronger ocean focus. The way in which the Blue Economy is interpreted by PICs puts a greater emphasis on social and cultural sustainability than other regions (c.f. [16,45]) because of the prevalence on customary marine tenure and strong cultural ties to ocean environments. The Blue Economy framing also gives greater attention to enabling institutional arrangements, power relations and the influence of external agents than conventional sustainability models because of the mounting pressures being felt by small island states. By applying the Blue Economy framework to the case studies to follow, this article assesses its practical value for evaluating the sustainability of ocean activities.

4. Solomon Islands: Blue Economy under pressure

Solomon Islands consists of almost 1000 islands covering a total land area of 28,000 km^2 (Fig. 2) and in the most recent census (2009) had a population of approximately 516,000 people [57], with more recent estimates reaching 640,000. The population is increasing rapidly, 2.4%, with its capital city, Honiara, growing at almost twice this rate— an urban growth rate which exceeds all others in the region. This rapid growth coupled with service shortfalls and low levels of economic development contribute to Solomon Islands poor development performance – it is ranked 142 out of 187 countries on the Human Development Index [67].

The country boasts one of the most diverse coral reef systems in the world [63]. Eighty percent of the population is rural and rely heavily on agriculture and small scale fisheries (SSF) as the main sources of food and income. Fish is the primary source of animal protein in the region [3,7]. But rapid human population growth, climate change and market pressures are degrading reef fisheries to the point where by 2030 they will not be able to meet future demands [7]. National government agencies across relevant sectors lack the resources, capacity and often will, to manage competing values and priorities in coastal fisheries

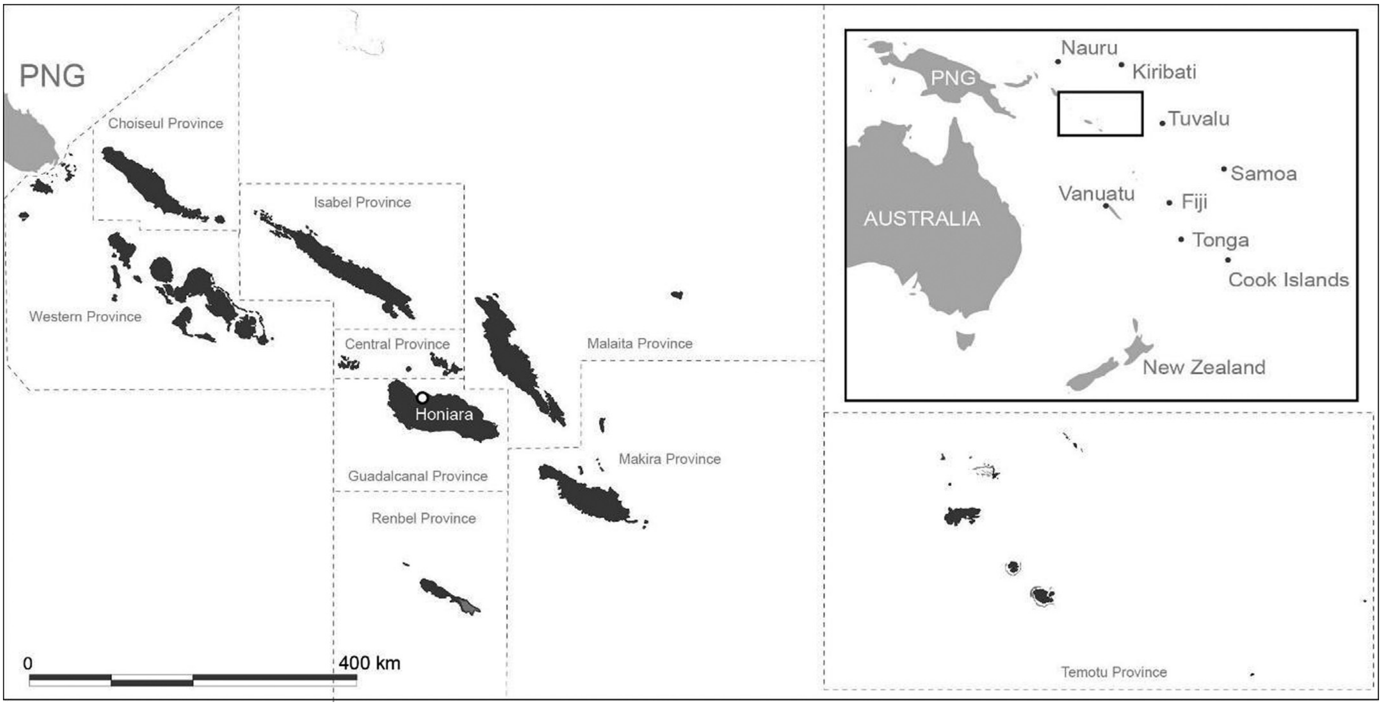

Fig. 2. Location of Solomon Islands.

[26]. There is growing evidence that food security for cities is coming at the cost of ecosystem integrity in rural areas [10].

Recently, there have been steps to strengthen the sustainable use of coastal and ocean resources using principles that align to the identified components of the Blue Economy. For example, the Fisheries Management Act (FMA) spells out 18 principles that are compatible with key FAO [19] guiding principles for an Ecosystem Approach to Fisheries Management (EAFM) and so create some loose vertical linkages between local and global level governance, and integrate social, ecological and economic goals. Recognizing that many sectors have a stake in the coastal and oceanic environment, Solomon Islands is also in the early phases of developing a national policy for integrated oceans governance by engaging multiple stakeholders and agencies in ocean planning.

At a national Ocean Summit held in June 2015, participants recognized that the increasing reliance of many sectors on the ocean for economic benefits may come at the expense of ecosystem integrity. The Summit developed a vision for a ‘healthy, secure, clean and productive ocean which benefits the people of Solomon Islands and beyond’ (Solomon Islands Ocean Summit Communique, 2015). To progress the vision, ocean planning will be coordinated through a ministerial working group referred to as Oceans 12+, referring to 12 government ministries and other stakeholders.

Currently, policies are not well integrated with little vertical or horizontal integration between, and within, agencies. Key challenges for the Ocean 12+ process are: clarifying rights and jurisdiction over the ocean space; integrating legal frameworks with informal ones such as customary marine tenure; dealing with outdated and sector specific legislation, and managing external pressures on ocean environments. The implications of pursuing integration across sectors and the necessary trade-offs that might entail are only just becoming clear. To better understand some of these trade-offs and issues on the ground, this article now turns to an examination of three cases.

5. Putting the Blue Economy into practice: case studies

The cases selected have been functioning for decades and are considered locally to be relatively successful either in terms of ecological or socio-economic outcomes (although there are still opportunities for improvement), in line with thinking that there is often less to learn where things have not worked well [46]. The first is the case of SSF management which operates largely at the local scale, but has links to provincial and national scales of governance and economy. The second is the case of the fish markets in the capital city, Honiara. These markets are a magnet for fishers from provincial coastal areas and are significant drivers of harvesting, as well as sources of income. The third case is that of the national tuna fishing fleet operating from Noro, Western Province. The fleet and the onshore processing facilities are greatly influenced by regional management regimes given tuna's migratory nature, global markets (e.g. EU markets for products), and internationally recognized certification processes which are the gateway to lucrative Western markets.

5.1. Case 1. Small scale fisheries management and development

The subsistence and coastal-commercial catches for local markets in Solomon Islands are poorly quantified and published estimates vary. In the most recent repudiable estimate for 2014, the subsistence and coastal-commercial catches were valued at USD$32.5 and USD$12.5 million respectively [24]. The high value of subsistence fisheries is rarely quantified, despite its core importance to sustainable and equitable development. Management of coastal resources is largely decentralized; eighty percent of coastal resources fall under customary marine tenure (CMT), a common property system in which particular groups of local people have informal or formal rights to coastal areas, and historical rights to use and access marine resources [53]. CMT is recognized in the Solomon Islands constitution [38] and the Fisheries Management Act (2015) as an important foundation for SSF management. However, factors external to communities and fisheries such as socio-economic changes and the growth of urban and global market opportunities have weakened CMT's effectiveness for enforcing rights and limiting exploitation [52].

Nevertheless, CMT and the traditional practice of customary owners restricting access to certain fisheries has underpinned contemporary conservation and resource management initiatives supported by organizations working in partnership with communities since the

1980s [12]. Drawing on co-management principles [48], there has, in recent decades, been a shift from a primarily Marine Protected Areas (MPA) approach based on external and often exclusionary conservation premises (e.g. [6]) to regionally-initiated locally managed marine area (LMMA) approaches [15,25]. LMMAs are described locally as community based resource (or fisheries) management (CBRM). This approach is based on a mix of scientific and traditional knowledge, and locally developed access rules recognized and supported by higher level institutional arrangements. There are now more than 250 community managed areas in Solomon Islands[1] ranging from traditional short-term closures to communities with formal written management plans developed with partners and recognized beyond the community [13,41].

Typically, CBRM initiatives include: broad and inclusive participation (including women, youth and resource owners and users); the application of both scientific and local knowledge; diversification of livelihood options, and the involvement of provincial government and appropriate national ministries, mostly through existing formal and informal networks (for elaboration see: [75,55]). It is consistent with Melanesian research findings that adaptation of customary tenures may be more appropriate for resource management than mere imposition of external models [18,34]. Even so, local elites bend rules to increase their or their supporters' access; institutional arrangements are not always enforced at higher levels; decision making often excludes women; and, external pressures from outside fishers and climate change can overwhelm local management initiatives.

Community management priorities commonly articulated when designing LMMAs relate to improved productivity to increase food or cash. Communities are most committed to initiatives where there is evidence that gains can be realized under effective management regimes [14]. However, there is insufficient understanding of the role that community managed areas play in sustaining local economies and ecosystems with many struggling to maintain rules and norms as they were originally envisaged [1,72], and some adapting rules to meet economic needs [15], and social or cultural priorities. The ongoing challenge for SSF management is that institutional and technical ability to enforce rules, key enabling components in the Blue Economy, can be lacking [1,27].

The recently developed FMA in Solomon Islands will, once regulations have been developed, enable resource owners to register Community Fisheries Managed Areas as legal entities with the national government. The registration process involves provincial governments, and thus can be an avenue to strengthen vertical integration amongst community, provincial and national level governance. The FMA and other recent enabling legislation (e.g. the Protected Areas Act) highlight increasing political and institutional recognition of the importance of community engagement and institutional linkages.

There is potential for enhanced food and nutrition security, as well as economic gains, from measures to boost community management, but at this stage, national and provincial government resources allocated to coastal marine resource management remain inadequate [26], compromising ecosystem resilience and economic sustainability. International NGO and donor support via partnerships and projects are often sought, but this can bring unwelcome external agendas or concerns about 'ocean or green grabs' [9,8]. External finances and capacity can also distort local power relations if effective community engagement is lacking. While regional policy developments in the last decade increasingly support community-based approaches (e.g. [59,60]), without institutional arrangements that are nested across scales and enjoy strong political commitment at all levels, the foundations of these management systems remain shaky.

5.2. Case 2: Honiara fish markets

In the PICs, the Blue Economy concept is often focused on livelihoods that are dependent on maintaining ecosystem productivity and resilience – these dual objectives come into sharp relief in fish markets. Markets create a meeting point for diverse sectors, such as fisheries, agriculture, commerce, lands and health sectors, and multiple stakeholders. The Honiara Central Market (HCM) was established in the 1950s and is part of the social and economic fabric of Solomon Islands. With Honiara being around ten times larger than any of the markets in other provincial centres, it dominates internal trade and returns on fish sales are the highest [10]. The market is located on prime waterfront in the city, allowing boats from rural and regional areas to deliver produce directly. Water transport is a vital element of the marine economy both for national connectivity and the movement of goods and services, yet universally reliable, affordable and energy efficient services remain elusive in Solomon Islands.

Proximity to market is related to indicators of overfishing (fish size, quantity and catch per unit effort) [11] indicating that ecological resilience can be undermined if efforts to boost income from market sales to fishing communities occurs without adequate ecological monitoring and management. This runs counter to the ecological economics goal, referred to earlier, of co-evolving economic and ecosystem management. The Solomon Islands Ministry of Fisheries and Marine Resources (MFMR) has begun to collect quantitative data on the species, size and source of fish coming into HCM in a bid to monitor the fishery and to inform management recommendations and institutional evolution. More attention to fish markets as a linkage mechanism across Blue Economy sectors, scales and stakeholders has high potential for enhancing sustainable development and economic returns.

The number of vendors at HCM has outgrown the site's capacity, so informal markets are springing up around the city with few facilities. For example, three to five fish markets operate on the Honiara waterfront on any one day. Only the HCM has market by-laws gazetted, but these are poorly enforced by the City Council; a situation that is expected to continue until vendor and buyer engagement with the Council is enhanced [70]. Because none of the markets have adequate sanitation or security, there are safety and personal welfare concerns for the vulnerable, particularly women. Inadequate infrastructure results in much product wastage, or poor quality fish sold at low prices, because of the lack of ice, cool storage and running water.

The Honiara markets are at the end of the value chain for most coastal fish from the provinces. In 2015, less than USD8,000 worth of reef fish was exported from Solomon Islands (MFMR records). This contrasts with an estimated USD$1.4 million worth of fish passing through HCM alone, in 2014/15 (MFMR records) (Fig. 3). Studies of the fish value chains between the provinces and Honiara have identified distinct players including fish sellers, middlemen, fish food vendors and retailers [10]. This is significant because their needs, social contexts, and thus incentives for fishing can vary. There are few initiatives that specifically investigate these interrelationships and tailor management to behavioural drivers.

Another neglected area of inquiry relevant to Blue Economy, and markets in particular, is gender and gender equity. Fish are the highest valued commodity in the markets and men dominate in selling all but the low value 'salt fish' obtained from the commercial purse seiners. How earnings are distributed in families, and between men and women, is poorly quantified. Continued economic viability will depend in part on shaping the market mechanisms to better respond to gendered contexts. A study by Kruijssen and colleagues [36] found gender issues are seldom considered in assessments of fish value chains in Solomon Islands. They recommend that assessments of, and interventions in, marine livelihoods, need to go beyond identifying the visible differences in roles between men and women and attempt to explain the underlying causes of disparities.

[1] http://ctatlas.reefbase.org/mpadatabase.aspx?country=Solomon%20Islands

Fig. 3. Provincial sources and values of fish for sale in Honiara Central Market (data sourced with permission of Solomon Islands Ministry of Fisheries and Marine Resources).

Local markets, although vital to livelihoods and fishing behaviour, receive remarkably little policy attention, despite their importance to the Blue Economy. An integrated approach which creates national standards and networks to support stronger regulations, improve vendor rights and enhance economic benefits requires community engagement and stronger institutional arrangements. Simple technology can make a big difference. For example, cool storage is critical to enable fish to be transported in good condition from provincial fishing grounds to Honiara. The provision, servicing and effective management of ice machines in the provinces has had a chequered history and despite many donor and government efforts to fund ice making projects, most provincial facilities remain in a state of disrepair [5]. This is just one demonstration of how neglect of enabling factors continues to hinder the achievement of sustainable ocean management.

5.3. Case 3: Onshore processing of the national tuna fishery at Noro

Solomon Islands tuna accounts for around 10% of the total Western and Central Pacific Ocean catch, more than 120,000 t [23]. The value of the catch in 2014, at market prices, was estimated at more than USD130 million [24] Following on from the Vava'u declaration in 2007 [50], the key framework for managing regional tuna exploitation is the Parties to the Nauru Agreement (PNA). The waters of the eight member countries, including Solomon Islands, account for the region's most significant fisheries.

The PNA facilitates regional cooperation and harmonized approaches between members — a rare example of strong horizontal integration between nations, although not without its weaknesses and breaches. Regionally allocated national quotas are then implemented by member countries, resulting in a degree of vertical integration. PNA efforts have increased returns to Solomon Islands and other member states [76] — in the last six years, revenues have risen 600%. Now countries like Solomon Islands, are setting policies to boost local returns even higher by maximizing the landing of tuna in country, and promoting onshore processing [40].

Regional organizations such as Forum Fisheries Agency (FFA) and Pacific Community (SPC) provide technical expertise which is leveraged by members of the PNA and the Western and Central Pacific Ocean region to enhance monitoring, control and surveillance and fisheries management planning and implementation [20]. Innovative tracking systems are now in place to monitor fishing effort and target surveillance, as well as share data across jurisdictions. The tuna fishery data collected by SPC member countries are used extensively to increase sustainable fisheries management through research and monitoring (c.f. [62]).

In Solomon Islands, external economic and political pressures in the form of the EU issued 'yellow card' in 2013, provided an impetus to fast track more sustainable management policies and ensure ongoing EU market access. Regional institutional technical assistance, coupled with a fear of losing lucrative tuna market share, underpinned cabinet support for a National Tuna Management and Development Plan (2013), and subsequent work to strengthen procedures for licensing in the FMA. While there are concerns that external frameworks can reduce local agency, this is an example of outside economic and institutional pressure raising the bar for the sustainable oceans management. This reminds all that external influence and engagement are complex, multifaceted and, at times, useful for reducing unsustainable local socio-political arrangements.

Within this context tuna processing in Solomon Islands is represented by one large company, SolTuna, which operates at Noro in Western Province and is supplied with tuna by a locally registered company, National Fisheries Developments (NFD) Limited. The supplier is wholly owned by the multinational tuna trading company TriMarine which also has controlling shares in SolTuna. International investment is essential to the viability of the tuna industry as it secures the capital required for construction and improvement of port facilities to offload, process and export tuna to distant markets in Europe [66]. TriMarines's large stake in the local market and dependence on a sustainably managed resource helps influence development of the tuna fishery in a manner that is compatible with sustainability goals. In 2016 the Solomon Islands skipjack and yellowfin tuna fishery achieved Marine Stewardship Council (MSC) certification in recognition of the well-managed stocks and sustainable fishing practices.

NFD and Soltuna are locally managed and collectively employ over 2000 Solomon Islanders, [37], representing one of the country's largest private sector employers. In response to localized demographic pressures caused by the pull of the cannery for job seekers, Soltuna is increasing its commitment to providing adequate housing and health care. It is also implementing affirmative employment policies and international standards for staff employment and production quality. This could influence expectations for industries beyond the sector and certainly in other planned cannery areas in the country. The processing centre provides a positive example of integration across ecological, economic and social components of the Blue Economy, albeit with some ongoing challenges, particularly in the social realm.

6. Discussion: linking practice with policy

Mapping the cases to the Blue Economy conceptual framework illustrates that the core and the enabling elements have received different levels of attention depending on the case and the scale of activity. In the SSF example, ecosystem resilience (EAFM approaches) and community engagement feature strongly. Institutional arrangements are widely recognized as a critical enabling factor, but are at rudimentary levels. While sustainable revenue generation is identified by communities as a priority for resource management, evidence suggests this remains a poorly managed goal — this comes into sharp relief in the market case where local markets are seen as the engines of livelihoods but the true costs and benefits across social and ecological systems are poorly known. A lack of investment in infrastructure, fragmented responsibilities and policy gaps impede vertical integration of governance and sectors in the Honiara fish market and SSF cases, and undermines sustainability.

Surprisingly, the locally-based tuna industry at Noro presents the most balanced attention to the different elements of Fig. 1 of the three cases. Ecosystem resilience is recognized as being central to economic sustainability, and effective community engagement gets attention to ensure a reliable workforce, and a stable socio-political operating environment. Nevertheless, a deeper dive into the elements of Fig. 1 highlights the complexity of fully implementing an effective 'Blue Economy' approach. Despite explicit attention being paid to enabling components and strong community engagement (including across genders) – challenges remain. The company has had to be self-sufficient or create external partnerships to advance technological capacity and institutional arrangements, including the provision of port facilities, the development of employment standards, and provision of basic housing and health facilities. This highlights that many drivers for ocean development go beyond one sector, and in developing countries will require partnerships.

Balancing competing multi-sectoral goals requires analytical capacity to assess trade-offs, and the implications of vertical and horizontal gaps in institutional arrangements, for example in regulation, in government investment, and in fishery value chains. The necessary skills and structures to address such trade-offs at a national level are as yet poorly developed. With limited resources in a low income country, interventions need to target high return areas in a socially equitable manner. Analysis of, and support along, entire market value chains have the potential to integrate sectors and scales of production.

Attention to gender equitable approaches was identified in all of these cases as key to sustainable development of ocean resources. In the offshore fisheries industry in Noro, gender issues are getting some attention in part because of the high number of women who work in the cannery and international standards, but insufficient action with regard to gender issues in the other two case studies leaves women potentially vulnerable to economic, physical and social disadvantage. This finding is consistent with development literature and donor programs which target gender equity as a key issue in achieving sustainable development, and is driving programs such as the UN Women market vendor work referred to in the Honiara market case.

To sustain drivers of change, political constituencies and agency at the domestic level need to be taken into account, that is the political context represented in the outer circle of the conceptual framework. The Solomon Islands Oceans12+ group is explicitly a political process aimed at gaining whole-of-government commitment and political support. The Group also utilises technical support from a donor funded project which aims to gain national commitment to regional frameworks like the Convention on Biodiversity, and the United Nations Sustainable Development Goal 14 on oceans. The Ocean12+ working group accepts that well governed and planned ocean space will provide more benefit for the nation, however there are concerns that at the conclusion of technical support Ministries may retreat to operating in a sectoral and fragmented approach again, or outcomes will be biased toward more politically powerful agencies.

Truly integrative policy frameworks and regulations that support the fisheries sector across local, national, regional and international scales, are still evolving but are becoming more prevalent. For example, the LMMA, FMA, the PNA, MSC certification, and Western and Central Pacific Fisheries Commission provide the foundations for enabling and multi-scalar linking mechanisms to underpin the Blue Economy. However, managing multi-scalar and multi-sector interests requires more attention to power relations and issues of agency as interests and agendas vary across stakeholders [4].

External influence, often through regional and international roadmaps and policies, can help guide the development of a Blue Economy but achieving sustainably still depends on national commitment, cultural fit, relevant capacity and policies. A considerable degree of change and political commitment can be required to develop and implement regional policies at a national or local level. When significant structural changes are required, mobilizing resources in low income countries can be very difficult given competing demands, and the lack of tailored and targeted revenue raising instruments.

The case studies presented here support others in the region [30] that suggest that much can be learnt from brokering knowledge across sectors and communities. Practical examples include the *New Song for Coastal Fisheries* – Noumea Strategy [60] which was designed based on lessons, knowledge and experiences of people from PICs, and the collaborative efforts occurring under the *Pacific Ocean Alliance*. The Blue Economy framework may offer the opportunity to tailor and refine more broad sustainable development frameworks to ocean specific issues.

7. Conclusion: sustaining oceans, sustaining people

The Blue Economy has become a commonly used term that captures the goals of sustaining economic development opportunities while maintaining ocean ecosystem health, and for PICs, a means to boost recognition of cultural ties to ocean derived from tradition and customary marine tenure. The growing pressures on oceans, and the recognition of their central importance for human well being have heightened policy attention and the development of local, national and international policies, roadmaps and benchmarks for sustainable ocean governance.

The Blue Economy concept appears to have resonance in the South Pacific region because it embodies the dual need to protect ocean systems for the future and to meet pressing development needs. Explicitly mapping the components of the Blue Economy provides a valuable tool for assessing coverage of multiple elements of sustainable ocean development. The case studies presented here suggest that well defined conceptual frameworks can be useful to identify core components and interactions embedded within a particular terminology. Even so, it is less clear that the new label, Blue Economy, advances sustainable development concepts significantly. In the South Pacific, it appears to have been used as a refinement of ocean management approaches to better fit the region context, and to heighten attention to place-specific issues of customary marine tenure, strong cultural ties to ocean, and shifting power dynamics affecting ocean governance and ocean economies.

There is a risk, however, that creating new labels that essentially embody familiar concepts, like sustainable development, can confuse. For example, the use of 'economy' without 'sustainable' can raise concerns among those eager to protect ecosystem functions. This proliferation in terms (Blue Economy, Ocean Economy, Green Economy) adds complexity to an already challenging management space for small gains. Catchy labels also have potential to mislead. Sustainable ocean development and governance depends on managing not just 'blue' or marine environments, but the land-ocean interface, sometimes referred to in the South Pacific as a 'Ridge to Reef' approach and evident in the above case studies, for example the need to examine the SSF to urban market resource flows. Any new term needs to keep this commitment to integrated and sustainable land-ocean interface management sharply in focus.

Looking to the future, new opportunities and pressures will emerge that will require strong and sustainable ocean governance, including seabed mining, tourism and bioprospecting. While this article has not explicitly addressed these activities, the framework presented, regardless of headline labels, and the subsequent analysis has direct relevance. The goal of 'co-evolution' in space and time of economic, social and ecological systems is well articulated in sustainable development and ecological economic literature which underlie the Blue Economy, but still remains elusive in practice. The five components of the Blue Economy framework, as defined in the South Pacific, are a useful guide when evaluating new ocean development initiatives in the region. For example, efforts to develop political and management constituencies, and better incorporate customary tenure and values, hold potential to address future challenges as new economic activities such as seabed mining and tourism emerge.

Importantly for the future of oceans, this study found the Blue Economy literature and cases tended to neglect many socio-political elements related to power, agency and even gender, all areas that need elevation for sustainable ocean governance to be achieved. From all of the above, the authors conclude that the Blue Economy conceptual framework is a valuable heuristic — not only to structure evaluations of practice, but also to help reveal missing ingredients necessary for the sustainable development of healthy oceans and to refine sustainable development models to better address ocean issues.

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