nature portfolio

Peer Review File

Multi-use of offshore wind farms with low-trophic aquaculture can help achieve global sustainability goals

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

12th Apr 23

Dear Professor Maar,

Your manuscript titled "Multi-use platforms combining offshore wind farms with low-trophic aquaculture show great potential to support the global sustainability goals" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

In addition, we are asking for some important editorial thresholds that you may consider in a new version:

Editorial threshold 1: Provide an in-depth analysis the carbon budget of the study system, including carbon sequestration sources and OWF LTA compartment),

Editorial threshold 2: Justify the current model design, explaining the scenarios (realistic, optimistic, pessimistic) and models used to address the main objective; include why some variables were not selected in the model (Temperature, chlorophyll-a, water turnover).

Editorial threshold 3: Provide comprehensive details of all assumptions made for a global scaling up and demonstrate that they are robust and appropriate to be applied at a global scale; for example, the link between nutrients, phytoplankton and mussels components, especially in temperate and cold waters.

Editorial threshold 4: Revise and re-work the manuscript; it requires better method description, new results figures including key variables, and a discussion including the carbon footprint and ecosystem services concepts

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter) and any completed checklist:

[link redacted]

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

Please do not hesitate to contact me if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Jose Luis Iriarte Machuca, PhD
Editorial Board Member
Communications Earth & Environment

Clare Davis, PhD
Senior Editor
Communications Earth & Environment

EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

Editorial Policy Policy requirements (Download the link to your computer as a PDF.)

For your information, you can find some guidance regarding format requirements summarized on the following checklist:(https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The overall claims are addressed and the study presents new input for the scientific community. It is very nicely structured with clear paragraphs per idea and concept. I also appreciate that the socio-economic dimension that need to be considered with such an upscaled system are mentioned. The paper does try to cover a lot, and thus it is clear, that those aspects can't also be the focus of this paper.
I think overall the work is convincing and relevant, but some claims need to be written with more care. For instance

Regarding carbon:
Line 65 : Attention to saying that storing carbon in the lower trophic species equals mitigation of climate change. Even if in line 193 – 197 It is explained that assumptions are made for he C sequestration in the mussel shells, but only in the discussion part. I suggest, as this is a hot topic right now, to mentioned it earlier in the results and abstract. And in line 208-212, it is explained in which case the climate mitigation potential is used. As it is a hot topic, this is a big claim to be made early on, and should be accompanied with a short version of this explanation. And also, in Line 201 - 206 it is explained that not the 11% of C ending up in the deep sea are included in the calculations but rather the C removed by the sugar kelp, which is then made available for the bioeconomic system on land. This in itself is clear, but it then cannot be called climate mitigation. Line 382: extra fuel to operate the OWF LTA was not calculated in the carbon budget. I would argue that this may be a big part of the carbon budget, see LCA studies by Sleger et al. 2021: DOI: 10.1016/j.jclepro.2021.128689.
Line 93-94: The main aim was noted to explore the model of OWF-LTA as means to achieving multiple global SDGs. However the text focuses more on ES and the link to SDG is rarely made. The link might seems obvious, but it leaves the reader waiting for more consideration of the specific targets or goals.

This paper is based on models and predictions and when reading the results, it leaves the reader with questions on what is considered in the scenarios and models. Knowing, that it will be explained later on in the material section, it could help to list very briefly, what are the considered variables and what not. For a reader not being an expert in models, it seems in some parts as untransparent. The limitations to the scenarios and projections are not clearly stated in the results and leave the reader with questions. For instance,
Line 86: 'depends on economic background', can you clarify what is meant here? Economic viability? You could link I tot the paragraphs on socio economic carrying capacity.
Line 109 (and more): pessimistic, optimistic and realistic models. I cannot find (or see) in the methodologies links to what realistic, optimistic and pessimistic models are based on. Link to figure 3 and Table 2.

Line 114: Salinity is mentioned as an important limiting factor for harvest potential. However, many other papers mention nutrients and temperature, which are only mentioned when reading further. If you mention salinity here, I suggest to briefly mention that other variables are also considered, but salinity was identified as the main threshold to reduced growth (as in line 299). Link to figure 2 as well. Line 298, 299: Again, it is just mentioned, that as a threshold to growth, salinity is used. Only in line 321 and then later in line 356, it is explained that other variables are used for the production models, like Chl a and temperature. This could be mentioned earlier, as it leaves the reader wondering why only salinity is mentioned before.

Line 119 and 300: the authors calculate that 10% of the area are to be used, why? Even if this is not

the focus of the study and the authors are basing themselves on a different study, it would be helpful to understand in a sentence, what the main criteria were for 10%. Would the nutrients not be sufficient above this? Salinity?
Other small remarks:
Line 163: typo: used a, instead of a used
Line 182: what are specific-specific conditions? Typo?
Line 183: Could OWF-LTA really 'provide food security' or maybe rather formulating it 'could add to solving the food security issues'?

Reviewer #2 (Remarks to the Author):

The authors argue that farming mussels and kelp within offshore wind farms can have important benefits for nutrient and carbon removal from the sea. They have estimated removal rates for waters in and between the eastern North Sea and the western Baltic Sea, and then scaled these estimates globally. Although I agree with the authors that there is a potential to produce blue biomass in offshore areas used for wind-farming, which could reduce user conflicts, I am not convinced by the detailed arguments, for the reasons set out below, following the excerpts from the numbered lines of the manuscript.

63 ... Hence, harvesting of bivalves and seaweeds removes nitrogen (N), phosphorous
64 (P), and carbon (C) from the sea, thereby improving water quality in eutrophic areas and
65 mitigating climate change ..

Removal of carbon from the sea will mitigate green-house gas load only if the carbon is sequestered or used to replace fossil-fuel carbon: this should be made clear

67 .. Coastal communities, however, show concerns with respect to the visual disruption of the
68 waterscape, competition for space, generation of waste, and negative influence on tourism [16].
69 As a result, the expansion of LTA, e.g., bivalves, has been hindered in Europe over the last two
70 decades [17].

This is a valid point, but LTA expansion has been hindered by a number of other factors, including economics, inappropriate regulation, and lack of market

71 Multi-use platforms

The manuscript deals with cultivation of Low-Trophic Species (LTS) in areas allocated for offshore renewable energy (ORE) generation, and not the use of the same platform for LTA and ORE

115... LTA production models predicted harvest
116 potential from 34 to 36 Kt-fresh weight (FW) ha-1 y-1 in the more saline North Sea and Danish

Is there a units error here? 34-36 tonnes ha-1 yr-1 seems more likely (on the basis of the figures for kelp production contained in METHODS and which I further discuss below)

124 Nutrient and carbon removal potential in the study area. Nutrient and carbon removal by
125 harvesting of blue mussels and sugar kelp ...

It isn't clear whether the carbon removed in mussels is in the mussel flesh or the shell, and what the likely fate of this carbon is: presumable, if flesh, will be consumed and the carbon respired; shells might be sequestered?

132 Global projections of OWF-LTA. In all world regions, current LTA produces mussel species
133 belonging to the family Mytilidae and brown seaweeds comparable to the species in the study
134 area (Table 3) ...

I'm somewhat critical of the assumptions made in this global scaling up. The kelps are cold-water seaweeds, requiring high winter nutrient concentrations. The mussels grow best where there is abundant larger phytoplankton. These requirements have not been considered and likely reduce the potential global production of this LTA.

246 Generally, LTA has a considerably lower carbon footprint than terrestrial bio-based products
247 [9, 13]. Mussel biomass can substitute terrestrial protein sources in food and animal feed, and
248 sugar kelp biomass may substitute imported biomass e.g., food, feed, biofuels, and
249 pharmaceuticals [9, 12, 27]. ...

This is addressing the point about the fate of the exported carbon. I agree about the substitution of mussel protein for terrestrial protein, but conversion to animal feed doesn't seem to have gotten very far, and human consumption is limited by supply chain and market issues. The european market for seaweed as food is currently small, although attempts are being made to grow it; the production of significant quantities of biofuel from kelp farming would require enormous areas for cultivation. None of these are trivial issues.

338 Mussel harvest and nutrient removal model. In a previous study [83], a modular spatial
339 model was developed and used to estimate explicit growth potentials and nutrient removal rates
340 of mitigation cultures of blue mussels (Mytilus spp.) across the western Baltic Sea. In this
341 model, the harvest of mussels is a function of monthly salinity, temperature, Chlorophyll a (Chl
342 a) concentrations, and farm configuration.

In my experience of modelling the production of cultivated mussels, a crucial variable is the exchange rate of farm water with surrounding water, because the animals under each square meter of farm consume much more than phytoplankton produce in that square meter. This is not taken into account, as far as I can see, and constrains the upscaling of production figures for small scales to those of the larger scales envisaged here.

352 estimates of FW, dry matter (DM), and N-, P- and C tissue concentrations, where DM, N, P,
353 and C contents of mussels are assumed to be a constant fraction of the mussel FW of 10.3%,
354 1.45%, 0.083% and 4.61% (only shell), respectively [83, 85]. ...

Don't understand '(only shell)'

361 Seaweed production estimates. The production of seaweed in Denmark and Europe is

362 centered on the production of sugar kelp (Saccharina latissima), an endemic species, with high
363 growth rates and yield potentials [86]. ...
375 ... The salinity function is multiplied by the maximum production of 18.4 tons FW ha-1
376 by sugar kelp reported from three Danish areas with salinity >20 psu [4].

I am told that the potential maximum annual production of sugar kelp on experimental long-lines in Scottish waters is about 10 kg FW per linear metre, on lines spaced about 3 m apart: which corresponds to about 3 kg FW m-2 or 30 tonnes ha-1. In most circumstances production is less, so the figure of 18.4 tons FW ha-1, seems reasonable.

However, what the calculations fail to take into account is the effect of large-scale kelp cultivation on nutrients, which depends on the cultivation area and its exchange rate with surrounding waters. This constrains the scaling-up calculations, and, additionally, regulators may not allow substantial reductions in nutrient availability.

418 References

I missed a reference to Lindahl et al., 2005, doi: 10.1579/0044-7447-34.2.131
They were one of the earliest to propose mussel cultivation for bioremediation, and examined many of the key issues.

Reviewer #3 (Remarks to the Author):

The paper presents the results of an integrated environmental model based on copernicus data showing scenarios of potential development of low trophic aquaculture in combination with offshore wind farms.
The topic is interesting, the paper is clearly written and well describes the method and the results. However it would be helpful to revise the paper under the two following aspects.
The method description should highlight assumptions, inputs, outputs in order to be replicable by others.
The results should be also presented on a world map, showing the development scenarios and the related contribution to the production.
The discussion should clearly state the reduction of carbon footprint and benefit for ecosystem services from one side and the engineering challenge and carbon footprint (transportation, maintenance).

Decision on manuscript COMMSENV-23-0198-T

Dear reviewers

We thank you for providing this detailed and constructive reviews. We have inserted our answers below in blue text, where we addressed each point. In the revised manuscript, all changes are highlighted in yellow. In brief:

- We have made a new figure 3 with a global map showing the locations of the offshore wind farms (OWF) in the projections including tables with total area covered by wind farms, and percentage distributions between regions.
- We have made a new figure 5 showing the environmental data extracted globally for all OWF sites. In addition, all regions have low trophic aquaculture with similar species adapted to these environments (Table 2). Salinity is mostly above 30 psu at all OWF sites and low trophic aquaculture should be feasible in all areas.
- Calculations of the critical flow velocity ratio for potential food limitation in mussel farms is shown in Figure 5f. This shows that food limitation is not a problem for most of the study sites and that all regions would be suitable for mussel farming.
- We have made a new table 3 with reported values of low trophic aquaculture harvest (t-fresh weight (FW) per farm area) from all regions supporting our applied value of 18 t-FW/hectare.

We hope that you will find the paper considerably improved for publication.

On behalf of the authors,

Marie Maar

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The overall claims are addressed and the study presents new input for the scientific community. It is very nicely structured with clear paragraphs per idea and concept. I also appreciate that the socio-economic dimension that needs to be considered with such an upscaled system are mentioned. The paper does try to cover a lot, and thus it is clear, that those aspects can't also be the focus of this paper. I think overall the work is convincing and relevant, but some claims need to be written with more care.

1) For instance regarding carbon:
Line 65 : Attention to saying that storing carbon in the lower trophic species equals mitigation of climate change. Even if in line 193 – 197 It is explained that assumptions are made for the C sequestration in the mussel shells, but only in the discussion part. I suggest, as this is a hot topic right now, to mentioned it earlier in the results and abstract.

-we have corrected the sentence in the **abstract**: "Total C harvested from seaweed biomass and mussel shells would equal 40% of the CO_2 emissions from the Danish agricultural sector"

Introduction: "CO_2 and dissolved nutrients are built into seaweed biomass through photosynthesis, uptake, and growth. CO_2 is built into mussel shells by bio-calcification, whereas organic carbon (C) and nutrients are incorporated into mussel tissue through filtration of suspended particulate organic matter"

2) And in line 208-212, it is explained in which case the climate mitigation potential is used. As it is a hot topic, this is a big claim to be made early on and should be accompanied with a short version of this explanation.

Introduction. "In addition, the extractive species of LTA take up nutrients and store carbon from the water column [11]. CO_2 and dissolved nutrients are built into seaweed biomass through photosynthesis, uptake, and growth. CO_2 is built into mussel shells by bio-calcification, whereas organic carbon (C) and nutrients are incorporated into mussel tissue through filtration of suspended particulate organic matter [4, 15]. Hence, harvesting of bivalves and seaweeds removes nitrogen (N) and phosphorous (P) from the sea, thereby improving water quality in eutrophic areas [16, 17]. Seaweed photosynthesis increase pH and produce oxygen, hereby mitigating ocean acidification [18] and de-oxygenation [19]. LTA can further contribute to climate change mitigation if peoples diet is shifted from terrestrial animal-based proteins to seafood with a lower carbon footprint [14]. As harvesting offers the potential for efficient recirculation of nutrients and carbon from sea to land, LTA also makes a positive contribution to the circular bioeconomy [20].".

3) And also, in Line 201 - 206 it is explained that not the 11% of C ending up in the deep sea are included in the calculations but rather the C removed by the sugar kelp, which is then made available for the bioeconomic system on land. This in itself is clear, but it then cannot be called climate mitigation.

- We refer to the paper of Zhang et al. 2022 [4].

Discussion: "The potential mitigation of climate change through greenhouse gas reductions from this C removal, is only realized in cases where i) the downstream LTA value chain emissions are lower than the net negative emission at the time of harvest [4], ii) the seaweed substitutes an ingredient or product with a higher carbon footprint [9], or iii) the LTA contains bioactive components which reduce ruminant enteric fermentation, and hence methane emission from cattle production [56]. Globally, estimated C capture and removal was up to 4,226 Kt-CO_2 by OWF-LTA in the 'realistic' scenario (SDG 13)."

We have also emphasized that climate change mitigation is not only sequestering C, but also mitigating effects of climate change, such as ocean acidification and de-oxygenation. Here seaweed cultivation has been documented to increase pH and oxygen concentration locally.

Discussion: "The regulating ESS of LTA also manifests their positive effect on marine water quality as increased water clarity, lower chlorophyll *a* concentration, lower sedimentation, and increased oxygen concentration on basin-scale [16, 32, 60, 61]. In addition, seaweed culture produce oxygen and increase pH locally [16]."

4) Line 382: extra fuel to operate the OWF LTA was not calculated in the carbon budget. I would argue that this may be a big part of the carbon budget, see LCA studies by Sleger et al. 2021: DOI: 10.1016/j.jclepro.2021.128689.

Since we are not aiming at performing an LCA of the global warming potential in this paper, we modified the sentence to:

Discussion: "Generally, the regenerative nature of LTA enables the simultaneous delivery of ESS of both a provisioning and a regulating/maintenance nature and has a considerably lower carbon footprint than terrestrial bio-based products [9, 14]. The extent to which the climate/environmental footprint of the LTA will increase due to longer transport to offshore locations or sharing of logistics and infrastructure (e.g., sharing of boats and personnel, charging of electric boats, monitoring by robotics) between multiple users will lead to an overall footprint reduction, remains to be tested [7, 11, 72]."

5) Line 93-94: The main aim was noted to explore the model of OWF-LTA as means to achieving multiple global SDGs. However, the text focuses more on ES and the link to SDG is rarely made. The link might seems obvious, but it leaves the reader waiting for more consideration of the specific targets or goals.
- we have added references to the SDGs in brackets in the discussion where relevant.

6) This paper is based on models and predictions and when reading the results, it leaves the reader with questions on what is considered in the scenarios and models. Knowing, that it will be explained later on in the material section, it could help to list very briefly, what are the considered variables and what not. For a reader not being an expert in models, it seems in some parts as untransparent.

We agree that this could be better explained and have added new text in the results briefly mentioning the scenarios and variables in the models.

Results:

Line 116: "**OWF development**. Information on the OWF development was obtained from the 4C global offshore database and used to make three projections ('realistic', 'pessimistic', and 'optimistic') based on 12 project status categories (see method section) for marine waters (Figure 3, Table S3)."

Line 132: "Harvest potential in the study area. "Salinity is an important factor for LTA harvest yield due to the hampering of species growth at lower salinities in the study area. Spatial models of harvest potential were applied for blue mussels and sugar kelp. The blue mussel harvest model was a function of temperature, chlorophyll *a*, and salinity. Model calculations of the critical flow velocity ratio (0.65 to 21) showed that there was sufficient food supply to avoid food limitation for the mussels at all sites. Mussel farms at salinity >16 psu were configured as commercial culture (human consumption), whereas the mussel farms at lower salinity were configured as nutrient mitigation culture. The total production potential of commercial mussel farms in the more saline North Sea and Danish Straits (>16 psu) showed an average area-specific harvest potential of 16-18 t-fresh weight (FW) ha^{-1} y^{-1} (Table 1, Fig. 2). In the brackish Baltic Sea (8-16 psu), mussel harvest potential was considerably higher with 33 t-FW ha^{-1} y^{-1} because of higher densities of small mussels (not suited for human consumption) with lower growth rates designed to remove as much nutrients as possible per farm area.

The sugar kelp harvest model was a function of salinity only, since salinity is the dominating environmental factor determining the yield potential of kelp. It is assumed that sugar kelp is harvested before potentially high summer temperatures limit productivity (see method section). The sugar kelp model predicted a 3-4 times higher harvest potential of 16-18 t-FW ha^{-1} y^{-1} in the more saline North Sea and Danish Straits compared to the brackish Baltic Sea (Table 1, Fig. 2). The model assumed that nutrient limitation for sugar kelp aquaculture within OWF regions are unlikely [30]. Our deployment of sugar kelp farms, covering just 10% of the wind farm area, and the strong water exchange typical of offshore areas, reduce this possibility. Overall, potential LTA harvest was 17 t-FW ha^{-1} y^{-1} and 19 t-FW ha^{-1} y^{-1} at salinities >16 and <16, respectively, assuming a 50/50 areal distribution of mussels and sugar kelp.

According to the experience with wind farm operators and other multi-use projects, not all of the area between the pillars can be used for the LTA, as there are other multi-use scenarios (ecotourism, passive fishing, etc.) that also require space. Further, there must be accessible routes to the wind turbine installations without long detours (crossing of a maintenance vessel), and safety zones around the entire wind farm area, cables, and the respective pylons. Based on this, we have made a conservative calculation of the possible OWF-LTA areas, which are derived from the long-term results of other multi-use projects on a national (Germany) and international (EU) basis [36-38]."

7) The limitations to the scenarios and projections are not clearly stated in the results and leave the reader with questions. For instance,
Line 86: 'depends on economic background', can you clarify what is meant here? Economic viability? You could link to the paragraphs on socio-economic carrying capacity.

We corrected the paragraph:

Line 354: Discussion: "The economic carrying capacity of expanding the production and market of LTA products must also be considered, as increasing the landings will likely negatively influence the price of blue mussels and sugar kelp on the global market. Further, the individual business plans of LTA in the OWF must be viable considering the market value of the end products, the longer transports from land increasing fuel, and potential sharing of operational costs (SDG 17) [11]".

8) Line 109 (and more): pessimistic, optimistic and realistic models. I cannot find (or see) in the methodologies links to what realistic, optimistic and pessimistic models are based on. Link to figure 3 and Table 2.

We changed former table 2 to a new figure 3 showing a map of the global projections.

Line 116: "OWF development. Information on the OWF development was obtained from the 4C global offshore database and used to make three projections ('realistic', 'pessimistic', and 'optimistic') based on 12 project status categories (see method section) for marine waters (Figure 3, Supplementary Table 3)."

Line 374: "**Scenario of OWF-LTA multi-use in the study area.** The realistic potential of OWF-LTA was estimated in the study area of the North Sea-Baltic Sea transition zone (Figure 2). Data on OWF locations, names, and areas in the study were mainly obtained from the 4C global offshore database version of January 2023 (accessible via https://map.4coffshore.com/offshorewind/). The two OWFs Vesterhav Nord & Syd (sites 4 and 6) (Figure 2, Supplementary Table 1) are combined in the 4C global offshore database. However, we used area and location data from EMODnet [76], where both are listed individually. This was to consider the large distance and different LTA production characteristics between these two OWF sites. In the 4C global offshore database, there are two OWFs named Kriegers Flak. Therefore, we added corresponding country codes for Denmark (DK) and Sweden (SE) to the names (sites 12 and 25) (Figure 2, Supplementary Table 1). The OWF we called 'Nordsøen (3GW)' (site 1) (Figure 2, Supplementary Table 1), refers to a 3GW scenario taking into account the areas 'Nordsøen Tender 1-3' from the 4C global offshore database, which roughly corresponds to scenario 1a outlined in [85]. Only wind farms in open marine waters were considered.

In the study area, 31 potential OWF sites could serve for multi-use with LTA in the future: 16 OWF are in operation, one is under construction, eight are approved and six are planned in the three countries Denmark, Sweden, and Germany (Figure 2, Supplementary Table 1). The newly planned OWF projects by the Danish National Authorities to be realized before 2030 are in the North Sea (sites 1 and 2), the Danish Straits (site 9), and the Baltic Sea (sites 26, 30, and 31) (Figure 2, Supplementary Table 1). The OWFs are located across a salinity gradient from 34.5 psu in the North Sea to 7.8 psu in the Baltic Sea (Supplementary Table 1). We divided the study area into three sub-areas according to salinity; the North Sea with salinities above 25 psu (sites 1-7), the Danish Straits with salinities from 16 to 25 psu (sites 8-14), and the Baltic Sea with salinities below 16 psu (sites 15 to 31) indicating the threshold for reduced growth of blue mussels and sugar kelp [86, 87]. The multi-use scenario applied in this study was defined as a total of 10% of the OWF area dedicated to LTA. This is a conservative estimate and corresponds to scenarios applied in the German and Dutch parts of the North Sea [88, 89]. The main criteria for the 10% was the available space within the wind park, which is limited by wind turbine foundations, scour protections, underwater cables, service routes, and associated safety zones [41]. Within the 10% of each OWF area dedicated to LTA, a 50/50 areal distribution between the production of mussels and seaweeds was assumed. The aquaculture period was assumed to be from June to November for mussels which are optimal for mitigation culture [61] and from October to May for seaweeds [4] in northern Europe. "

9) Line 114: Salinity is mentioned as an important limiting factor for harvest potential. However, many other papers mention nutrients and temperature, which are only mentioned when reading further. If you mention salinity here, I suggest to briefly mention that other variables are also considered, but salinity was identified as the main threshold to reduced

growth (as in line 299). Link to figure 2 as well. Line 298, 299: Again, it is just mentioned, that as a threshold to growth, salinity is used. Only in line 321 and then later in line 356, it is explained that other variables are used for the production models, like Chl a and temperature. This could be mentioned earlier, as it leaves the reader wondering why only salinity is mentioned before.

-please see reply to point 6) where we improved the explanation in the results.

10) Line 119 and 300: the authors calculate that 10% of the area are to be used, why? Even if this is not the focus of the study and the authors are basing themselves on a different study, it would be helpful to understand in a sentence, what the main criteria were for 10%. Would the nutrients not be sufficient above this? Salinity?

We have added new sentences,

Line 399: Methods: "The multi-use scenario applied in this study was defined as a total of 10% of the OWF area dedicated to LTA. This is a conservative estimate and corresponds to scenarios applied in the German and Dutch parts of the North Sea [85, 86]. The main criteria for the 10% was the available space within the wind park, which is limited by wind turbine foundations, scour protections, underwater cables, service routes, and associated safety zones [38]."

Line 158: Results: "According to the experience with wind farm operators and other multi-use projects, not all the area between wind turbines can be used for LTA. This is because as accessible routes to the wind turbine must be maintained and safety zones around the wind farm area, and within the windfarm around cables, and the wind turbines. Additionally, this can be further combined with other multi-use scenarios (e.g., ecotourism, passive fishing, nature conservation) that also require space. Based on this, we have made a conservative calculation of the possible OWF-LTA areas, which is derived from the long-term results of other multi-use projects at both the national level (Germany) and international level (EU) [39-41]."

Other small remarks:
Line 163: typo: used a, instead of a used -corrected
Line 182: what are specific-specific conditions? Typo? Corrected to "species-specific conditions"
Line 183: Could OWF-LTA really 'provide food security' or maybe rather formulating it 'could add to solving the food security issues'? -corrected

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Reviewer #2 (Remarks to the Author):

The authors argue that farming mussels and kelp within offshore wind farms can have important benefits for nutrient and carbon removal from the sea. They have estimated removal rates for waters in and between the eastern North Sea and the western Baltic Sea, and then scaled these estimates globally. Although I agree with the authors that there is a potential to produce blue biomass in offshore areas used for wind-farming, which could reduce user conflicts, I am not convinced by the detailed arguments, for the reasons set out below, following the excerpts from the numbered lines of the manuscript.

11) 63 ... Hence, harvesting of bivalves and seaweeds removes nitrogen (N), phosphorous (P), and carbon (C) from the sea, thereby improving water quality in eutrophic areas and mitigating climate change ...

Removal of carbon from the sea will mitigate green-house gas load only if the carbon is sequestered or used to replace fossil-fuel carbon: this should be made clear

Please see reply to point 3).

12) 67 Coastal communities, however, show concerns with respect to the visual disruption of the waterscape, competition for space, generation of waste, and negative influence on tourism [16]. As a result, the expansion of LTA, e.g., bivalves, has been hindered in Europe over the last two decades [17].

This is a valid point, but LTA expansion has been hindered by a number of other factors, including economics, inappropriate regulation, and lack of market.

Thanks, this has now been added to the introduction:

Line 72: Introduction: "Coastal communities, however, show concerns with respect to the visual disruption of the waterscape, competition for space, generation of waste, negative influence on tourism, lack of market, economic viability, and inappropriate regulations [21, 22]. As a result, the expansion of LTA, e.g., bivalves, has been hindered in Europe over the last two decades [23]. The European Union has accordingly funded several projects under the umbrella of "Blue Growth Strategies", "Horizon 2020", and "Horizon Europe", where the use of the open ocean for LTAs has been promoted with the inclusion of economic and social aspects."

13) 71 Multi-use platforms

The manuscript deals with cultivation of Low-Trophic Species (LTS) in areas allocated for offshore renewable energy (ORE) generation, and not the use of the same platform for LTA and ORE

We see your point and have corrected the title to: "Multi-use of ocean space: Integration of offshore wind farms with low-trophic aquaculture shows great potential to support the global sustainability goals" and elsewhere.

14) 115... LTA production models predicted harvest potential from 34 to 36 Kt-fresh weight (FW) ha-1 y-1 in the more saline North Sea and Danish

Is there a units error here? 34-36 tonnes ha-1 yr-1 seems more likely (on the basis of the figures for kelp production contained in METHODS and which I further discuss below)

Sorry for the typo, this is now corrected to t/ha/yr. We have also reduced the LTA harvest potential to 18 t/ha/yr due to the use of commercial mussel culture instead of mitigation culture.

15) 124 Nutrient and carbon removal potential in the study area. Nutrient and carbon removal by harvesting of blue mussels and sugar kelp ...

It isn't clear whether the carbon removed in mussels is in the mussel flesh or the shell, and what the likely fate of this carbon is: presumable, if flesh, will be consumed and the carbon respired; shells might be sequestered?

Please see reply to points 1, 2, 3)

16) 132 Global projections of OWF-LTA. In all world regions, current LTA produces mussel species belonging to the family Mytilidae and brown seaweeds comparable to the species in the study area (Table 3) ...

I'm somewhat critical of the assumptions made in this global scaling up. The kelps are cold-water seaweeds, requiring high winter nutrient concentrations. The mussels grow best where there is abundant larger phytoplankton. These requirements have not been considered and likely reduce the potential global production of this LTA.

We have now inserted a new table 3 (former table 3 is now table 2) showing the reported harvest values from the different regions and our estimate is not unrealistic. We have inserted a new figure 5 showing the environmental variables at the OWF sites including the critical flow velocity ratio (fig 5f) indicating that the food supply to the mussel farms was not limiting growth.

Line 217: **Discussion**: "If the mussels are commercially produced for human consumption (salinity >16 psu), the areal efficiency (16-18 t-FW ha^{-1} y^{-1}) was similar to that from the OWF in the Exclusive Economic Zones (EEZ) of the German Bight (Northern Europe) with yields of 24 t-FW ha^{-1} y^{-1} [47-49]. Reported mussel harvest yields from other regions of the world varied from 5 t-FW ha^{-1} y^{-1} in Canada to 1300 t-FW ha^{-1} y^{-1} in Spain (Table 3). The lowest value from Canada is due to low water depth and extra-long distance between the mussel long-lines compared to the other sites, due to operational reasons. Hence, our estimate is conservative when used for the global upscaling.

The production potential of sugar kelp used in the current study (16-18 t-FW ha^{-1} y^{-1} in saline areas) was lower than reported for the nearby North Sea EEZ of the German Bight due to lower growth rates and less efficient production methods in our pilot [4]. In the German Bight, the estimated harvest value was around 30 t-FW ha^{-1} y^{-1} [31, 47, 48]. For other regions, sugar kelp and similar brown seaweed species are cultured (Table 2) and reported yields varied from 16 t-FW ha^{-1} y^{-1} in the U.S. to 124 t-FW ha^{-1} y^{-1} in Chile (Table 3). Hence, the modeled value of sugar kelp production should be considered as conservative in the global upscaling [4]."

Line 249: Discussion: "Northern Europe showed the highest OWF-LTA development potential among the regions. The uncertainty of the estimates is lowest in this region due to the overlap with the study area, whereas there may be local environmental and species-specific conditions not considered in the other regions. The higher temperatures in other regions compared to Northern Europe is not considered to be a major problem (Figure 5b), since seaweed and mussel cultivation is already taking place with locally adapted species (Tables 2 & 3). In the context of global warming, offshore areas may be cooler than shallow coastal waters and farm units can be lowered to deeper and colder waters offshore. Food limitation for mussel farming seemed not to be a problem in the majority of OWF areas according to the critical flow velocity ratio (Figure 5f). The highest uncertainty for OWF-LTA is in Africa due to few planned OWF sites, limited experience with LTA, and high variability in environmental data (Figure 5). In Australia-NZ, there is currently no cultivation of brown seaweed (e.g., *Undaria pinnatifida*, *Macrocystis pyrifera*, *Ecklonia radiata*) although it should be possible according to the environmental conditions."

17) 246 Generally, LTA has a considerably lower carbon footprint than terrestrial bio-based products [9, 13]. Mussel biomass can substitute terrestrial protein sources in food and animal feed, and sugar kelp biomass may substitute imported biomass e.g., food, feed, biofuels, and pharmaceuticals [9, 12, 27]. ...

This is addressing the point about the fate of the exported carbon. I agree about the substitution of mussel protein for terrestrial protein, but conversion to animal feed doesn't seem to have gotten very far, and human consumption is limited by supply chain and market issues. The European market for seaweed as food is currently small, although attempts are being made to grow it; the production of significant quantities of biofuel from kelp farming would require enormous areas for cultivation. None of these are trivial issues.

The conversion of mussel protein to animal feed looks promising as stated in the cited studies:
"Mussel mitigation cultures have a higher mussel density and the mussels are typically smaller and more uneven in size than mussels commercially produced for human consumption [42]. The harvested mitigation mussels can be used as feed ingredients for fish, pigs, or poultry substituting fish meal or providing spat for mussel cultures elsewhere [20, 43, 44]."

20. Petersen, J.K., et al., Nutrient Extraction Through Bivalves, in Goods and Services of Marine Bivalves, F.J. Smaal A., Grant J., Petersen J., Strand Ø., Editor. 2019, Springer: Cham. p. 179-208.
43. van der Heide, M.E., et al., The Potential of Locally-Sourced European Protein Sources for Organic Monogastric Production: A Review of Forage Crop Extracts, Seaweed, Starfish, Mussel, and Insects. Sustainability, 2021. 13(4): p. 2303.
44. Weiß, M. and B.H. Buck, Partial replacement of fishmeal in diets for turbot (Scophthalmus maximus, Linnaeus, 1758) culture using blue mussel (Mytilus edulis, Linneus, 1758) meat. Journal of Applied Ichthyology, 2017. 33(3): p. 354-360.

We agree that the market at the moment can be limiting for the LTA products for human consumption in some regions. We have therefore inserted a new sentence:

Discussion:" An expansion of the market for human consumption would need a shift in people's diet towards more seafood facilitated by the younger generations and may provide a sustainable food production option to a growing world population [9, 11].".

9. Gephart, J.A., et al., *Environmental performance of blue foods.* Nature, 2021. **597**(7876): p. 360-365.

11. Krause, G., et al., *Prospects of Low Trophic Marine Aquaculture Contributing to Food Security in a Net Zero-Carbon World.* Frontiers in Sustainable Food Systems, 2022. **6**.

18) 338 Mussel harvest and nutrient removal model. In a previous study [83], a modular spatial model was developed and used to estimate explicit growth potentials and nutrient removal rates of mitigation cultures of blue mussels (Mytilus spp.) across the western Baltic Sea. In this model, the harvest of mussels is a function of monthly salinity, temperature, Chlorophyll a (Chl a) concentrations, and farm configuration.

In my experience of modelling the production of cultivated mussels, a crucial variable is the exchange rate of farm water with surrounding water, because the animals under each square meter of farm consume much more than phytoplankton produce in that square meter. This is not taken into account, as far as I can see, and constrains the upscaling of production figures for small scales to those of the larger scales envisaged here.

We now estimated the critical flow velocity ratio (water turnover) for all sites, which should be above 0.5 to avoid food limitation (Holbach et al. 2020). This is the case for all the OWF sites in the North Sea-Baltic Sea transition zone (ratio >0.65). For the global regions, we now show these results in a new figure 5f. In most cases, the ratio>0.5 demonstrating that it is likely to produce mussels in all regions.

Please also see reply to point 6).

19) 352 estimates of FW, dry matter (DM), and N-, P- and C tissue concentrations, where DM, N, P, and C contents of mussels are assumed to be a constant fraction of the mussel FW of 10.3%, 1.45%, 0.083% and 4.61% (only shell), respectively [83, 85]. ...

Don't understand '(only shell)'

We have now clarified this:

Line 450: method section: "The model output includes estimates of FW, dry matter (DM), and N- and P- tissue concentrations, where DM, N, and P contents of mussels are assumed to be a constant fraction of the mussel FW of 10.3%, 1.45%, and 0.083%, respectively [84]. In addition, we estimated the C removal in mussel shells as 4.61% of FW [86]. Mussels sequester CO_2 into insoluble and indigestible calcium carbonate of the shells, which was assumed to act as a carbon sink [14]."

Please also see reply to points 1), 2), and 3).

20) 361 Seaweed production estimates. The production of seaweed in Denmark and Europe is centered on the production of sugar kelp (Saccharina latissima), an endemic species, with high growth rates and yield potentials [86]. ... 375... The salinity function is multiplied by the maximum production of 18.4 tons FW ha-1 by sugar kelp reported from three Danish areas with salinity >20 psu [4].

I am told that the potential maximum annual production of sugar kelp on experimental long-lines in Scottish waters is about 10 kg FW per linear metre, on lines spaced about 3 m apart: which corresponds to about 3 kg FW m-2 or 30 tonnes ha-1. In most circumstances production is less, so the figure of 18.4 tons FW ha-1, seems reasonable.

However, what the calculations fail to take into account is the effect of large-scale kelp cultivation on nutrients, which depends on the cultivation area and its exchange rate with surrounding waters. This constrains the scaling-up calculations, and, additionally, regulators may not allow substantial reductions in nutrient availability.

Please see reply to point 6).

21) 418 References
I missed a reference to Lindahl et al., 2005, doi: 10.1579/0044-7447-34.2.131
They were one of the earliest to propose mussel cultivation for bioremediation, and examined many of the key issues.

The reference has been inserted into the introduction.

Reviewer #3 (Remarks to the Author):

The paper presents the results of an integrated environmental model based on Copernicus data showing scenarios of potential development of low trophic aquaculture in combination with offshore wind farms. The topic is interesting, the paper is clearly written and well describes the method and the results. However, it would be helpful to revise the paper under the two following aspects.

22) The method description should highlight assumptions, inputs, outputs in order to be replicable by others.

Lines 374-567: The **method** section has been updated with more information on data use, assumptions, and outputs.

23) The results should be also presented on a world map, showing the development scenarios and the related contribution to the production.

Good idea. We have produced maps showing the global distribution of OWF in the current situation and in the three projections in the new Figure 3.

24) The discussion should clearly state the reduction of carbon footprint and benefit for ecosystem services from one side and the engineering challenge and carbon footprint (transportation, maintenance).

We have made changes to the manuscript as described above by adopting life cycle thinking by including the aspect of points 1) to 3) when discussing the net carbon footprint of seaweed cultivation, harvesting, and processing. Likewise, we have addressed the substitution of emission-intensive products adopted system expansion. However, we did not use LCA terminology as the paper does not target the LCA community.

18th Oct 23

Dear Professor Maar,

Your manuscript titled "Multi-use of ocean space: Integration of offshore wind farms with low-trophic aquaculture shows great potential to support the global sustainability goals" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

Please note that it may still be possible for your paper to be published before the end of 2023, but in order to do this we will need you to address these points as quickly as possible so that we can move forward with your paper.

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Senior Editor
Communications Earth & Environment

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REVIEWERS' COMMENTS:

Reviewer #3 (Remarks to the Author):

The Authors revised the paper according to the Reviewer's comments. The paper has been improved and is now ready to be accepted.

Reviewer #4 (Remarks to the Author):

I would like to thank you the authors for the interesting paper, showing the potential of a promising, sustainable, multi-use of the ocean space.

I would like to start with a caveat: my expertise is in offshore renewable energy engineering, so my knowledge in terms of the biology of the marine environment is very limited, although I often collaborated with experts in the fields in research projects.

Consequently, my comments are limited to my field of expertise.

The major claim of the paper, i.e., "Multi-use of ocean space, combining offshore wind farms with low-trophic aquaculture could provide sustainable energy, nutritious seafood, and restorative ecosystem services through nutrients and CO2 capture and utilization" seem to be well justified, presenting transparently the main assumptions and methodology, and including range of uncertainty.

This work builds up upon several previous works, many of which conducted by the author of this work, and it represents a valuable contribution to knowledge, incremental rather than radical, but still worth of publication.

The work is convincing and can represent a valid reference for the offshore wind and aquaculture stakeholder community willing to assess the potential of a multi-use of the ocean space.

For the topic in the article nearer to my expertise, I have seen that conservative assumptions on the use of the offshore wind farm area (10%) have been considered, to make sure that operation & maintenance for the offshore wind turbines is not compromised by the presence of seaweed/mussel cultivations.

Although beyond the scope of the present article, I would like to suggest to the authors to further investigate this aspect: nowadays, there are sophisticated O&M cost models for offshore wind turbines, used by operators to perform planned and unplanned O&M actions, which can give a much more informed picture of these operations. This would allow a better estimation not only of the aera available to seaweed/mussel cultivation, but also an assessment of the potential to share O&M resources (vessels, personnel, time) - which can make a convincing economic case.

Another suggestion, potentially for a future article, is to consider the British waters, since most offshore wind turbines are located there.

Response to Referees, second revision

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Thanks a lot for this suggestion. In the EU OLAMUR project, we have a work package that will investigate the economic, climate footprint and environmental sustainability of the multi-use and we will certainly look more into the O&M cost models. The project only started this year and last 4 years so we will have time to more into deep with the costs in another publication.

Another suggestion, potentially for a future article, is to consider the British waters, since most offshore wind turbines are located there.

Thanks for this suggestion, the concept will be further tested for all of the North Sea and Baltic Sea in the OLAMUR project.