Response to editor's and reviewers comments, and marked-up document

Associate Editor Decision: Reconsider after major revisions (05 Oct 2017) by Marilaure Grégoire
Comments to the Author:
Dear Johan,
I have read the comments of the three reviewers on your manuscript as well as your answers to them. Based on that I encourage you to submit a revised version of your work. On some points reviewers agree which strengthen their criticisms.

Dear Marilaure,

Thank you for your comments. Please find responses in italics below, and a marked-up version of the manuscript.

In particular, I would appreciate you consider the remarks raised by two of the reviewers on the organization of the manuscript.

See response to comments by Fabian Groβe.

In particular, I also agree that the last lines (16-21) of section 1.1 page 3 are as you say very important and certainly worth to be mentioned. I find however, that this part would be even more understandable if it was placed after having analyzed the results. I guess that the point of the reviewers is not that you remove this part but rather than it would be better fit in a discussion section.

We have moved this to the discussion.

Same remark for the limitation of the low resolution, this is already a conclusion and recommendation gained based of the analysis of model results and that will be more easily interpreted when having read the results.

We have moved this to the discussion.

Another point on which reviewers agree is that the description of the model structure needs to be enhanced. You can for instance write the model equations for the concerned state variables. Even if it is described somewhere else, it would be helpful for a reader to find the information in the manuscript and to be able to reproduce the modeling exercise.

The equations are now included in a table.

I support your idea to add a table with parameters and variables associated to the modeling of the macroalgae.

We have added such a table.

One of the reviewers strongly recommend that you enhance the discussion on how the limitations of the modelling approach may impact the conclusions of this study

An extra paragraph discussing the limitations has been added to the discussion.

Please note that the revised version will be sent to the reviewers for a second round.
I thank you very much for your efforts in revising the manuscript.

Kind regards
Marilaure

Anonymous Referee #1 Received and published: 14 July 2017

The manuscript with the title "Modelling potential production and environmental effects of macroalgae in UK and Dutch coastal waters" by Johan van der Molen et al. provides estimates for existing and hypothetical seaweed farms within the UK and the Netherlands based on the simulations with a 3D marine ecosystem model. For the production sitethemodeldoesnotonlyprovideestimatesfortheoverallproductionbutalsoonthe quality in terms of carbon content of the macroalgae. In contrast, the summary of the environmentaleffectswasthattheywerenotdetectablewhencomparingthereference run and the scenario run. For my understanding the later conclusion is too simple to justify the expression "environmental effect" in the title. The authors should re-think if they can support this claim in the title, some hints will be expressed in detail below, or drop this part in the title. Since clarification are needed on the production part as well, the manuscript should be published after major revision.

My suggestion to back up the claim to provide information related to "environmental effect" would be to calculate the flux of nutrient and carbon uptake by the farmed macroalgae in comparison to the phytoplankton usually used in the model. The nitrogen and phosphate uptake is already presented as time series for each farm site in Fig. 9 – 12 in the graphs k and l. With this quantitative information one could underpin in which way the phytoplankton, in the grid call where the aquaculture is applied, was still able to develop in a way that is not detectable by simply plotting concentration differences. Especially at sites where the nitrogen concentration is depleted is summer it would be very interesting to see how the phytoplankton could manage its uptake in comparison to the newly introduced macroalgae. In addition this information could be supported by the rather simple calculation of the nutrient content in the water column exposed to farming both in winter and in summer, or other crucial important period like autumn. In doing so one can still not define in which way changing transport of either nutrients or phytoplankton led to the indistinguishable concentration differences between the two runs, but one would provide some quantitative background information on the "environmental effects".

In principle, comparing the nutrient uptake with that of phytoplankton to get more information on environmental effects is a good idea. However, from a practical point of view this is not possible with the current simulations as nutrient uptake by phytoplankton was not stored, and we are not in a position to repeat the model runs. From a biological point of view, it is not immediately clear what the meaning of such a comparison would be, because i) phytoplankton is advected by the currents, hence spends only a limited amount of time within the farm area and may compensate when it arrives elsewhere; within the farm area the phytoplankton population is continuously being replaced; ii) because of their much larger surface to volume ratio, phytoplankton out-compete macroalgae in terms of nutrient uptake, the niche of macroalgae is their ability to *buffer and grow on nutrients accumulated in winter when phytoplankton can't grow. We did not only compare nutrient concentrations, but also phytoplankton biomass and found no significant change. The text will be updated to clarify this. We have removed the environmental effects from the title.*

One more small detail, in chapt. 3.2 "Environmental effects" the "differences between the two reference runs" (Page 12, line 7) should rather be the difference between the reference run and the scenario with the seaweed farm application or is this a misinterpretation?

The text is correct. Because the model does not reproduce values exactly between two 'identical' runs, only differences between the run with farm and the first reference run that exceed the difference between the two reference runs are considered significant. We have adjusted the text to make this clearer.

On the other hand the study goes beyond a simple feasibility study by providing information not only on the potential harvest that can be expected but also about the seaweed quality in relation to the use for biofuel in terms of the carbohydrate content. Especially for this "fledging industry" the relation of nutrient limitation leading to higher carbon content in context with higher product quality should be expanded into more general consideration that go beyond the individual site description. With Horizon 2020 calls on the co-use of technical structures like offshore windfarms in the North Sea for aquaculture or seaweed farms, this aspect has the potential to go beyond a pure coastal application and would raise the impact of this study towards more general consideration in this context. These additional consideration would compensate the problem that the model over- or underestimates the individual nutrients and/or chlorophyll-a concentrations at different validation or farm sites, so that it is difficult to draw more general conclusions from these aspects of the model performance.

This is a very good suggestion, but such work should be done thoroughly using a combination of experimental and 1D modelling work to rigorously cover the relevant parameter space. The current model results would only provide a few scattered 'samples'. Work is in progress at NIOZ to start to address the effects of e.g. environmental conditions and time of harvest on carbohydrate and protein contents as well as composition in different native North Sea macroalgal species; we do not think it's advisable to use the current results for this purpose.

When describing the nutrient validation results for Sound of Kerrera farm site (Fig. 10a and b), the question is not only on the nutrient concentration reached in comparison to the measurements. The more profound question is why the measurement show a rather different cycle compared to the simulated concentration. Is there any local source that is not reproduced in the model that brings about these differences?

This is a good point. We have wondered about this, but do now know of one. There could be other causes such as higher local re-generation than modelled. Without additional information, we thought it best not to speculate here, and still have that opinion, so we have not make changes on this point.

Since the mortality term is one of the key parameter for the seaweed yield a more detailed description of this process is needed. The simple hint toward "erosion" does not help the reader in which way the mortality process interacts within the simulation throughout the year. As a simple example, when at site A (Strangford

Lough) the macroalgae biomass is about an order of magnitude lower than the observed one but the mortality is low throughout the farming cycles, one would interpret that the light and/or nutrient condition were not suitable in the model to efficiently reproduce the measured biomass. This implies that the mortality pressure is not an important factor when it is applied as proportional to the biomass, but this is not clear from the incomplete explanation provided.

The model uses the same equation that relates apical frond loss exponentially to frond area as used by Broch and Slagstad. We have added a few words to this effect.

Smaler details: For a more simple way of attributing the different sites, the characterisation A-G as used in Fig. 1 should be used as site specification next to the full locality description of the farms throughout the paper.

We have added further references at the first use in each section.

In this context the site specification for each farm and validation location should be highlighted in a different colour in Fig. 1 rather than simply black.

We think that the letters and numbers provide sufficient distinction.

In addition, since the Doggerbank and the Norwegian Trench areusedinthecharacterisationoftheNorthSeahydrodynamics,thesefeaturesshould be more pronounced in the topography map in Fig. 1, e.g. in the smaller map showing the full domain.

We have changed the colour scale to make these features stand out more.

Is Fig. 2 in this full detailed information overview really needed?

Yes. Lumping all human use into one category would raise the question to provide more detail.

The general statement on the model confirmation that “These results are not reproduced here” (page 10, line 27) should be placed on top of this subchapter.

We cannot implement this suggestion in a form that would lead to a more legible text.

Page 20 line 19 The first author is Jo Folden not Foden

The text is correct.

F Große (Referee) fabian.grosse@dal.ca Received and published: 21 July 2017

General comments The manuscript by van der Molen et al. deals with the representation of macroalgae – more specifically kelp – farms in the physical-biogeochemical model system GETM/ERSEM-BFM. Their study aims for the model-based analysis of their impact on the ecosystem as well as the productivity of such farms. A number of near-shore (four existing and one non-existing, but potentially suitable) farm sites off the British and Dutch coasts are used for this analysis. The increasing interest in macroalgae farms, which is well described in Sect. 1.1, provides a good background for this objective. Due to model limitations, e.g., with respect to spatial resolution or agreement with SPM or chlorophyll a observations, the authors clearly state that their study rather constitutes a "proof of concept" than a detailed analysis of the likely environmental impact and productivity of these farms (at end of Sect. 1.1). Despite this clearly stated limitation, I consider the objective of the study as relevant and feasible for publication. However, I have a few major and some minor points that should be addressed by the authors. My first major point of criticism is that the "environmental effects" included in the title are barely addressed in the manuscript (except for the information, that there are basically none in Sect. 3.2) and, therefore, either the title should be adapted or the manuscript should be extended with respect to that. For the relevance of the manuscript, I would propose to do the latter and will provide some suggestions in my specific comments below. Second, a partial re-ordering of the Sects. 1 and 2 (and subsections), from my perspective, would clearly improve the readability of these parts of the manuscript. Third, I would request a more detailed discussion of the model setup and the implementation of the kelp farms (and a more detailed description of the latter). For the latter, this could be especially relevant in relation to the potential environmental effects and may provide the reader with a better understanding of why the effects appear to be negligible in the present study. Provided this more detailed description and discussion of the limitations and constraints, this study may serve as a first guideline for investigating environmental effects and performance of macroalgea farms using 3D physical-biogeochemical models. Therefore, I recommend reconsidering the manuscript for publication after major revision.

Specific comments

1. Most parts of the last paragraph of Sect. 1.1 (page 3, end of line 16 to line 21) rather sound like a discussion/conclusion to me and I would suggest moving these parts correspondingly. Instead the authors could complete the short outline of the manuscript in this paragraph.

We have moved this section to the discussion.

In this paragraph the authors also mention that the large-scale model allowed for the inclusion of all farms in one model (page 3, line 16). The phrasing makes it sound beneficial – which is indeed the case from a technical point of view (setting up one model instead of one for each study site). However, considering the related limitations, this should be discussed critically in the discussion section.

We have added a line to the recommendations stating that high resolution simulations are desirable for the Norfolk farm.

2. Organisation of Sects. 1.2 to 2.2.2: I had difficulties going through this part of the manuscript as it partly caused a back and forth reading. This mainly relates to the fact that the characteristics of the study sites (bathymetry, hydrography etc.) are provided in Sect. 1.2, followed by the description of the considered kelp species (S. latissima) in Sect. 1.3, again followed by a now more technical description of the setup of and – if existent – the sampling at the different farm sites in Sects. 2.1. I see the difficulties with the separation/combination of Sects. 1.2 and 2.1 as the former is a more general description, while the latter is more of a methodological nature. However, considering the analysis of selected study sites as part of the methodological approach, I would propose to combine the currently two subsections on the individual study/farm sites into one subsection for each farm. These subsections should then also include the representation of the individual farms in the applied model setup (e.g., position in the vertical – are all farms in the surface layer of the model?). These (general and technical) descriptions of the study sites would then be part of the methodology section (Sect. 2), preferably after the description of the implementation of the macroalgae farms to ERSEM (Sect. 2.2.2). Current Sect. 2.2.3 would then become Sect. 2.2.4. In relation to this suggestion, current Sect. 1.3 (description of S. latissima) would become Sect. 1.2. From my perspective, this is feasible as Sect. 1.1 already indicates that this study focuses on UK and Dutch sites, where S. latissima is a species of interest.

We have adhered to the classical structure of a scientific paper in which general knowledge is summarized in the introduction, the methods are described in a methods section etc. We also think that observations should be presented before models (but have in this case put the smart-buoy and satellite data at the end so as not to interrupt the flow between the farm observations and farm implementation in the model). We recognize that there may be other ways to organize this, but adhering to the classical structure of a scientific paper is preferable and makes it easier for the reader to find the information and to know what's old and what's new. However, as two reviewers and the editor prefer this alternative structure, we have made the requested changes.

3. Sect. 1.2.1 (Southern North Sea): As the North Sea study sites are both located in the south-western North Sea and kelp farms will most likely be placed in the shallower southern North Sea and coastal areas (I assume, correct me if I am wrong), I would shorten the North Sea description to the parts relevant for this region, and rather extend those parts slightly. For instance, the Norwegian Trench and Skagerrak (page 3, lines 26-27) and the stratification characteristics in the central and northern North Sea (page 4, line 4) are less relevant for the context of this study, whereas the paragraph on North Sea primary production (page 4, lines 12-18) could be underpinned by some literature and more focused on the southern/coastal North Sea (those regions suitable for macroalgae farms). Differences in productivity between the Norfolk and Rhine plume sites may be stated in the subsequent paragraph (page 4, lines 20-25).

This section was removed, as we could not find a logical position for it in the re-structured document.

4. Sect. 2.1.1. (Strangford Lough): I am no specialist in macroalgae at all, which is definitely one reason for the following two questions: The actual farm consists of 2 lines with S. latissima (that is also implemented to ERSEM) and 19 lines with other species. Though, for the model 21 lines with the former are assumed. To what extent may this affect the results? Are there strong inter-species differences, e.g., with respect to nutrient

requirements? Maybe a short note on that can be made in the discussion. It is assumed “that the dry plant material consists predominantly of CH2O groups” (page 6, line 31) – is this a reasonable assumption? (Maybe underpin with literature.)

We have only used field observations from the S. latissima long lines. We have added a sentence stating this explicitly. CH2O groups: we have added a reference to Atkinson & Smith (1983).

5. Sect. 2.1.2 (Sound of Kerrera ...): The last sentences (page 7, end of line 10 to line 14) should be moved to the corresponding time series results or even to the discussion.

We have removed this sentence, an equivalent statement was already included in section 3.4.

6. Sect. 2.2.2 (Macroalgae farms in ERSEM): It is stated that the farms are implemented to the model by means of number of lines, line length etc. for which the parameter values are provided in Table 2. However, no information is provided on how the actual description/implementation in the model is done, nor is a reference provided containing such description (if existent). From my point of view this step is quite essential when presenting the study as a “proof of concept”. As I could not find any other literature attempting to include macroalgae farms in a large-scale 3D model, I assume that this manuscript presents the first approach. In this case the technical description of the implementation needs to be part of the publication – not necessarily as part of the main text, but in an (electronic?) appendix or as supplementary material.

It’s simply a biomass concentration, like all other state variables in ERSEM. We have added a line to make this point more clearly, and have also expanded the section that describes the model, including tables listing variables, parameters and the model equations.

Regarding the model schema (Fig. 3) I also wonder whether the light climate in all parts of the water column below the farms is affected, i.e., including the below-farm parts of the grid cell with the farm itself, or only the grid cells below the farm grid cell. Depending on the vertical extent and the position of the farm, this may influence surface layer primary production by other algae (e.g., diatoms)

Both. We have added a line to make this point more clearly.

7. Sect. 2.2.3 (Model scenarios): For the farm scenarios, the model was run from 1 October to end of July of the subsequent year (page 9, line 33). Again a question as a non-specialist: How does this relate to the actual farming practice?

Yes, this is a likely farming practice. We have added a statement to this effect.

8. Sect. 3.1 (Model confirmation): Although it is probably the case, it would help to clearly state at the beginning of this section that the provided model confirmation/validation is based on the reference run.

We have added this.

With respect to the satellite vs. model comparison (Figs. 4and5) I wonder whether the map section could be reduced, more focusing on the regions of interest of this study (e.g.,similartoFig. 1). This would also allow for a more detailed description/discussion of the model quality in the areas of interest.

We have changed this and modified the text accordingly.

Furthermore, it should be mentioned which months are used for the "summer", respectively, "winter" maps.

This information was in the figure captions, but is now added to the text as well.

With respect to the time series (Figs. 6-8), I have several comments/questions: On page 11, lines 15/16, it is stated that peak spring bloom chlorophyll a at Warp Anchorage (Fig. 6) is about 10 mg m-3. Does this refer to the observations as the model shows much higher values (up to 30 mg m-3)? If so, this should be made clear.

This should be: 'modelled peak spring-bloom chlorophyll concentrations were within 10 mg Chl m^{-3} *of the observations '. We have corrected this.*

Since chlorophyll is the main quantity used in the validation, it would help to provide brief information on how the chlorophyll concentration is calculated/derived (prognostic, diagnostic using fixed/variable chlorophyll-to-carbon ratios) by the model in the model description (a reference is sufficient).

Chlorophyll is a state variable and the model uses variable chlorophyll to carbon ratios. This information can be found in the list of references provided at the beginning of Section 2.2.2. have added a remark on chlorophyll to that description.

I further wonder about the large discrepancy between simulated and observed salinity and in relation to that – as also mentioned by the authors – nutrients. Does this relate to the applied river forcing? Or are there other likely causes? Although not in the focus of the study, a brief comment on that would be useful.

This may indeed be related to the river forcing or to resolution-related issues with the representation of the river plume. We have added a remark to this effect.

9. Sect. 3.2 (Environmental effects): As stated in my general comments this aspect is barely addressed in the manuscript. The authors mention "maps of differences in biogeochemistry and plankton dynamics" without further specifying what kind of maps. Considering, e.g., that the kelp farms affect the light availability in the deeper model layers (as indicated in the schema in Fig. 3), I wonder whether only surface maps were analysed or whether quantities in deeper layers (affected by potential changes in the light climate) were also analysed?

This is described in section 2.2.3, with reference to an earlier paper that contains a more extensive description. The maps contained depth-averaged results, this was not mentioned and we have added this.

At least at the farm scale, I would expect changes in the light climate in the water column below each farm. Such change may not necessarily lead to distinct changes in the biogeochemistry, due to the small farm sizes or nutrient limitation, however, it may be used as an indicator when considering an up-scaling, i.e., larger farms. Therefore, I would propose to either specify what kind of quantities were analysed without including additional results, or to show and briefly discuss the difference map of one meaningful quantity (e.g., light availability in the deeper layers during the phytoplankton spring bloom period and/or corresponding spring bloom primary production). This would strengthen the manuscript with respect to that objective of the study.

As mentioned in section 2.2.3, we analyzed all stored model variables. We did not find significant effects for any of these, i.e. all the maps were essentially blank (give or take a few isolated spots). We would have liked to be able to present some results here, but we don't think it is useful to include and discuss a blank map… It may be possible to find short(er) periods of time that do show differences, but the objective was to look for substantial, meaningful changes, so we did not look at that level of detail.

Furthermore, the authors refer to "differences between the two reference runs" (page 12, line 7) – based on the scenario description (Sect. 2.3) I do not understand what the second reference run is? I suppose the scenario run (incl. the farms) is referred to? This should be made clear.

This is indeed an omission. Re-running the model with the same settings, forcings, etc. gives slightly different results. So we ran two instances of the reference run to provide a baseline difference that the scenario run needs to exceed to indicate a significant difference. We have expanded the description in section 2.2.3 to reflect this.

10. Sect. 3.3 (Strangford Lough time series): A short in-text definition of the structure-to-mass ratio (as given in the caption of Fig. 9) would be helpful.

We have added this.

Principally, the authors may consider defining a Sect. 3.3 "Kelp farm performance/productivity" (or similar) with the current Sects. 3.3-3.8 as subsections (then 3.3.1-3.3.6), providing a more distinct separation from the "environmental effects".

We have adopted this suggestion.

11. Figs. 9-13: panels k and l: What do negative uptake rates mean? Do the plots show the net uptake, i.e., uptake minus respiration? This should be clarified in the text.

We have changed the caption to 'net uptake'.

Panels c and d: To me it is not fully clear to what the provided extinction coefficients relate – is it the one in the water column above the kelp farms or the average of the grid cell in which the farms are located? I suppose it is the former as the figure captions state "excluding contribution of macroalgae". However, it would help clarifying this in-text.

The caption clearly states that this is at the surface.

Similarly,Iwonderabouttheirradiance–isittheirradianceatdepthofthemacroalgae, that directly at the sea surface, or that at the centre of the grid cell? Considering, e.g., the Rhine plume farm, with a line depth of 2m and high extinction coefficients, this may result in well different values. It may help to include a brief general description of the quantities displayed in the time series at the beginning of the time series section.

The caption clearly states that this is at the surface.

12. Discussion/Recommendations: In relation to the authors' statement early in the introduction ("this study is a proof of concept") and the general performance/setup of the model (e.g., partly unsatisfactory reproduction of observed chlorophyll concentrations, coarse spatial model resolution), I understand that those two sections are rather general and focus on the discussion of the results on the farm performance, and provide suggestions for improved analyses of environmental impacts and farm performance. However, I would request a more detailed discussion of which limitations of the study affect the results in what way (e.g., low spatial resolution vs. small-scale environmental effects or small farm size vs. larger scale environmental effects). Part of this is already indicated during the course of the manuscript (e.g., small farm size in Sect. 3.2). Following the "proof of concept" approach of the authors, a discussion subsection dedicated to the limitations of the setup in relation to the model outcome should be provided, incl. potential effects of an improved setup, where applicable. Some of the potential limitations I raised in the previous comments. Such subsection would also provide a good basis for the recommendations section, in which the suggestions for an improved study setup can be made. From my perspective, setting up the discussion/recommendation like this would clearly strengthen the "proof of concept" aim and provide a good basis for future, more detailed studies taking into account the suggestions by the authors.

We have inserted a paragraph in the discussion on the limitations of the model.

Technical corrections/comments 1. The authors should go through the in-text citations thoroughly and check for consistency regarding punctuation (e.g., commas before years, semi-colons between multiple citations), ordering of multiple citations (chronological or alphabetical – if I am not mistaken the journal has a preference for one of the two), in-text author names and names in the reference list (e.g., "Grosse" in-text, "Große" in the references; in "van der Molen" the V is partly uppercase, partly lowercase).

We have addressed this.

2. When providing ranges of a quantity (e.g., 15-25m) or areal extents (e.g., 5x5km) I would recommend providing the unit after both numbers.

We will take guidance from the editor on this.

3. Abstract: Line 2: I would rather write "and for biofuel production".

We have changed this.

4. Introduction: Page 2, lines 26/27 and 29/30: "associated with high biodiversity is doubled. Page 4, line 13: "reduced" instead of "reducing"? Page 4, line 15: "matter" instead of "material" Page 4, line 31 to page 5, line 2: I would propose re-ordering these sentences such that there is no jump in the description from currents to depth and back to currents.

We have changed these.

Page 5, line 4: the farm site "is" located (instead of "was")

No, the text is correct, this farm is no longer in operation.

Page 5, line 10: “The site range from 15-25m depth” sounds a bit odd. Maybe “The depth ranges from 15-25m at the site”?

We have corrected the text.

Page 5, line 27: Would it be suitable to write “nitrate” instead of “nitrogen” as only nitrate uptake by kelps is considered?

The text was correct, but we have changed it into ammonium and nitrate and also modified Figure 3.

Page 5, lines 23-30: I would change the order of the two paragraphs, as the latter is related to kelp in general while the former is region-specific.

The first of these two paragraphs is related to the one before, so we have kept the current order.

5. Methods Page 6, lines 25 and 30: “MPA” is used without introducing the abbreviation (line 25), while later “Marine Protected Area” is used (line 30).

We have corrected this.

Page 6, last paragraph: I would suggest to include a sentence stating that the conversion factor used in Table 3 (24.919) results from the combination of the two factors listed in this paragraph.

We have added this.

Page 7, line 17: The abbreviation “ROFI” is introduced on page 3, line 11, so simply use ROFI here.

We have changed this.

Page 7, line 29: I think, 2 digits after the comma are sufficient for the geographical information of the site.

As this is a matter of taste, we will retain the current precision.

Page 8, Sect. 2.2.1: Some links are shown as hyperlinks, others are not. Should be consistent.

We have removed the hyperlink.

Page 9, line 15: typo in “diynamics” Page 10, lines 16/17: Should the parenthesis be closed after the link, and the closing parenthesis at the end of the sentence be removed?

We have corrected these.

Figure 2 has a rather poor quality/low resolution and the green box indicating the Norfolk kelp farm is hard to find as the map contains a lot of information. I wonder whether this map is actually necessary or if the in-text description is sufficient. If the authors prefer to keep this figure, a smaller map section may help – or addition of an arrow pointing to the farm site. In case of keeping the figure, its resolution needs to be increased.

The map will be provided at adequate resolution. The map is necessary, and the information cannot be reduced or simplified.

6. Results Page 12, line 21: I think it should be 0.05 kg C m-1 instead of 0.5 g C m-1. Page 12, line 24: typo in "carbohydratate"

We have changed these.

Page 13, line 13: It is stated that Lynn of Lorne shows a slightly higher yield than Sound of Kerrera. There's a factor of 2 between most of the years that is clearly more than "slightly higher".

We have corrected this.

Page 13, very last sentence (ending page 14): should be moved to the description of the study site and its representation in the model in the methodology section.

This is a chicken and egg situation because we need the result of the high extinction coefficients for this. So we prefer to keep it here. It is also included in the footnotes of table 2, which is referenced in the methods section.

Page 14, line 3: "Mortality did not increase as much as at some other sites". To my understanding this only applies to the Lyne of Lorne farm among "the other sites".

We have removed the sentence.

Page 14, Sect. 3.7 and Table 3: As the in-text description only refers to the wet biomass, I would display these numbers first in the table and show the harvest in parentheses or even omit the harvest and only state in the table caption that wet biomass was calculated from the harvest with reference to updated methods section (see my previous comment on the conversion factor).

We have included both number to relate to different communities used to different units. If the editor insists we can swap the order.

I would further omit the information on the individual Norfolk farm grid cells in the table, as the differences are quite small. Related to that the hint on the differences in the discussion could be removed (page 15, lines 22-24).

We think that the gradient is illustrative, and may be useful if a smaller farm is implemented than simulated here.

Figs. 9-13: Panels d: The unit of the irradiance is µmol m-2 s-1, however, in Sect. 3.8 (page 14, lines 14 and 23) µE m-2 s-1 is used. Although both are in fact the same, consistent usage of one of the two units (preferably the latter) might be helpful for the reader not too familiar with this irradiance unit.

We thought that we had removed all instances of the µE unit, and have now corrected these as well.

Panels k: Those could be named as nitrate uptake (as the parameterisation by Bloch and Slagstad only considers nitrate uptake).

Our implementation also includes ammonium uptake, but values are likely to be small.

Fig. 14: I would recommend re-ordering the figure panels according to the order in which the study sites are described in the text and presented in Figs. 9-13 (excl. Lyne of Lorne)

We have changed the order of the graphs.

7. Discussion Page 15, lines 12-14: It is stated that kelp production at Rhine plume was lower than in the Sound of Kerrera and Lyne of Lorne. For the former, this is obviously not the case (see Figs. 10f and 12f).

This is indeed an error, we have changed this.

Also, light availability and extinction are quite similar for Rhine and Sound of Kerrera sites.

The base-line extinction at Kerrera is 0.2 m^{-1}, and at the Rhine site 0.5 m^{-1}. This is not quite similar.

Page 15, lines 19-21: There is a factor of 2 between the production per metre between Norfolk and Sound of Kerrera, which I would not describe as “comparable”.

We have corrected this.

Page 16, line 2: “although” in combination with “however” sounds like a doubling to me. Maybe omit the latter?

We have changed this.

Page 16, line 25: a period is missing in “eg.”

We have changed this.

Anonymous Referee #3 Received and published: 8 August 2017

I am the 3rd reviewer of this manuscript and, having read the other reviews, I agree with most of the comments made by the reviewers so I am not going to repeat those, although I will highlight specific ones I find more relevant, and I will concentrate on a general evaluation. Overall, I found the article interesting and eventually deserving publication. The article is well written but I agree with Fabian Grosse's comments 1 and 2 about structuring and organisation.

Please see our responses to Fabian's comments.

I have a number of general comments, below, that I think should be considered before the manuscript is acceptable for publication. Ithasbeenhighlightedbyboththeauthorsandthereviewersthatthisislargelya"proof of concept" study and I agree with this. In that sense, I am not particularly surprised thattheenvironmentaleffectsofthemacroalgaefarmswerefoundtobenegligible,taking into account the experimental and small scale nature of all of these farms, with the exception of the "hypothetical" one off the Norfolk coast. Incidentally, the suggestion by Referee #1 of using a "comparison to the phytoplankton usually used in the model" may be an interesting way of putting their environmental effect into context.

Please see response to comments of Referee #1.

Another consideration is that ERSEM does not seem to do such a good job of matching observational data. This does not surprise me because I fully acknowledge the difficulties involved (e.g. due to lack of a sufficiently comprehensive forcing dataset, etc.) but it does detract somewhat from the "real-life" applicability of the present study. Therefore, I would be tempted to suggest a lesser emphasis on how the model replicates observational data (if you have those data, by all means present the comparisons but maybe just present a subset of these in the main body of the text and move the rest to supplementary material) and to dedicate more space to:

1) the technical description of the new aspects of the model (the implementation of macroalgae farms, as suggested by Fabian Grosse's comment no. 6), probably by a combination of providing a bit more detail in the main text, in addition to supplementary material;

We have enhanced the description to provide more clarity, and include tables with the parameter settings, variables and model equations.

and 2) the potential largescale development of macroalgae farming and its environmental effects. In that sense, I found the combination of a number of "real" small scale farms and a large "hypothetical" one a bit unsatisfactory; maybe the real farms should be used to illustrate how well the model fits observations (but taking into account my comments above) and a number (>1) of larger ("commercial") scale hypothetical farms could be used on a separate simulation exercise to illustrate the harvest potential (in terms of quantity and quality) of a macroalgae farming industry.

This is exactly what is intended with the current manuscript, and this is stated in the introduction. For the hypothetical commercial farm, we have focused on a realistic possibility that is supported by regulatory bodies, *rather than selecting a range of sites more or less at random, which could cause controversy. Moreover, we are not in a position to repeat the model runs within the current context and publication. This could be considered for further work.*

This relates to the comment made by Referee#1 about "more general consideration that go beyond the individual site description".

Please see our response to the comments of Referee #1.

This may also help address the issue of potential environmental effects, which in the present version (as identified by both reviewers) receives insufficient attention to deserve an explicit reference in the title.

We have removed the environmental effects from the title.

Finally, the model limitations (Fabian Grosse's comment no. 12) should also be discussed, in particular scale and resolution aspects, as well as what aspects of the model should be developed and how.

See response to Fabian's comment.

Modelling potential production ~~and environmental effects~~ of macroalgae farms in UK and Dutch coastal waters

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Abstract. There is increasing interest in macroalgae farming in European waters for a range of applications, including food, chemical extraction and ~~as biofuels~~for biofuel production. This study uses a 3D numerical model of hydrodynamics and biogeochemistry to investigate potential production and environmental effects of macroalgae farming in UK and Dutch coastal waters. The model included four experimental farms in different coastal settings in Strangford Lough (Northern Ireland), in Sound of Kerrera and Lynn of Lorne (northwest Scotland), and in the Rhine Plume (The Netherlands), as well as a hypothetical large-scale farm off the UK north Norfolk coast. The model could not detect significant changes in biogeochemistry and plankton dynamics at any of the farm sites averaged over the farming season. The results showed a range of macroalgae growth behaviours in response to simulated environmental conditions. These were then compared with *in-situ* observations where available, showing good correspondence for some farms and less good correspondence for others. At the most basic level, macroalgae production depended on prevailing nutrient concentrations and light conditions, with higher levels of both resulting in higher macroalgae production. It is shown that under non-elevated and interannually varying winter nutrient conditions, farming success was modulated by the timings of the onset of increasing nutrient concentrations in autumn and nutrient drawdown in spring. Macroalgae carbohydrate content also depended on nutrient concentrations, with higher nutrient concentrations leading to lower carbohydrate content at harvest. This will reduce the energy density of the crop and so affect its suitability for conversion into biofuel. For the hypothetical large-scale macroalgae farm off the UK north Norfolk coast the model suggested high, stable farm yields of macroalgae from year to year with substantial carbohydrate content and limited environmental effects.

1 Introduction

1.1 Background, aims and approach

Worldwide macroalgae (seaweed) production is in excess of 28 million ton p.a. and has doubled between 2000 and 2014 (FAO, 2014). The majority of this production (> 95%) is from the SE Asian region where macroalgal cultivation is well established (FAO 2014;, West et al., 2016). The harvested macroalgae biomass is mainly used directly for human consumption, although other uses include the extraction of phyllocolloids (gelling agents), animal feed, fertilizer, water remediation and as probiotics in aquaculture (see van der Burg et al. 2016; West et al. 2016).

There has been increasing interest in the potential of macroalgae cultivation across the Northern Hemisphere and Europe (van der Burg et al., 2016), partially driven by research on biofuel technologies (Kerrison et al., 2015). The characteristics of Phaeophyta macroalgae, in particular high productivity, fast growth rate and high polysaccharide content, make them a suitable biomass for biofuels production (Hughes et al., 2012; Kerrison et al., 2015; Schiener et al., 2016; Fernand et al., 2017). A further advantage is that such third generation biofuels do not need additional freshwater and do not compete for agricultural land like many existing biofuel sources.

Marine macroalgae fix CO_2, acting as a sink for anthropogenic CO_2 ("Blue Carbon", Nellemann et al., 2009; Duarte et al., 2017) and absorb dissolved nutrients from the water column, helping to remediate nutrient release from anthropogenic sources such as agricultural runoff, waste water treatment and aquaculture ('bioremediation', e.g. Chopin et al., 2001; Lüning and Pang, 2003; Fei, 2004; He et al., 2008; Chopin et al., 2001; Lüning and Pang, 2003; Sanderson et al., 2012; Smale et al., 2013). Therefore, large-scale cultivation and harvesting of macroalgae could play a role in removing carbon from the marine environment, as well as reduction of coastal nutrient enrichment.

Kelp species, such as *Saccharina latissima* (a brown algae), have been identified as candidate macroalgae for bioenergy production (Kerrison et al., 2015). Its cultivation has been trialled across Europe, including Scotland, Strangford Lough in Northern Ireland, southern North Sea, and northwest of Spain (Buck and Buchholz 2004; Kerrison et al. 2015; Buck and Buchholz 2004; Sanderson et al. 2012; Peteiro et al. 2012; Kerrison et al. 2015; van der Burg et al. 2016).

Kelp naturally occurs in sublittoral coastal waters in temperate and polar regions. These macroalgae aggregations have been shown to modify the surrounding environment by reducing water velocity and attenuate waves (Jackson, 1997; Gaylord et al., 2007; Jackson, 1997), and by modifying sedimentation rates of suspended particles (Eckman et al., 1989). They are also associated with high biodiversity (Burrows, 2012), providing numerous ecosystem services including habitat, shelter and food for many species including fish (Hartney, 1996), benthic organisms (lobster, crabs; Bologna and Steneck, 1993; Daly and Konar, 2008), herbivorous organisms (Kang et al., 2008), and birds (Fredriksen, 2003), and are associated with high biodiversity (Burrows, 2012), see also Walls et al. (2017).

While a large scale kelp farm might replicate some of the ecosystem services of a natural kelp forest, assumptions as to the extent of the similarity should be considered with caution (Wood et al., 2017). Since kelp farms are monocultures suspended within the water column, and are likely to undergo a yearly cycle of growth and harvesting, they are not synonymous with mature kelp beds which contain a mixture species, of different ages attached to the benthos (Wood et al. 2017).

Studies on the potential environmental effects of macroalgae farms are limited. This lack of information, in combination with limited knowledge on expected farm yields, results in uncertainty for potential investors, developers and macroalgae farmers, as well as legislators, who provide the relevant farming licence (Wood et al., 2017).

The aim of this modelling study was to investigate environmental effects and potential yield of macroalgae farms, at different locations in UK and Dutch coastal waters, using the ERSEM-BFM (European Regional Seas Ecosystem Model - Biogeochemical Flux Model). In particular, four farms were simulated: three experimental farms (Sound of Kerrera, Scotland; Strangford Lough, Northern Ireland; the Rhine region of fresh-water influence, ROFI, The Netherlands) and a hypothetical farm (Norfolk, UK) (Figure 1). Observations from the experimental farms in Scotland and Northern Ireland were used to ground truth the model.

This modelling exercise is a proof of concept, and did not aim for a detailed representation of the farm localities, nor did it involve extensive tuning to reproduce detail of farm performance. We used an existing 3D model setup of the northwest European continental shelf (Section 2.2), which allowed all farms to be included in one model, albeit with a very coarse representation of coastal geometries. Farm implementation included a level of sub-grid parameterisation. The model was run with forcings for years pre-dating farm deployments, so comparisons with observations collected during the actual deployments can only be qualitative. Despite these limitations, we obtained reasonable confidence in the model, as well as valuable results in terms of farm functioning and performance, macroalgae quality, and farming-induced changes in environmental conditions. These predictions are necessary to progress the future development of this fledgling industry.

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1.2 Study area

1.2.1 Southern North Sea

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Two of the sites were located in the southern North Sea. The North Sea (Figure 1) is a shallow shelf sea of depths up to 600 m, but typically averaging only several tens of metres in the south. The glacial ice-pushed ridge that forms Dogger Bank separates the southern area from the central and northern North Sea where average depths are ca. 100 m. The Norwegian Trench and Skagerrak separate these areas from the Scandinavian coast with depths of several hundreds of metres.

An overview of the hydrography of the North Sea was compiled by Otto et al. (1990). The tides are predominantly semi-diurnal, with ranges of up to several metres along the coasts, and amphidromic points of the main M_2 tidal constituent in the Southern Bight, the German Bight and near the southern tip of Norway (Proudman and Doodson, 1924; Prandle, 1980). Model-based estimates of a range of tidal constituents were derived by Holt et al. (2001), and also Davies et al. (1997). Tidal currents can reach speeds of over 1 ms^{-1} in coastal areas (Dietrich, 1950; Holt et al., 2001).

The central and northern North Sea stratify in summer, while southern area remains well-mixed (Pingree et al., 1978; Van Leeuwen et al., 2015). The residual circulation is generally clock-wise, with inflows along the Atlantic boundary in the North and through the Strait of Dover (North Sea Task Force, 1993), but with seasonal variations (Holt et al., 2001).

Contributions by wind and tides are of comparable magnitude (Prandle, 1978). During stratified conditions in summer, subsurface jet-like currents occur near the thermocline around the Dogger Bank (Brown et al., 1999; Hill et al., 2008). Tracing of accidental radioactive releases in the 1970s indicated that it takes several years for waters to traverse the region (Kautsky, 1973).

The North Sea supports a high level of primary productivity, which is augmented by varying levels of anthropogenic riverine nutrient loads, which have been gradually reducing since 1985. This phytoplankton production is also modulated by turbidity and light availability, influenced by among others the concentration of suspended particulate materials (SPM) in the water (e.g., Lenhart et al., 2010). The anthropogenic nutrient load is typically contained within coastal plumes that propagate in a clockwise direction along the coasts (Menesguen, 2006; Painting et al., 2013; Los et al., 2014; Desmit et al., 2015). Potential oxygen depletion as a result of eutrophication has received attention recently, focusing in particular on the German Bight (Topcu and Brockmann, 2015; Grosse et al., 2016).

The north Norfolk coast of the UK and the southern coast of the Netherlands, where two of the farms under investigation were located, are characterized by shallow water depths (<25 m), high winter nutrient concentrations (Hydes et al., 1999; Proctor et al., 2003; Foden et al., 2011; Laane, 2005; Troost et al., 2014), and high turbidity (Dyer and Moffatt, 1998; Bristow et al., 2013; Pietrzak et al., 2011; Van der Hout et al., 2015). In contrast to the north Norfolk coast, the Dutch coastal area has lower salinity, potential for episodic salinity stratification (De Ruyter et al., 1997), and a higher N/P ratio due to larger reductions in anthropogenic riverine phosphate loading since the late 1980's (Lenhart et al., 2010).

1.2.2 Strangford Lough (Northern Ireland)

The Northern Irish farm site run by Queen's University, Belfast, is located at 54.4N, 5.58W within the semi-enclosed Strangford Lough. The Lough covers an area of approximately 134 km2, with water depths from 0-70 m, is 8 km long and the Narrows (0.5 km wide at narrowest) connect the Irish Sea to the main inlet of the lough (Smyth et al. 2016; Kregting and Elsäßer, 2014). The lough is fully saline ranging from 32 to 34 with negligible freshwater input from three small point sources (Boyd, 1973; Smith, 2010) and is predominantly well mixed (Taylor and Service,1997). The experimental site is located off the southern shore in the vicinity of the Narrows, but is relatively sheltered with an average current speed of 0.3 ms-1. There can be moderate wave action when the wind is coming from northerly and easterly directions. The depth profile is variable, ranging from 2 m to 13 m at Mean Low Water Spring (MLWS). The current predominantly runs in a west – east direction (Mooney-McAuley et al. 2016).

1.2.3 Sound of Kerrera and Lynn of Lorne (Northwest Scotland)

The first Scottish farm site was located at 56.38N, 5.54W within the Sound of Kerrera which separates the island Kerrera from the mainland by ca. 500m, near Oban. The Sound reaches 60m depth and experiences a semi-diurnal tidal current of 0.77 m·s-1 during spring tides. The island shelters the Sound from all but the predominant south-westerly winds from the Atlantic. At the farm site, the depth ranges from 5-25m.

The second Scottish farm is located at 56.49N, 5.47W in the Lynn of Lorne, which separates the island of Lismore from the mainland. The site range from 15-25 m depth and has a mean current speed of 0.1 m·s-1, 5 m below the surface. The Lynn of Lorne is 3km wide at the location of the farm and so is very exposed to the predominant south-westerly winds from the Atlantic.

1.31.2 Saccharina latissima

Saccharina latissima, or sugar kelp, is a subtidal phaeophyte macroalga native to Europe, common to UK rocky shores. It is a brown algae, with leather/rubbery texture, which in the adult form is constituted by a holdfast, a stipe, and a large undivided blade (or frond, or lamina), with undulated margins (Kain, 1979; White and Marshal, 2007).

The growth of *S. latissima* is affected by environmental factors such as light availability, wave action and water currents, nutrient concentration, type of substratum, temperature, salinity and grazing pressure (Birkett et al. 1998; Lobban and

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Harrison, 1997; Birkett et al., 1998). A recent study by Kerrison et al. (2015) summarises the optimal range of environmental variables for *S. latissima* growth (see Table 1 in Kerrison et al. 2015).

In coastal waters around the UK, kelp species show high growth rates from late autumn to early summer. This is then followed by a slower growth phase between July and December (Parke, 1948; Kain, 1963). Maximum length developments are also associated with maximum fresh weights (Parke, 1948; Black, 1950).

Kelp plants show effective uptake of nutrients (~~nitrogen~~ ammonium, nitrate and phosphate) from seawater (Birkett et al. 1998; Kregting et al., 2014; Kregting et al., 2016). When nutrients are abundant and exceed metabolic requirements, these plants have the ability to store nutrient in the plant tissues (Birkett et al., 1998). For example, *S. latissima* has been shown to store nitrogen reserves at levels of more than 1000 times the external ambient concentration (Chapman et al., 1978).

S. latissima stores energy in the form of carbohydrates (e.g. mannitol and laminarin), the concentrations of which vary widely during the year, and peak in the second part of the year (Black, 1950; Kain, 1979; Bartsch et al., 2008; Schiener et al., 2015). For example, Gevaert et al. (2001) observed that for *S. latissima* in the English Channel, the maximum carbon content is reached in September with the lowest concentrations occurring in March. Similar trends have also been reported for Norway (Sjøtun, 1993) and Scotland (Connolly and Drew, 1985). The minimum carbon concentration in March occurs when the growth rate of the algae is high and the plant growth is carried out at the expense of carbohydrate reserves. By contrast during summer, carbon assimilation exceeds carbon-utilisation allowing the formation of carbon reserves (Gevaert et al., 2001).

The presence of these carbohydrate reserves and a fast growth rate make *S. latissima* an interesting potential biomass for production of renewable energy (Kraan, 2013; Fernand et al., 2017). For these reasons, *S. latissima* has become a focus for experimental farming in Europe. For a comprehensive summary of modelling efforts on *S. latissima* we refer the reader to Broch & Slagstad (2011) and references therein.

2 Methods

~~2.1~~1.1 ~~Macroalgae farms~~

~~2.1.1 Strangford Lough research farm~~

~~The Strangford Lough research farm is located near the southwestern shore of the Lough (Figure 1, farm A), and run by Queen's University, Belfast. The farm cultivated a mixture of *S. latissima*, *Laminaria digitata* and *Alaria esculenta*. Here we use observations from the 2012-2013 deployment, when 2 x 100m longlines of *S. latissima* were cultivated and 19 with the other species. The growing lines were suspended horizontally at 1 m below the surface, and were pre-seeded at deployment.~~

Monthly sampling was carried out after two months at sea. At each sampling time, five samples were taken from each rope removing all plants on a 30 cm section. The total wet biomass of all plants in these 30 cm intervals was determined, and used to calculate the mean biomass per line (kg wet weight/m). Total number of plants, total wet and dry biomass were measured. Total length, blade length, blade width and stipe length were also measured for the 12 largest plants in the sample. For the purpose of this modelling study, we have assumed that all 21 lines of the farm were cultivated with *S. latissima*.

The mean biomass per line (kg wet weight/m) was used to estimate the total farm carbon biomass for comparison with the model results (see Section 3.3). Overall, 354 samples were analysed for wet and dry weight, giving a combined total wet weight of 3549.9 kg, and a dry weight of 380.38 kg, resulting in a wet/dry weight ratio of 9.333. For conversion from dry weight to carbon weight we assume that the dry plant material consists predominantly of CH_2O groups, resulting in a dry weight to carbon ratio of 32/12=2.67.

2.1.2 Sound of Kerrera and Lynn of Lorne research farms

For the Sound of Kerrera farm, observations of nutrient concentrations, light and temperature are available from a 17 month period in 2013-14. Nutrient concentrations were collected in triplicates at 1.5 m depth, whereas light and temperature were collected at half hourly intervals at 1.5 m depth, using HOBO Pendant data loggers (Onset Computer Corp, MA, USA). Here, we use the means of the triplicates for nutrients, and monthly means for light and temperature. The nutrient data showed a typical seasonal cycle with high winter concentrations and low concentrations following the spring bloom, but with surprisingly high summer concentrations in 2013, which are unexplained. Early summer concentrations in 2014 were substantially lower. The Lynn of Lorne farm (Figure 1, C) consists of a 100x100 m grid submerged 3 m below the surface. This can contain up to 24 lines of 100 m length, spaced 4 m apart, with growing lines suspended horizontally at a depth of 1.5 m below the surface.The Sound of Kerrera and Lynn of Lorne farms (Figure 1, farms B and C) are located in the Firth of Lorne, and operated by the Scottish Association for Marine Science (SAMS), see also Section 1.2.3. The farm at Sound of Kerrera (Figure 1, B) consists of 180 m of double headed longline buoyed by mussel floats, with growing lines suspended at 1.5 m depth. The Lynn of Lorne farm (Figure 1, C) consists of a 100x100 m grid submerged 3 m below the surface. This can contain up to 24 lines of 100 m length, spaced 4 m apart, with growing lines suspended horizontally at a depth of 1.5 m below the surface. For the Sound of Kerrera farm, observations of nutrient concentrations, light and temperature are available from a 17 month period in 2013-14. Nutrient concentrations were collected in triplicates at 1.5 m depth, whereas light and temperature were collected at half hourly intervals at 1.5 m depth, using HOBO Pendant data loggers (Onset Computer Corp, MA, USA). Here, we use the means of the triplicates for nutrients, and monthly means for light and temperature. The nutrient data showed a typical seasonal cycle with high winter concentrations and low concentrations following the spring bloom, but with surprisingly high summer concentrations in 2013, which are unexplained. Early

~~summer concentrations in 2014 were substantially lower. Typical macroalgae yields for Sound of Kerrera were ca. 10 kg wet weight m^{-1} in 2013, and 4 kg wet weight m^{-1} in 2014.~~

~~2.1.3 Rhine plume experimental farm~~

~~Another experimental farm, run by North Sea farm foundation (Stichting Noordzee boerderij), was deployed for the first time in the autumn of 2016 within the nutrient-rich Rhine Region of Fresh-water Influence (ROFI) off the port of Scheveningen, The Netherlands (Figure 1, D). The farm consists of a single line of 100 m, undulating between 0 and 4 m below the surface. Data from this farm will only become available in the summer of 2017. The farm was included in the model to obtain predictions of potential performance.~~

~~2.1.4 Norfolk hypothetical commercial farm~~

~~The hypothetical commercial farm off north Norfolk was selected based on the method of Capuzzo et al. (2014), with minor modifications. The method consisted of over-laying maps of suitability scores (optimal, sub-optimal, unsuitable) of key limiting environmental variables (temperature, light, tidal velocity, wave height and nutrient concentrations; Table 1) and spatial use data (shipping, structures, MPA's, wind farms, etc.) in a GIS system. The modifications applied here consist of slight variations to the threshold levels of certain environmental variables, and the adoption of a farming area based on the suitability data rather than rectangles of pre-defined size.~~

~~The area selected by this method was nearly rectangular (53.0545N 0.7745E to 53.11N 0.9775E), and located off the north Norfolk coast near Wells-next-the-Sea, in approximately 20 m water depth, between a coastal Marine Protected Area, wind farms and a Marine Conservation Zone further offshore (Figure 2). On the model grid, this area was approximated by a hypothetical farm covering three adjacent cells of 0.08 degree longitude and 0.05 degree latitude (approx. 5x5 km, Figure 1, E-G).~~

~~It was assumed that within each grid cell of 25 km^2, roughly half of the surface area would be effectively farmed, and the rest would be required for a mesh of navigation corridors for service vessels and occasional navigation lanes for other traffic. As details of such lay-outs are beyond the resolution of the model, it was assumed for simplicity that a solid block of 3.5x3.5 km was farmed within each 5x5 km grid cell with lines 50 m apart to avoid entanglement.~~

~~2.2~~2.1 GETM-ERSEM-BFM model

~~2.2.1~~2.1.1 GETM: North-west European Shelf set-up

The 3D hydrodynamic model GETM (General Estuarine Transport Model, www.getm.eu; Burchard & Bolding, 2002) solves the shallow-water, heat balance and density equations. It uses GOTM (General Ocean Turbulence Model, Burchard et al., 1999; www.gotm.net) to solve the vertical dimension. GETM was run using the north-west European shelf setup that has been used by Van der Molen et al. (2016) to study the potential large-scale effects of tidal energy generation in the Pentland Firth, and by Van der Molen et al. (2017) to develop a suspended particulate matter model. The set-up includes a spherical grid covering the area 46.4°N-63°N, 17.25°W-13°E with a resolution of 0.08° longitude and 0.05° latitude (approximately 5.5 km), and 25 non-equidistant layers in the vertical. The model bathymetry was based on the NOOS bathymetry (www.noos.cc/index.php?id=173). The model was forced with tidal constituents derived from TOPEX-POSEIDON satellite altimetry (LeProvost et al., 1998), atmospheric forcing from ECMWF ERA-Interim (Dee et al., 2011; Berrisford et al., 2011; www.ecmwf.int/en/research/climate-reanalysis/era-interim), interpolated river runoff from a range of observational data sets (the National River Flow Archive (www.ceh.ac.uk/data/nrfa/index.html) for UK rivers, the Agence de l'eau Loire-Bretagne, Agence de l'eau Seine-Normandie and IFREMER for French rivers, the DONAR database for Netherlands rivers, ARGE Elbe, the Niedersächsisches Landesamt für Ökologie and the Bundesanstalt für Gewässerkunde for German rivers, and the Institute for Marine Research, Bergen, for Norwegian rivers; see also Lenhart et al., 2010), and depth-resolved temperature- and salinity boundary conditions from ECMWF-ORAS4 (Mogensen et al., 2012; Balmaseda et al., 2013; Mogensen et al., 2012; http://www.ecmwf.int/products/forecasts/d/charts/oras4/reanalysis/http://www.ecmwf.int/products/forecasts/d/charts/oras4/reanalysis/). Boundary conditions for nutrients are taken from the World Ocean Atlas monthly climatology (Garcia et al., 2010).

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2.2.22.1.2 Macroalgae farm representations in ERSEM

The ERSEM-BFM (European Regional Seas Ecosystem Model - Biogeochemical Flux Model) version used here (01-06-2016) is a development of the model ERSEM III (see Baretta et al., 1995; Ruardij and Van Raaphorst, 1995; Ruardij et al., 1997; Vichi et al., 2003; Vichi et al., 2004; Ruardij et al., 2005; Vichi et al., 2007; Van der Molen et al., 2013; Vvan der Molen et al., 2014; Vvan der Molen et al., 2016; www.nioz.nl/northsea_model), and describes the dynamics of the biogeochemical fluxes within the pelagic and benthic environment. The ERSEM-BFM model simulates the cycles of carbon, nitrogen, phosphorus, silicate and oxygen and allows for variable internal nutrient ratios and chlorophyll content inside organisms, based on external availability and physiological status. The model applies a functional group approach and contains five pelagic phytoplankton groups, four main zooplankton groups and five benthic faunal groups, the latter comprising four macrofauna and one meiofauna groups. Pelagic and benthic aerobic and anaerobic bacteria are also included. The pelagic module includes transparent exopolymer particles (TEP) excretion by diatoms under nutrient stress, the associated formation of macro-aggregates consisting of TEP and diatoms, leading to enhanced sinking rates and food supply to the benthic system especially in the deeper offshore areas (Engel, 2000), a *Phaeocystis* functional group for improved simulation of primary production in coastal areas (Peperzak et al., 1998), a pelagic filter-feeder larvae stage, and benthic diatoms, including resuspension, transport and pelagic growth. The suspended particulate matter (SPM) module, included for improved simulation of the under-water light climate, contains contributions by waves and currents, and full 3D transport (V~~v~~an der Molen et al., 2017). Finally, the model includes resuspension of particulate organic matter as a proportion of the SPM resuspension, and also 3D transport.

A macroalgae functional type representing *Saccharina latissima* was introduced in ERSEM-BFM, closely following the implementation of Broch and Slagstad (2012) (see Figure 3 for a schematic diagram of the implementation). The macroalgae were represented by a non-advective biomass concentration, in analogy to other ERSEM functional types.~~,~~ ~~but with addition of~~To conform with the structure of ERSEM, phosphate dynamics were added in analogy to the nitrate d~~i~~ynamics, as well as inclusion of and assuming an optimum N/P ratio for structural mass of 25, slightly below the median reported by Atkinson & Smith (1983); see also Duarte (1992). The nutrient uptake method for the macroalgae was changed to the dynamic one presented by Droop (1973, 1974) in order to be consistent with the nutrient uptake of phytoplankton in ERSEM (Baretta-Bekker et al., 1997). Ammonium uptake was also added. ~~See Figure 3 for a schematic diagram of the implementation.~~ The method includes growth, mortality (~~'erosion'~~simulated by an equation that relates apical frond loss exponentially to frond area), nutrient and carbon biogeochemistry, and effects of light, temperature, and nutrient concentrations. Plant structural biomass, nutrient buffers and carbohydrate biomass were represented separately. ~~For further detail see Broch and Slagstad (2012).~~ For inclusion in ERSEM-BFM, the macroalgae were represented in terms of biomass density rather than frond dimensions. The revised set of variables, parameters and equations is given in Table 2 to Table 4. The effect of marcoalgae on light extinction was included both within the layer containing macroalgae and on the layers below. Only farmed macroalgae were included in the model. The implementation of farms assumed the use of lines as an anchoring material. Farms were prescribed, per model grid cell, in terms of line length, number of lines, depth below the surface, deployment and harvest time, and initial biomass and plant density (see Table 5~~Table 2~~ for detail). For the calculations, the model converts these data to biomass density in the model layer coinciding with the depth of the lines below the surface. The simulated farms coinciding with the experimental farms in Strangford Lough, Sound of Kerrera, Lynn of Lorne and the Rhine Plume were given dimensions coinciding with typical deployments. The background of the dimensions of the north Norfolk farm (Figure 1, Site E-G) ~~was~~ is given in Section 2.2.4 ~~2.1.4~~. To facilitate the comparisons, all simulations used the same deployment and harvest dates.

Macroalgae farms

2.2

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2.2.1 Strangford Lough research farm

The Northern Irish farm site run by Queen's University, Belfast, is located at 54.4N, 5.58W within the semi-enclosed Strangford Lough (Figure 1, Site A). The Lough covers an area of approximately 134 km^2, with water depths from 0-70 m, is 8 km long and the Narrows (0.5 km wide at narrowest) connect the Irish Sea to the main inlet of the lough (Smyth et al. 2016; Kregting and Elsäßer, 2014). The lough is fully saline ranging from 32 to 34 with negligible freshwater input from three small point sources (Boyd, 1973; Smith, 2010) and is predominantly well mixed (Taylor and Service,1997). The experimental site is located off the southern shore in the vicinity of the Narrows, but is relatively sheltered with an average current speed of 0.3 ms^{-1}. The current predominantly runs in a west – east direction (Mooney-McAuley et al., 2016). There can be moderate wave action when the wind is coming from northerly and easterly directions. The depth profile is variable, ranging from 2 m to 13 m at Mean Low Water Spring (MLWS).

The Strangford Lough research farm is located near the southwestern shore of the Lough (Figure 1, farm A), and run by Queen's University, Belfast. The farm cultivated a mixture of *S. latissima*, *Laminaria digitata* and *Alaria esculenta*. Here we use observations from the 2012-2013 deployment, when 2 x 100m longlines of *S. latissima* were cultivated and 19 with the other species. The growing lines were suspended horizontally at 1 m below the surface, and were pre-seeded at deployment. Monthly sampling was carried out after two months at sea. At each sampling time, five samples were taken from each rope removing all plants on a 30 cm section. The total wet biomass of all plants in these 30 cm intervals was determined, and used to calculate the mean biomass per line (kg wet weight/m). Total number of plants, total wet and dry biomass were measured. Total length, blade length, blade width and stipe length were also measured for the 12 largest plants in the sample. For the purpose of this modelling study, we have assumed that all 21 lines of the farm were cultivated with *S. latissima*; only field observations from the *S. latissima* long lines were used.

The mean biomass per line (kg wet weight/m) was used to estimate the total farm carbon biomass for comparison with the model results (see Section 3.4). Overall, 354 samples were analysed for wet and dry weight, giving a combined total wet weight of 3549.9 kg, and a dry weight of 380.38 kg, resulting in a wet/dry weight ratio of 9.333. For conversion from dry weight to carbon weight we assume that the dry plant material consists predominantly of CH_2O groups (Atkinson & Smith, 1983), resulting in a dry weight to carbon ratio of 32/12=2.67. The resulting conversion factor from wet weight to carbon is 24.919.

2.2.2 Sound of Kerrera and Lynn of Lorne research farms

The Sound of Kerrera and Lynn of Lorne farms (Figure 1, farms B and C) are located in the Firth of Lorne, and operated by the Scottish Association for Marine Science (SAMS).

The first Scottish farm site was located at 56.38N, 5.54W within the Sound of Kerrera (Figure 1, Site B) which separates the island Kerrera from the mainland by ca. 500m, near Oban. The Sound reaches 60m depth and experiences a semi-diurnal tidal current of 0.77 $m \cdot s^{-1}$ during spring tides. The island shelters the Sound from all but the predominant south-westerly winds from the Atlantic. At the farm site, the depth ranges from 5-25m.

The farm at Sound of Kerrera (Figure 1, B) consists of 180 m of double headed longline buoyed by mussel floats, with growing lines suspended at 1.5 m depth. For the Sound of Kerrera farm, observations of nutrient concentrations, light and temperature are available from a 17 month period in 2013-14. Nutrient concentrations were collected in triplicates at 1.5 m depth, whereas light and temperature were collected at half hourly intervals at 1.5 m depth, using HOBO Pendant data loggers (Onset Computer Corp, MA, USA). Here, we use the means of the triplicates for nutrients, and monthly means for light and temperature. The nutrient data showed a typical seasonal cycle with high winter concentrations and low concentrations following the spring bloom, but with surprisingly high summer concentrations in 2013, which are unexplained. Early summer concentrations in 2014 were substantially lower.

The second Scottish farm is located at 56.49N, 5.47W in the Lynn of Lorne (Figure 1, Site C), which separates the island of Lismore from the mainland. The site has a depth ranging from 15-25 m and has a mean current speed of 0.1 $m \cdot s^{-1}$, 5 m below the surface. The Lynn of Lorne is 3km wide at the location of the farm and so is very exposed to the predominant south-westerly winds from the Atlantic.

The Lynn of Lorne farm (Figure 1, C) consists of a 100x100 m grid submerged 3 m below the surface. This can contain up to 24 lines of 100 m length, spaced 4 m apart, with growing lines suspended horizontally at a depth of 1.5 m below the surface.

2.2.3 Rhine plume experimental farm

The southern coast of the Netherlands is characterized by shallow water depths (<25 m), high winter nutrient concentrations (Laane, 2005; Troost et al., 2014), and high turbidity (Pietrzak et al., 2011; Van der Hout et al., 2015). The Dutch coastal area is influenced by the Rhine river and has lowered salinity, potential for episodic salinity stratification (De Ruyter et al., 1997), and a higher N/P ratio due to larger reductions in anthropogenic riverine phosphate loading since the late 1980's (Lenhart et al., 2010).

Another experimental farm, run by North Sea farm foundation (Stichting Noordzee boerderij), was deployed for the first time in the autumn of 2016 within the nutrient-rich Rhine ROFI off the port of Scheveningen, The Netherlands (Figure 1, D). The farm consists of a single line of 100 m, undulating between 0 and 4 m below the surface. Data from this farm will only become available in the summer of 2017. The farm was included in the model to obtain predictions of potential performance.

2.2.4 Norfolk hypothetical commercial farm

The north Norfolk coast of the UK is also characterized by shallow water depths, high winter nutrient concentrations (Hydes et al., 1999; Proctor et al., 2003; Foden et al., 2011), and high turbidity (Dyer and Moffatt, 1998; Bristow et al., 2013).

Turbidity is higher than off the coast of the Netherlands, allowing for comparatively lower primary production by phytoplankton.

The hypothetical commercial farm off north Norfolk (Figure 1, Site E-G) was selected based on the method of Capuzzo et al. (2014), with minor modifications. The method consisted of over-laying maps of suitability scores (optimal, sub-optimal, unsuitable) of key limiting environmental variables (temperature, light, tidal velocity, wave height and nutrient concentrations; Table 1) and spatial use data (shipping, structures, Marine Protected Areas, wind farms, etc.) in a GIS system. The modifications applied here consist of slight variations to the threshold levels of certain environmental variables, and the adoption of a farming area based on the suitability data rather than rectangles of pre-defined size.

The area selected by this method was nearly rectangular (53.0545N 0.7745E to 53.11N 0.9775E), and located off the north Norfolk coast near Wells-next-the-Sea, in approximately 20 m water depth, between a coastal Marine Protected Area, wind farms and a Marine Conservation Zone further offshore (Figure 2). On the model grid, this area was approximated by a hypothetical farm covering three adjacent cells of 0.08 degree longitude and 0.05 degree latitude (approx. 5x5 km, Figure 1, E-G).

It was assumed that within each grid cell of 25 km^2, roughly half of the surface area would be effectively farmed, and the rest would be required for a mesh of navigation corridors for service vessels and occasional navigation lanes for other traffic. As details of such lay-outs are beyond the resolution of the model, it was assumed for simplicity that a solid block of 3.5x3.5 km was farmed within each 5x5 km grid cell with lines 50 m apart to avoid entanglement.

~~2.2.3~~2.2.5 Model scenarios

GETM-ERSEM-BFM was run without macroalgae farms from 1990 to 2011, using initial conditions from an earlier model version. The first 10 years of this simulation were considered as spinup time to enable the biogeochemistry of the model to adjust. The years 2001-2011 constituted the reference conditions (absence of farms). Farming scenarios were run for five consecutive seasons, starting on the first of October in 2006-2010, and running until the end of July of the following year in accordance with potential farming practice. The scenario runs were hot-started for each year from the corresponding conditions of the reference run on 1 October. To detect potential environmental effects, differences with the reference run were calculated of farm-season averaged, depth-averaged model scenario output for all routinely stored variables (covering nutrient concentrations, functional type biomass and a selection of fluxes for both pelagic and benthic systems), filtered for model variability using the method of Van der Molen et al. (2016), and plotted as maps. The filtering method discarded differences between the reference run and the scenario run that were smaller than similarly calculated differences between the reference run and a duplicate of the reference run. Time series consisting of daily values were extracted for pelagic nutrients, light conditions and macroalgae conditions at each model grid cell containing a macroalgae farm to assess farm performance and functioning.

2.3 SmartBuoy and satellite observations

SmartBuoys, instrumented moorings (Mills et al., 2005) have been deployed in UK and Dutch waters as components of monitoring programmes, and were configured to determine turbidity, chlorophyll fluorescence, salinity, temperature and dissolved oxygen and data processed according to Greenwood et al. (2010). Concentrations of suspended particulate matter and chlorophyll were derived from measurements of turbidity and chlorophyll fluorescence respectively (Greenwood et al., 2010). Discrete samples were collected using an automated Aquamonitor and subsequently analysed for TOxN (total oxidisable nitrogen) and silicate according to Gowen et al. (2008). In addition on most buoys, TOxN was determined using an automated *in-situ* NAS-2E or NAS-3X nutrient analyser. Daily mean values were calculated from all data which passed the quality assurance process.

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Daily spatial distributions of chlorophyll concentrations were derived from the MODIS satellite (modis.gsfc.nasa.gov), obtained from the Ifremer ftp server (~~ftp.ifremer.fr.:/ifremer/cersat/products/gridded/ocean-color/atlantic~~ftp.ifremer.fr.:/ifremer/cersat/products/gridded/ocean-color/atlantic), and ~~which~~ were processed as described by Gohin et al. (2005) and Gohin (2011)~~)~~. These data were further processed, in conjunction with modelled surface chlorophyll concentrations, to yield spatially resolved summer and winter statistics of model performance.

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3 Results

3.1 Model confirmation

Modelled M_2 tidal elevations and currents were compared with observations by Van der Molen et al. (2016), showing reasonable agreement, with elevation amplitudes typically within 20 cm, currents typically within 15 cm s^{-1}, and phases for both typically within 30°. Compared with *in-situ* SmartBuoy observations (Greenwood et al., 2010), modelled SPM concentrations showed a reasonable representation of the seasonal cycle, but over-estimating peak values. They were mostly within a factor of three, and with positive correlations, when compared with satellite observations on a seasonal scale (Van der Molen et al., 2017). These results are not reproduced here.

Surface chlorophyll concentrations from the reference run were compared with satellite observations for 2007-2008 (see also Van der Molen et al., 2016). Winter concentrations (October 2007 to March 2008, Figure 4a,b) were low in both the model and the satellite data. For a better comparison, the model output was subsampled for each grid cell (Figure 4c) using the available clear-skies satellite observations (Figure 4d). Subsequently, the relative offset (Figure 4e) and correlation coefficient (Figure 4f) were calculated. The resulting plots show that the model over-predicted ~~in the Atlantic Ocean, in the~~

North Sea along the northern UK coast, and in the Norwegian Trenchcoastal areas in the Celtic Seas. Correlations showed a patchy pattern, with typically better correlations in the northern North Sea and along the continental Dutch and Belgian coast.

In summer (April 2008 to September 2008, Figure 5) the model had a small bias in offshore waters in the North Sea and English Channel, but tended to over-estimate coastal and oceanic chlorophyll concentrations. It achieved good correlations in large parts of the North Sea and on the south-western shelfin parts of the Celtic Seas.

In the vicinity of the North Norfolk farm (Figure 1, Site E-G), the model bias for surface chlorophyll was slightly negative in winter, and the correlation coefficient was low (Figure 4e,f). In summer, chlorophyll concentrations were slightly over-estimated, and correlations were moderate (Figure 5e,f). Near the Rhine Plume farm (Figure 1, Site D), bias was slightly positive and correlations high in winter (Figure 4e,f), and bias was slightly positive and correlations moderate in summer (Figure 5e,f).

The model results from the reference run were compared with time series of *in-situ* observations from SmartBuoy for chlorophyll, nitrate, silicate, salinity, temperature and suspended sediment. For Warp Anchorage (see Figure 1 for location) modelled peak spring-bloom chlorophyll concentrations were within 10 mg Chl m^{-3} of the observations for most years (Figure 6a). The blooms tended to have longer duration than observed. Winter nitrate and silicate concentrations exceeded observed values for most years (Figure 6b,c), and were related to lower salinity values than observed (Figure 6d), possibly related to the river forcing or to resolution-related issues with the representation of the river plume. The modelled annual range in temperatures was several degrees more than observed (Figure 6e), and suspended sediment concentrations were much more variable, and had high event-driven peak values (Figure 6f).

In Liverpool Bay (see Figure 1 for location), spring and summer chlorophyll concentrations generally exceeded observed values from the SmartBuoy by a factor of two (Figure 7a). Nitrate concentrations were reproduced well in the last five years of the simulation, but were over-estimated in the first four winters (Figure 7b). Winter silicate concentrations were also higher in the first few years, but exceeded observed winter values for all the years in the time series (Figure 7c). Modelled salinities were slightly higher than observed (Figure 7d), and there was no apparent relationship with winter nutrient concentrations as for Warp Anchorage. Summer temperatures were reproduced mostly within a degree, while winter temperatures were underestimated by up to 2 °C (Figure 7e). The seasonal cycle of SPM concentrations was reproduced, but with substantially higher variability (Figure 7f).

At the more offshore location of West Gabbard (see Figure 1), peak chlorophyll concentrations were underestimated for most, but not all of the years (Figure 8a). Nitrate concentrations were under-estimated by a factor of 2-3 (Figure 8b), whereas silicate concentrations were reproduced fairly closely (Figure 8c). Summer salinities were over-estimated by 0.8-1.2 (Figure 8d). Maximum summer temperatures were exceeded by up to 2 °C in most years, and minimum winter temperatures were, with a few exceptions, reproduced closely (Figure 8e). Winter suspended sediment concentrations were 4-5 times higher than observed, with much higher variability (Figure 8f). This general pattern was also observed at other offshore SmartBuoys (not shown here for brevity).

3.2 Environmental effects

None of the maps of differences in biogeochemistry and plankton dynamics with the reference run, averaged over the farming season, showed detectable changes in the region of any of the farm sites, i.e. any differences between the run with farms and the first reference run were smaller than or of similar magnitude as differences between the two reference runs. For the experimental farms, this was to be expected because of their relatively small size. The north Norfolk farm (Figure 1, Site E-G) was located in a dynamic area with high tidal currents and substantial residual circulation, which may account for this result. Hence, in the following, we will focus on the performance of the macroalgae farms.

3.3 Macroalgae farm performance

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~~3.3~~3.4 Strangford Lough

Modelled winter nutrient concentrations at the Strangford Lough farm site (Figure 1, Site A; Figure 9a,b), 1.5-5 mmol N m^{-3} and 0.16-0.3 mmol P m^{-3}, showed substantial variation between years, and were lower than expected for a coastal location. Reported values for the Narrows and coastal offshore area for 2009 show values within, but also in exceedence of these ranges (Kregting et al., 2016). One reason for this could be that nutrient inputs from the largest river entering Strangford Lough, the Quoile, were not available for inclusion in the model. Summer concentrations were close to zero, with a suggestion that nitrogen was the limiting nutrient. Extinction coefficients (Figure 9c) ranged from peak winter values of up to 3 m^{-1} to summer values of 0.2-0.3 m^{-1} with fairly similar seasonal patterns per year. Surface irradiance (Figure 9d) showed a typical and stable seasonal cycle ranging from around 10 µmol m^{-2} s^{-1} in winter to maxima of 800 µmol m^{-2} s^{-1} in summer. Water temperatures (Figure 9e) ranged from about 16 °C in summer to 5-7 °C in winter, with the winters of 2008-2010 slightly colder than those of 2006-2007. Macroalgae biomass (Figure 9f) peaked at approximately 0.05 kg C m^{-1} line in all simulated years, about an order of magnitude lower than observed in the 2012-2013 farm deployment (plotted here in 2006). This under-estimation was caused by the low nutrient concentrations, as is also evident in the structure/mass ratio (mass of macroalgae structure over total (structure + carbohydrates) macroalgae mass, Figure 9g) and C/N and C/P ratio (Figure 9i,j), which show that the modelled macroalgae was high in carbohydra~~ta~~te content from the beginning and then rose throughout the cultivation. Mortality (Figure 9h) remained low throughout the farming cycles. Nutrient uptake rates per surface area of the farm (Figure 9k,l) were close to zero in summer, and peaked between 0.05-0.15 mmol N m^{-2} day^{-1} and 0.015-0.025 mmol P m^{-2} day^{-1}.

~~3.4~~3.5 Sound of Kerrera and Lynn of Lorne

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For the Sound of Kerrera farm (Figure 1, Site B; Figure 10), winter nutrients were higher, but also with substantial differences between years (7-15 mmol N m^{-3} and 0.6-1.4 mmol P m^{-3}). This is closer to expected values than at Strangford Lough (Figure 1, Site A), which is also illustrated by the observations from 2013-14, here plotted on 2010-11. The model did not reproduce the high summer concentrations evident in the first year of the observations. Extinction coefficients had similar values as in Strangford Lough, but with a lower base level in winter. Irradiance was also similar, and corresponded well with the monthly mean observed values from 2013-14. Water temperatures reached up to 18 °C in summer, and 3-6 °C in winter, ranges confirmed by the monthly mean observed values from 2013-14. Macroalgae biomass at harvest showed substantial interannual variability, between 0.11 and 0.48 kg C m^{-1} line. This range corresponds with the observed farm yield of 0.4 kg C m^{-1} line in 2013 and 0.16 kg C m^{-1} line in 2014, and also with the observed yield of 0.6 kg C m^{-1} line for the Strangford Lough farm in 2012/13. While the observed difference in yield seems to correspond with the observed difference in summer nutrient concentrations, the farm operators also reported heavy biofouling in 2014, which smothered the crop, possibly due to warmer spring temperatures in this particular year. The modelled differences in yield appear to relate to the nitrogen uptake rates. The final modelled carbohydrate content was high. Rates of mortality increased with biomass.

The Lynn of Lorne farm (Figure 1, Site C; Figure 11) showed a very similar pattern, but achieved ~~slightly higher~~almost twice the yields due to higher modelled nutrient concentrations. Interestingly, the carbohydrate content at harvest was lower for the high-yield years. In the year with highest yield, mortality shot up ten-fold shortly before harvest, suggesting that timing of harvesting may be critical. This latter result corresponds with the experience of the farm operators.

~~3.5~~3.5.1 Rhine plume experimental farm

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For the Rhine plume farm (Figure 1, Site D; Figure 12), the model over-predicted winter nitrate concentrations as compared with observations from the Noordwijk-10 station further to the north by up to a factor of three (up to 180 mmol N m^{-3}), and also over-predicted summer concentrations. Phosphate concentrations were reproduced fairly closely, and both model and observations suggest that for a period after the spring bloom phosphate was the limiting nutrient. The model also reproduced the available observations of the extinction coefficient, which bottomed out at approximately 0.5 m^{-1}; higher than at the Scottish and Irish farm sites. Summer temperatures ranged up to 20 °C, which is near the thermal limit for this kelp species. Farm yields were relatively stable at around 0.7 kg C m^{-1} line, but carbohydrate content remained low as nutrients remained available throughout the summer. The observations suggest that this may not be as extreme in reality. Mortality increased during the later stages of growth, suggesting that if, in reality, the carbohydrate content does increase due to lower nutrient concentrations than in the model, there may be a fine balance in picking the right time to harvest.

~~3.6~~3.5.2 Norfolk hypothetical commercial farm

The results for the Norfolk hypothetical farm (Figure 1, Site E-G; Figure 13) showed winter nitrate concentrations of 40-50 mmol N m^{-3} and 1.5-2.5 mmol P m^{-3}, respectively. This corresponds with observed values of 45-48 mmol N m^{-3} and DIN/DIP ratios of 20-30 for the Eastern English Coast and East Anglia regions in 2001-2005 (Foden et al., 2011). Extinction coefficients were over-estimated by the model by a factor of 3-4. This was compensated for by setting the farm lines to 0.3 m below the surface instead of 1 m. Summer temperatures ranged up to 20 °C, while winter temperatures could be as low as 2.5 °C. Farm yields were stable and high at approximately 1 kg C m^{-1} line, and the final crop contained substantial concentrations of carbohydrates. ~~Mortality did not increase as much as at some of the other sites.~~

~~3.7~~3.5.3 Predicted farm yields

In addition to the per unit performance of the farms presented in the previous section, it is, from the point of view of biomass production, useful to list the total predicted yield of the farms at their current size. Total modelled farm yields are summarised in Table 6~~Table 3~~. In terms of wet biomass, yields were in the range of 2-3 t yr^{-1} for the Strangford Lough farm (Figure 1, Site A), 7-30 t yr^{-1} for the Sound of Kerrera farm (Figure 1, Site B), 20-60 t yr^{-1} for the Lynne of Lorne farm (Figure 1, Site C), around 1.5 t yr^{-1} for the Rhine plume farm (Figure 1, Site D), and 18 and 20 kt yr^{-1} for the combined Norfolk farm (Figure 1, Site E-G).

~~3.8~~3.5.4 Variations in farm yield

The model results suggested that macroalgae growth was dictated by combined availability of nutrients and a sufficient level of light. To illustrate this, nutrient uptake was plotted as a function of irradiance and nutrient concentration. The resulting graphs for nitrate (Figure 14) show that this was indeed the case: for the Rhine Plume farm (Figure 1, Site D; graph a) high uptake occurred, starting at high nitrate concentrations in winter, and for light levels over 100 µmol~~E~~ m^{-2} s^{-1}. For the Sound of Kerrera farm (Figure 1, Site B; graph b), there was only limited opportunity for high uptake, as under most conditions either light or nutrients were lacking. The Strangford Lough farm (Figure 1, Site A; graph c) did not experience high uptake at all. The Norfolk farm (Figure 1, Site E-G; graph c) experienced a good range of conditions that allowed high nitrate uptake. Results for phosphate showed very similar patterns, and are not shown here.

Plotting modelled macroalgae biomass for the Sound of Kerrera farm in a similar way and for the individual years (Figure 15) elucidates the mechanism behind the variability in farm yield in the model (Figure 11f). The final biomass appeared to be correlated not only with the winter nutrient concentration but also with structural biomass in spring, when nutrient concentrations were still elevated and light levels exceeded 50 µmol~~E~~ m^{-2} s^{-1} (compare also with the uptake rates, Figure 14b). A sufficient level of initial spring biomass was required to allow for sufficient uptake and storage of nutrients to facilitate the early summer growth. The initial spring structural biomass appeared to be correlated with the combination of light and nutrient concentrations in late autumn/early winter. Hence, it appears that the timing of the onset of increased nutrient levels, and the timing of nutrient drawdown are important determinants of farming success in areas where winter nutrient levels are not elevated and subject to interannual variation.

4 Discussion

The modelled production of macroalgae showed a range of responses that may illustrate the actual production that can be expected from commercially operated farms in these locations. Having said this, the model results were not highly accurate for all sites. At Strangford Lough (Figure 1, Site A), the modelled winter nutrient concentrations were likely too low, leading to low macroalgae production in the model. This result provides an analogue for potential lack of farming success at sites with naturally low winter nutrient concentrations.

The model results at the Sound of Kerrera site (Figure 1, Site B) were realistic, comparing in range with observed winter nutrient concentration levels (higher than at the Strangford Lough site), and also comparing in range with the observed variation in macroalgae production. Modelled production at the Lynn of Lorne site (Figure 1, Site C) was higher than at Sound of Kerrera, coinciding with higher modelled winter nutrient concentrations. However, as a side effect of this, macroalgae carbohydrate content was lower.

At the Rhine Plume site (Figure 1, Site D), modelled nitrate levels were substantially higher than observed. Despite this, macroalgae production per metre was ~~lower~~ higher than at Sound of Kerrera and the last three years at Lynn of Lorne ~~due~~ despite~~to~~ less favourable light conditions caused by higher concentrations of suspended solids and the line being deeper below the surface. This is most likely the result of more favourable nutrient concentrations. The modelled macroalgae contained low concentrations of carbohydrates, as they had continuous access to nutrients. The observed nitrate concentrations at a near-by location suggest limiting conditions in summer, and hence the real farm may yield macroalgae with a higher carbohydrate content.

The Norfolk farm (Figure 1, Site E-G), after compensating for the overestimated modelled suspended particulate matter concentrations by reducing the depth of the lines below the surface, produced modelled macroalgae biomass per metre of line ~~comparable with the higher values reported~~higher than those simulated for the Sound of Kerrera farm. This production showed good interannual stability, and contained up to 60% carbohydrates. Simulated winter nutrient concentrations were comparable with observed concentrations. There was a slight variation in macroalgae production between the three model grid cells occupied by the farm, in line with a slight gradient in suspended particulate matter concentrations. Even for this farm, which was the largest that was modelled, we did not find significant changes in temporal averages of other model environmental variables over the period of simulated farming. This is presumably because nutrient requirements of *S. latissima* are very modest, and there is a high level of flushing in the area. Overall, this result supports the potential for this site for macroalgae farming.

The model results suggested that, in areas where winter nutrient levels are modest, farming success could be sensitive to the timing of the autumn onset and spring draw-down of nutrient levels. This result should be further tested and investigated using more detailed field and laboratory observations.

The current shelf-wide model allows for first assessments of macroalgae farm performance at a wide range of locations on the northwest European continental shelf. The relatively course model resolution, however, clearly limits the accuracy of the farm production results, in particular in areas with large gradients in topography at scales finer than the model resolution. If more accurate simulations are desired for such locations, or if within-farm gradients in productivity need to be studied, local high-resolution models could be developed that take boundary conditions from the current model. The current model assumes horizontal lines, whereas some experimental farm configurations include vertical or diagonally undulating lines. The Rhine plume farm uses undulating lines, and hence the performance could be different from the simulations presented here. To better represent these different farm configurations, and/or investigate potential differences in performance between such configurations, the model could be adapted by introducing the ability to distribute macroalgae biomass in the vertical. Similar adaptations would also be required for the simulation of natural populations, in which plants are anchored to hard substrate and grow vertically towards the surface. The approximation for frond erosion suggested by Broch and Slagstad (2011) does not explicitly include effects of the environment, and might be refined with a suitable set of laboratory experiments and field observations. However, the currently simulated values are small, and experience from the experimental farms indicates that higher values only occur later in the season. Crops can be harvested before such mortality occurs, so accurate predictions of mortality are not of high relevance for the current application.

This modelling exercise is a proof of concept, and did not aim for a detailed representation of the farm localities, nor did it involve extensive tuning to reproduce detail of farm performance. We used an existing 3D model setup of the northwest European continental shelf (Section 2.1), which allowed all farms to be included in one model, albeit with a very coarse representation of coastal geometries. Farm implementation included a level of sub-grid parameterisation. The model was run with forcings for years pre-dating farm deployments, so comparisons with observations collected during the actual deployments can only be qualitative. Despite these limitations, we obtained reasonable confidence in the model, as well as

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valuable results in terms of farm functioning and performance, macroalgae quality, and farming-induced changes in environmental conditions. These predictions are necessary to progress the future development of this fledgling industry.

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5 Recommendations

This model study did not detect large-scale changes in environmental conditions in the vicinity of the simulated farms. Although this is encouraging, we do not, however, consider this finding to be a generic result, and further and specific investigations should be carried out for specific proposed farm implementations. Such work could include application of and contrasting with other models, and further up-scaling of farm size and intensity to explore safe limits. Moreover, the current model (as any model) only captured a subset of environmental processes. Also, simulations with a high-resolution model are recommended to confirm and refine the results obtained here, if further farm implementation plans are developed.

The results for the hypothetical Norfolk farm site (Figure 1, Site E-G) suggest favourable conditions for commercial macroalgae farming. However, suspended particulate matter concentrations may remain an issue, and accurate regulation of a very shallow depth of line below the surface is probably required. A small-scale field experiment is recommended to test this result in reality.

For the Sound of Kerrera site (Figure 1, Site B), with lower nutrient concentrations and variable farm yield, the model suggested a relationship between farm yield and autumn and spring nutrient concentrations coinciding with light at sufficient levels. This suggested relationship should be investigated further, and confirmed with more detailed observations than available for this study, as further understanding of these processes can help to determine minimum required conditions for successful farming.

The model results suggest high rates of macroalgae growth in early summer, accompanied with an increase in carbohydrate content, but also by an increase in mortality. This suggests that there is an optimum window for harvesting, in line with experience from the experimental farms; however, the simulated mortality was not enough to start to reduce biomass. The model suggested differences in this balance between the farm sites, but without further field evidence it is difficult to draw detailed conclusions. It is recommended to continue the field experiments, and to gather more detailed information on environmental conditions, carbohydrate content and mortality. This could be accompanied by suitable series of shore-based microcosm experiments. Associated modelling work can help to explain and extrapolate such results.

Concerning the model, improvements could be made in the simulation of nutrients and particulate suspended matter. Also, representations of different farm configurations could be considered (eg., undulating or vertical lines). Other macroalgae species could be included, as well as a capability to model natural, sea-bed attached macroalgae populations. Finally, inclusion of macroalgae grazers in the model could be investigated, as grazing can be a problem for farm operation.

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Table 1. Limiting environmental variables for macroalgae cultivation. Ranges in bold were satisfied within the selected farm area (green rectangle in Figure 2). Between brackets: values suggested by Capuzzo et al. (2014) if different.

Variable	**Unsuitable**	**Sub-Optimal**	**Optimal**	**Reference**
Contribution to suitability index	0	0.5	1	
Minimum temperature [°C]	<2	**2-5** (2-4)	>5 (>4)	Bolton and Lüning (1982)
Maximum temperature [°C]	Adapted farming methods assumed possible (>18)	Adapted farming methods assumed possible (16-18)	Adapted farming methods assumed possible (<16)	Bolton and Lüning (1982)
Wave height [m]	>6	4-6 (<1 & 4-6)	**0-4** (1-4)	Buck and Buchholz (2005)
Photic depth [m]	<1 (<2)	1-2 (2-4)	**>2** (>4)	
Winter nitrate [mmol m^{-3}]	<10	10-20	**>20**	Aldridge *et al*. (2012)
Tidal velocity [m s^{-1}]	>2	<0.25 & 1.5-2	**0.25-1.5**	Buck and Buchholz (2005)
Water depth [m]	<4 (<10 & >50)		**>4** (10-30)	

Table 2. Variables of the macroalgae model.

Symbol	Unit	Description
W_s	mgC m^{-2}	Structural biomass, state variable
A	m^2	Frond area
W_C	gC (g sw) $^{-1}$	Total biomass, state variable
W_N	mmol N m^{-2}	Biomass, state variable
W_P	mmol P m^{-2}	Biomass, state variable
W_L	Mg Chl m^{-2}	Biomass, state variable
μ	day^{-1}	Specific growth rate (area), derived variable
W_w	g	Total wet weight of sporophyte, derived variable
W_d	g	Total dry weight, derived variable
$E(d)$	µmol photons m^{-2} s^{-1}	Irradiance (PAR), environmental variable at depth d
$T(d)$	ºC	Water temperature, environmental variable at depth d
N	mmol m^{-3}	Substrate nutrient concentration, environmental variable

Table 3. Parameters of the macroalgae model.

Symbol	Value	Unit	Description
q_S^A	83 10^{-6}	m^2 (mg C)$^{-1}$	Unit area per Structural mass
γ	0. 5	gC g^{-1}	Exudation parameter
ε	22	m^{-2}	Frond erosion parameter
A_0	0.06	m^2	Growth rate parameter
m_1	0. 1085	–	Growth rate parameter
m_2	0. 03	–	Growth rate parameter
μ_m^S	0. 36	d^{-1}	Maximal specific growth of structural biomass (uncorrected for day length)
μ_m^C	0.36	d^{-1}	Maximal specific growth of biomass (uncorrected for day length)
q_{CS}^l	0. 05	gC (g C) $^{-1}$	Minimal quotum reserve C per Structural mass
q_{NS}^l	0. 142 × 10^{-3}	mol N (g C) $^{-1}$	Minimal quotum N per Structural mass
q_{PS}^l	6 × 10^{-6}	mol P (g C) $^{-1}$	Minimal quotum P per Strucutral mass
q_{NC}^m	0.3 × 10^{-3}	mol N (g C) $^{-1}$	Maximal quotum N per total mass Carbon
q_{PC}^m	12 × 10^{-6}	mol P (g C) $^{-1}$	Maximal quotum P per total mass Carbon
q_C^L	0.0278	gChla (g C) $^{-1}$	Optimal quotum Chlorophyll perTotal mass Carbon
K_e	20	µmol photons	Light affinity parameter (lowest light intensity at whivh primary

		$m^{-2}\,s^{-1}$	production is optimal.
a_N	0.5×10^{-3}	$m^3(mg\ C)^{-1}d^{-1}$	Nutrient affinity for nitrogen
a_P	0.7×10^{-3}	$m^3(mg\ C)^{-1}d^{-1}$	Nutrient affinity for phosphate
q_{10}	2	-	Q_{10} parameter
n_{pl}	user-defined	(number)	initial number of macrophyt plants
r_r	0.01	d^{-1}	respiration

Table 4. Equations of the macroalgae model. The last column lists the numbers of the corresponding equations used by Broch and Slagstad (2011).

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Equation	Unit	Description	
$\mu=\mu_m^S f_A f_L^S f_T^S(1\text{-max}\left\{\frac{W_S q_{NS}^l}{W_N},\frac{W_S q_{PS}^l}{W_P},\frac{W_S q_{CS}^l}{W_C-W_S}\right\}$	d^{-1}	Specific growth rate	2
$A=q_S^A W_S/n_{pl}$	-	Calculation of frond surface	
$f_A(A)=(m_1\left(e^{(-A/A_0)^2}\right)+m_2)/(m_1+m_2)$	-	Non-dimensional effect of size area on growth rate ($0<f_A\leq1$)	3
$f_T^C(d)=q_{10}{}^{(T(d)-10)/10}$	-	Effect of temperature on C-fixation rate. Assumed is an exponential increase	14
$f_T^S(d)=f_T^C(d)\left\{\frac{19-T(d)}{21-T(d)}\right\}$	-	Effect of temperature on structural growth. Structural growth is inhibited above 19 °C	4
$f_L^C(d)=1-\exp\left(-\frac{W_L q_C^L}{W_C}\frac{E(d)}{K_e}\right)$	-	Light limitation for C-fixation at depth *d* is dependent on Chl-C quotum and on light energy *E* at depth *d*	5
$f_L^S(d)=(f_L^C(d)>0)$	-	Only structural growth at daylight	5
$\nu(A)=\frac{10^{-6}e^{\varepsilon A}}{1+10^{-6}(e^{\varepsilon A}-1)}$	d^{-1}	Frond erosion	6
$u_n^m=a_n n W_C$	mmol n d^{-1}	Maximal nutrient uptake for *n*=Nitrogen (*N*) and for *n*=Phosphate (*P*)	8
$e_C=1-\exp\left[-\gamma\frac{W_C-(1-q_{CS}^l)W_S}{W_S}\right]$	d^{-1}	Carbon exudation only when more C-reserves are present than the minimum quotum q_{CS}^l	15
$\rho_L=q_C^L f_L^C\left(\frac{W_L}{W_C}q_C^L\right)\frac{K_e}{E(d)}$	gChl $(gC)^{-1}$	The ρ_L determines the size of the Chlorophyll (*L*) production. Low light and a low quotum Chl:C enhance	

		this production	
$\frac{dW_n}{dt} = \min\left\{u_n^m, (q_{nC}^m \mu + \mu_m (q_{nC}^m - \frac{W_n}{W_C}))W_C - f_T^C W_n\right\}$	mmol ***n*** d^{-1}	Rate of change in total content of ***n***=Nitrogen (*N*) and of ***n***=Phosphate (*P*)	7 8
$\frac{dW_C}{dt} = (\mu_m^C f_L^C - e_C - f_T^C r^C) W_C$	mg C d^{-1}	Rate of change in total Carbon content	9 10
$\frac{dW_L}{dt} = \rho_L (\mu_m^C f_L^C - e_C - f_T^C r^C) W_C$	mg C d^{-1}	Total Chlorophyll production by macrophytes	
$\frac{dW_S}{dt} = (\mu - \nu) W_S$	mg C d^{-1}	Rate of change of structural biomass	1

Table 5. Farm description.

	Strangford Lough	Sound of Kerrera	Lynn of Lorne	Rhine Plume	north Norfolk coast
Latitude	54.40	56.40	56.50	52.15	51.53
Longitude	-5.58	-5.58	-5.50	4.10	0.82-0.98
Line length [m]	100	100	100	85	3500
Number of lines per farm	21	24	24	1	350
Distance between lines [m][a]	5	4	4	-	50
Depth below surface [m]	1.0	1.5	1.5	2.0	0.3[b]
Initial biomass per m line [mg C m^{-1}]	2500	2500	2500	2500	2500
Number of plants per m line	100	100	100	100	100
Deployment day of year	274	274	274	274	274
Harvest day of year	183	183	183	183	183
Number of grid cells covered by farm	1	1	1	1	3
Location in Figure 1	A	B	C	D	E, F, G

[a]The model worked with an implicit line distance of 1 m.

[b]The depth of the farm for north Norfolk was set to 0.3 m instead of 1.0 m to compensate for the over-estimated SPM concentrations and corresponding lower light levels.

Table 6. Simulated farm yields at harvest at the end of July (10^3 kg C; 10^3 kg wet biomass between brackets; factor 24.919)

	Farm size (m of line)	2006/7	2007/8	2008/9	2009/10	2010/11
Strangford Lough	2100	1.1E-1 (2.8)	1.0E-1 (2.5)	1.1E-1 (2.7)	1.0E-1 (2.5)	8.4E-2 (2.1)
Sound of Kerrera	2400	9.7E-1 (2.4E1)	1.1 (2.8E1)	7.2E-1 (1.8E1)	4.3E-1 (1.1E1)	2.8E-1 (7.0)
Lynne of Lorne	2400	2.3 (5.6E1)	2.5 (6.1E1)	1.2 (3.0E1)	8.1E-1 (2.0E1)	7.8E-1 (1.9E1)
Rhine plume	85	6.5E-2 (1.6)	6.0E-2 (1.5)	6.0E-2 (1.5)	5.5E-2 (1.4)	5.9E-2 (1.5)
Norfolk A	245000	2.4E2 (6.0E3)	2.3E2 (5.8E3)	2.3E2 (58E3)	2.5E2 (6.1E3)	2.5E2 (6.2E3)

Norfolk B	245000	2.6E2 (6.4E3)	2.5E2 (6.2E3)	2.5E2 (6.3E3)	2.6E2 (6.6E3)	2.7E2 (6.7E3)
Norfolk C	245000	2.7E2 (6.6E3)	2.6E2 (6.4E3)	2.7E2 (6.8E3)	2.8E2 (6.9E3)	2.8E2 (7.0E3)
Norfolk total	735000	7.6E2 (1.9E4)	7.4E2 (1.8E4)	7.8E2 (1.9E4)	7.8E2 (2.0E4)	7.8E2 (2.0E4)

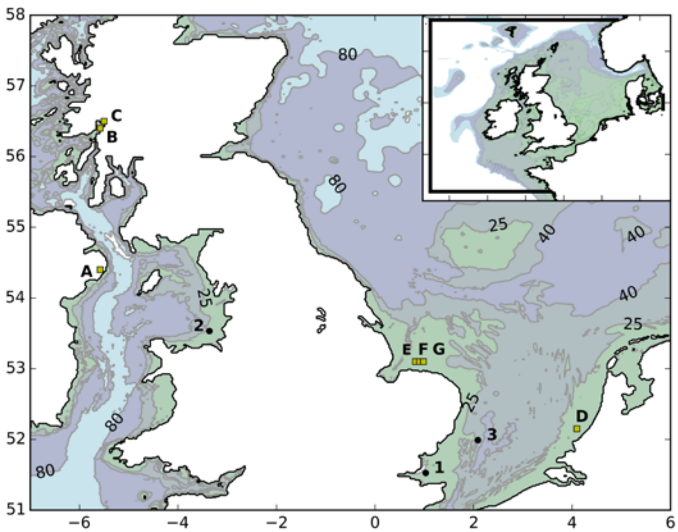

Figure 1. Study area with SmartBuoy stations (black circles: 1 = Warp Anchorage, 2 = Liverpool Bay, 3 = West Gabbard), and macroalgae farm locations (yellow squares represent the macroalgae farms: A = Strangford Lough; B = Sound of Kerrera; C = Lynn of Lorne; D = Rhine Plume; E-G = north Nolfolk; see Table 5~~Table 2~~ for more information). Depths are in metres. Inset: north-west European shelf seas with model domain boundaries (thick black lines).

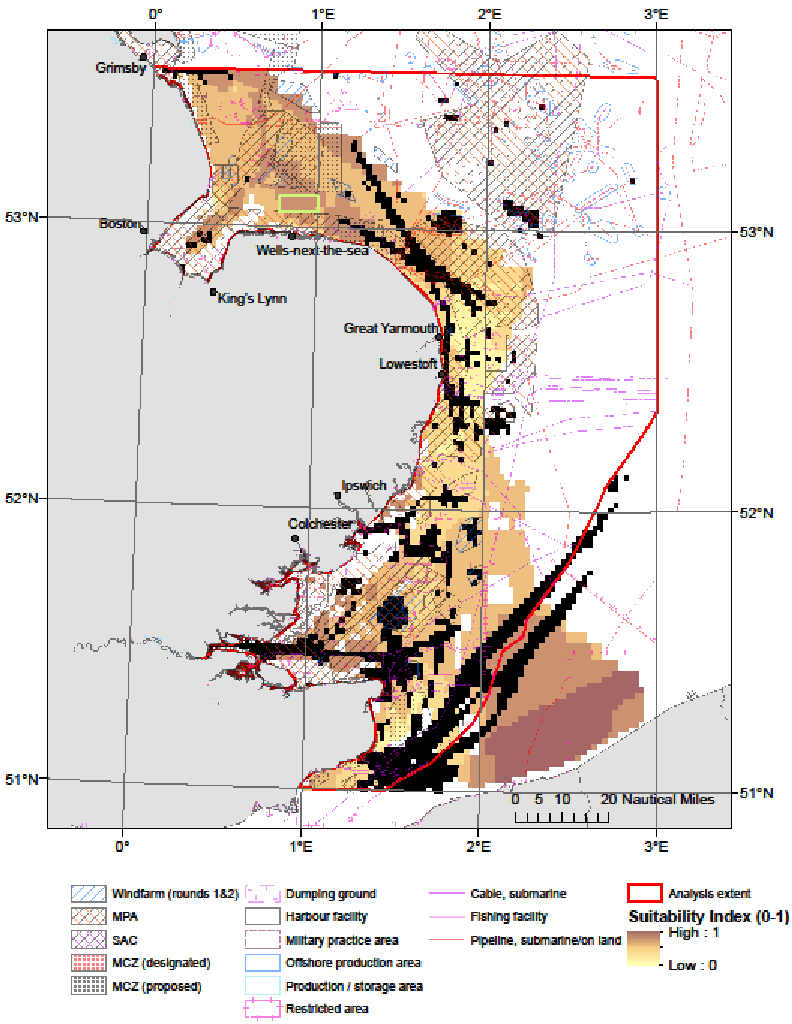

Figure 2. Potential areas for a commercial farm off the North Norfolk coast. Yellow to brown shading: suitability index. Black: moderately high to high shipping intensity (derived from Marine vessel Automatic Identification System ping data obtained from exactEarth Ltd., http://www.exactearth.com/http://www.exactearth.com/, for the year of 2013). Lines and hashes: various licensed use (Marine Reference dataset, Defra, collated by the Joint Nature Conservation Committee, 2011). Green rectangle: selected farm area.

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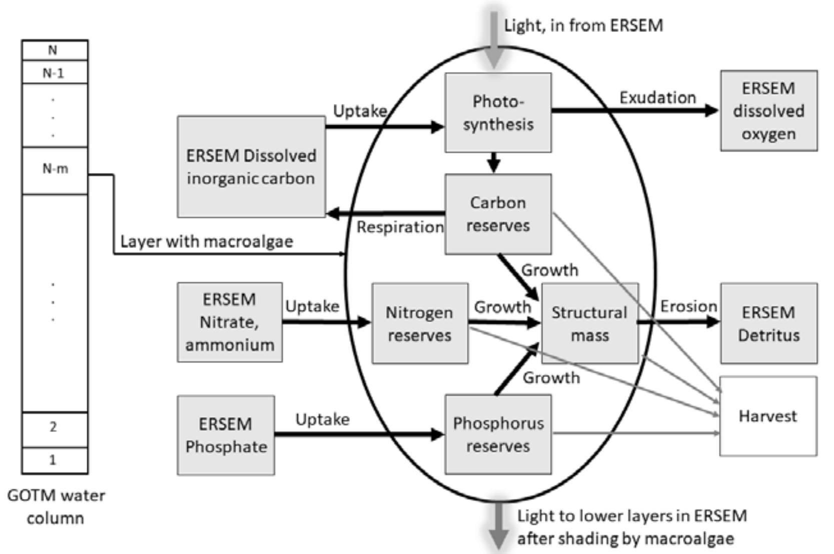

Figure 3. Schematic representation of the farmed macroalgae in ERSEM-BFM, modified and expanded after Broch and Slagstad (2012).

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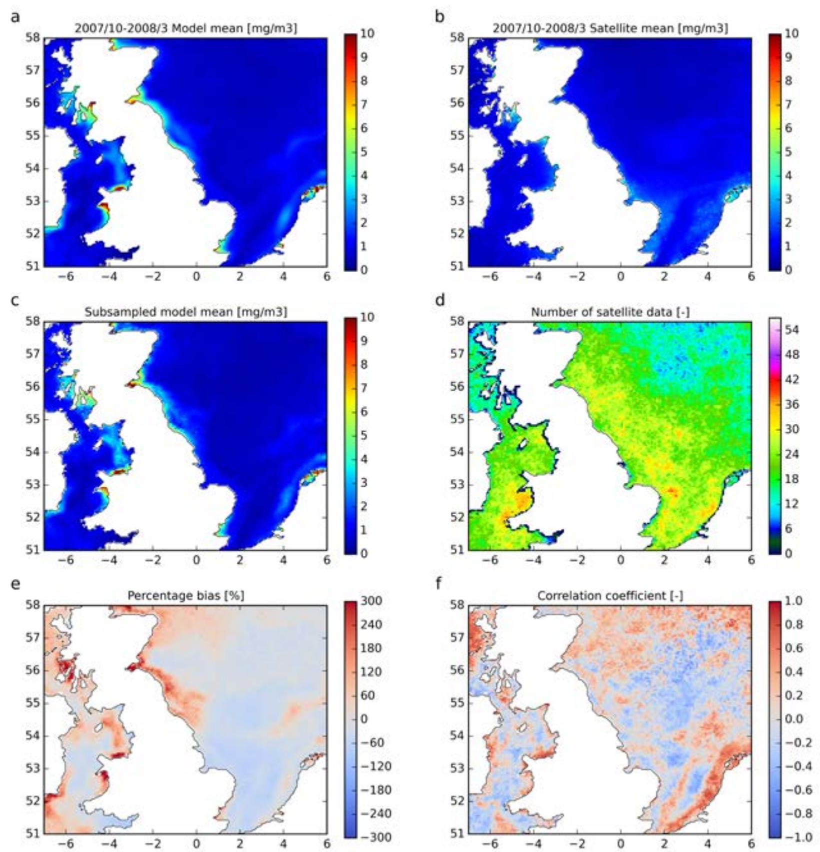

Figure 4. Comparison of winter chlorophyll-a concentrations between model and satellite, October 2007 to March 2008. a) model mean; b) satellite mean; c) model mean accounting for cloudy days; d) number of clear days from satellite; e) relative model bias; f) correlation coefficient.

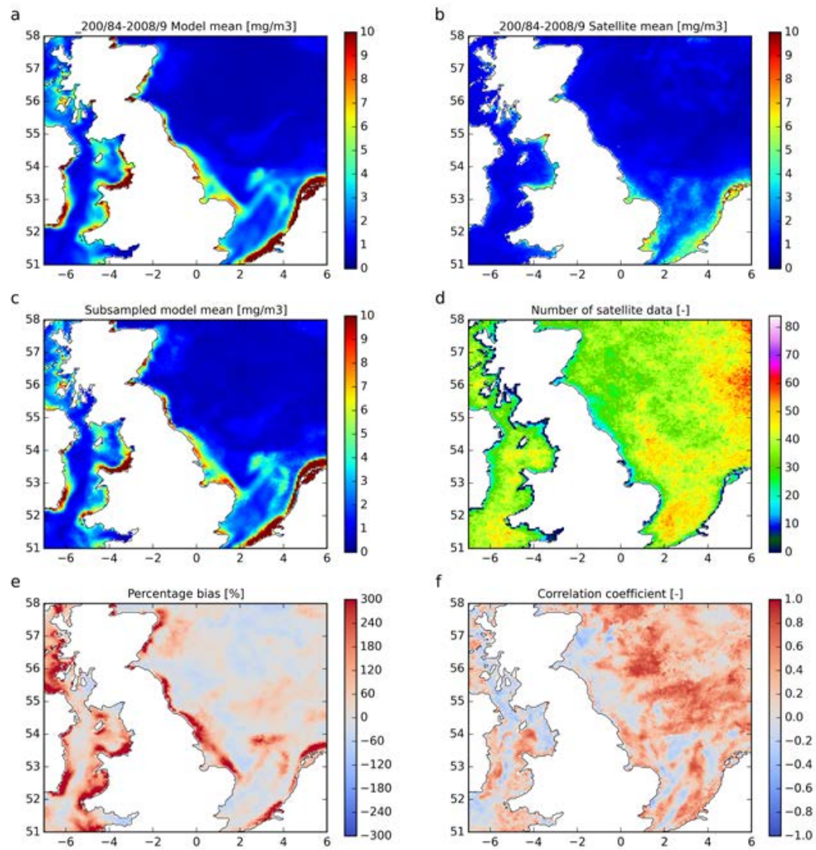

Figure 5. Comparison of summer chlorophyll-a concentrations between model and satellite, April 2008 to September 2008. a) model mean; b) satellite mean; c) model mean accounting for cloudy days; d) number of clear days from satellite; e) relative model bias; f) correlation coefficient.

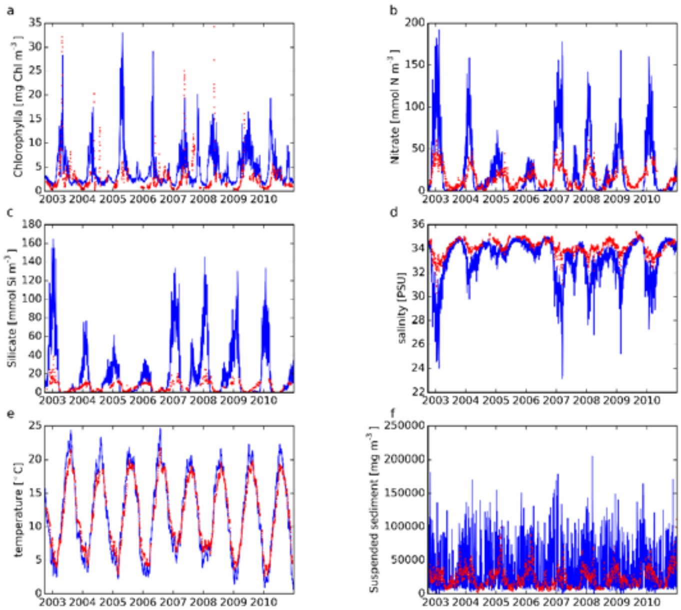

Figure 6. Time-series comparison with Warp Anchorage SmartBuoy, surface. Blue: model, red: observations. a) Chlorophyll-a concentration; b) nitrate concentration; c) silicate concentration; d) salinity; e) temperature; f) suspended sediment concentration.

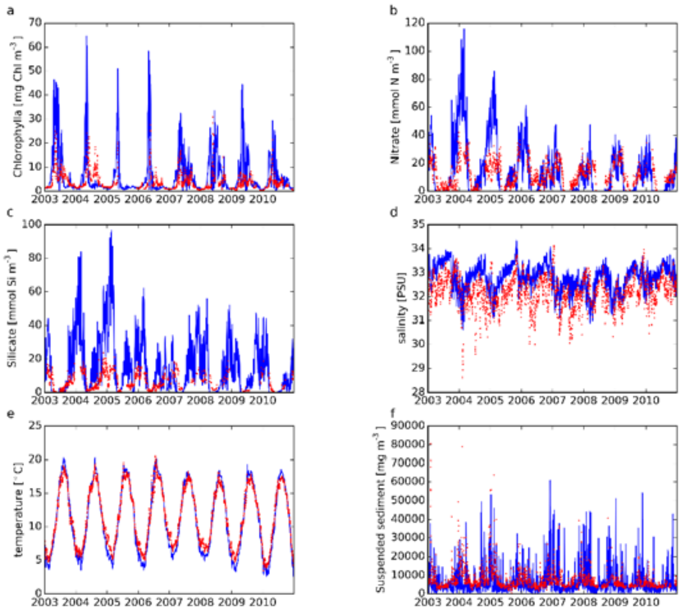

Figure 7. Time-series comparison with Liverpool Bay SmartBuoy, surface. Blue: model, red: observations. a) Chlorophyll-a concentration; b) nitrate concentration; c) silicate concentration; d) salinity; e) temperature; f) suspended sediment concentration.

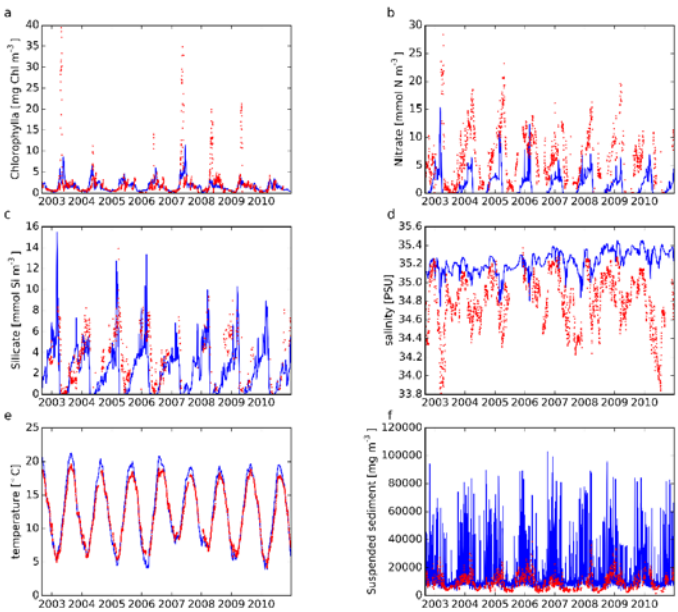

Figure 8. Time-series comparison with West Gabbard SmartBuoy, surface. Blue: model, red: observations. a) Chlorophyll-a concentration; b) nitrate concentration; c) silicate concentration; d) salinity; e) temperature; f) suspended sediment concentration.

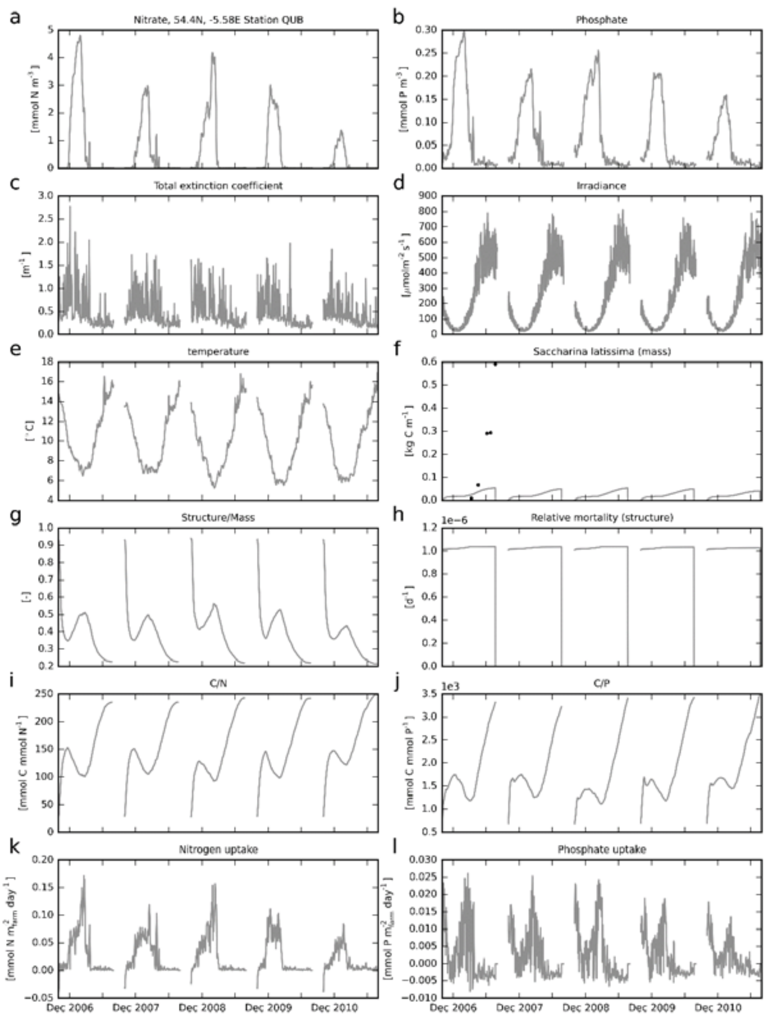

Figure 9. Model results for the Strangford Lough farm site. a) surface nitrate concentration; b) surface phosphate concentration; c) total extinction coefficient at the surface (excluding contribution by macroalgae); d) irradiance at the surface; e) surface water temperature; f) macroalgae carbon biomass (structure + carbohydrates) per m of line; g) mass of macroalgae structure over total (structure + carbohydrates) macroalgae mass ratio; h) relative mortality of macroalgae structure; i) C/N ratio of macroalgae; j) C/P ratio of macroalgae; k) farm net nitrogen uptake; l) farm net phosphate uptake. Black dots in f) are observations from the 2012-2013 deployment.

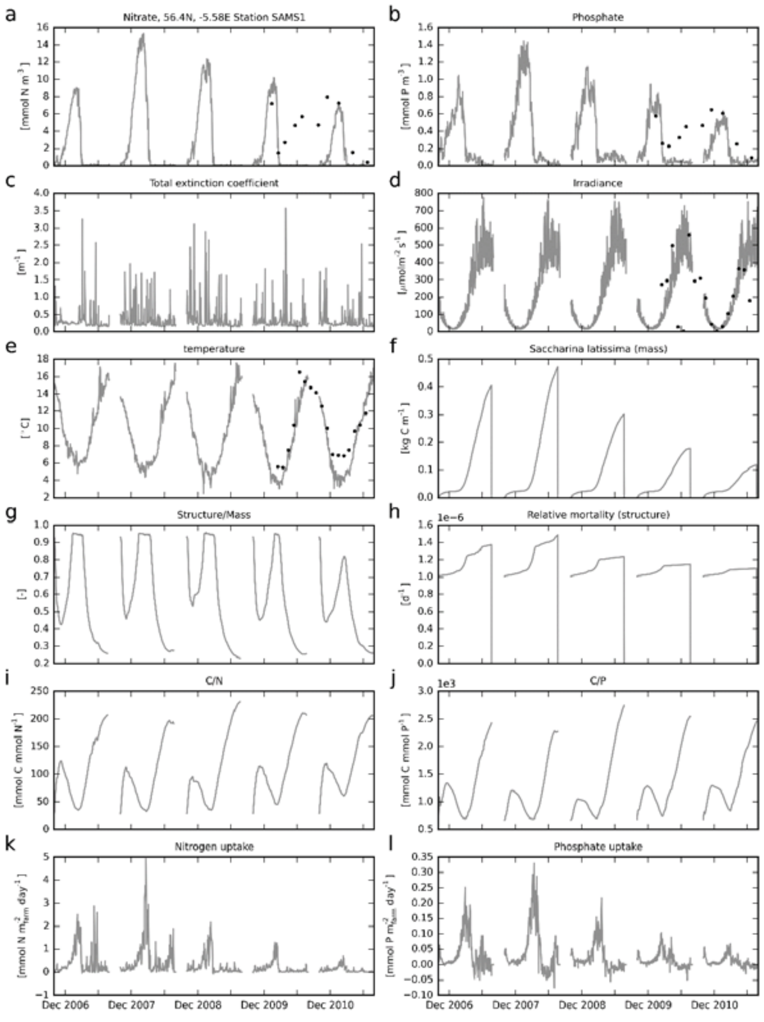

Figure 10. Model results for the Sound of Kerrera farm site. a) surface nitrate concentration; b) surface phosphate concentration; c) total extinction coefficient at the surface (excluding contribution by macroalgae); d) irradiance at the surface; e) surface water temperature; f) macroalgae carbon biomass per m of line; g) mass of macroalgae structure over total macroalgae mass ratio; h) relative mortality of macroalgae structure; i) C/N ratio of macroalgae; j) C/P ratio of macroalgae; k) farm net nitrogen uptake; l) farm net phospate uptake. Black dots are observations: in a) and b) from nutrient samples, in d) and e) monthly averages from a data logger.

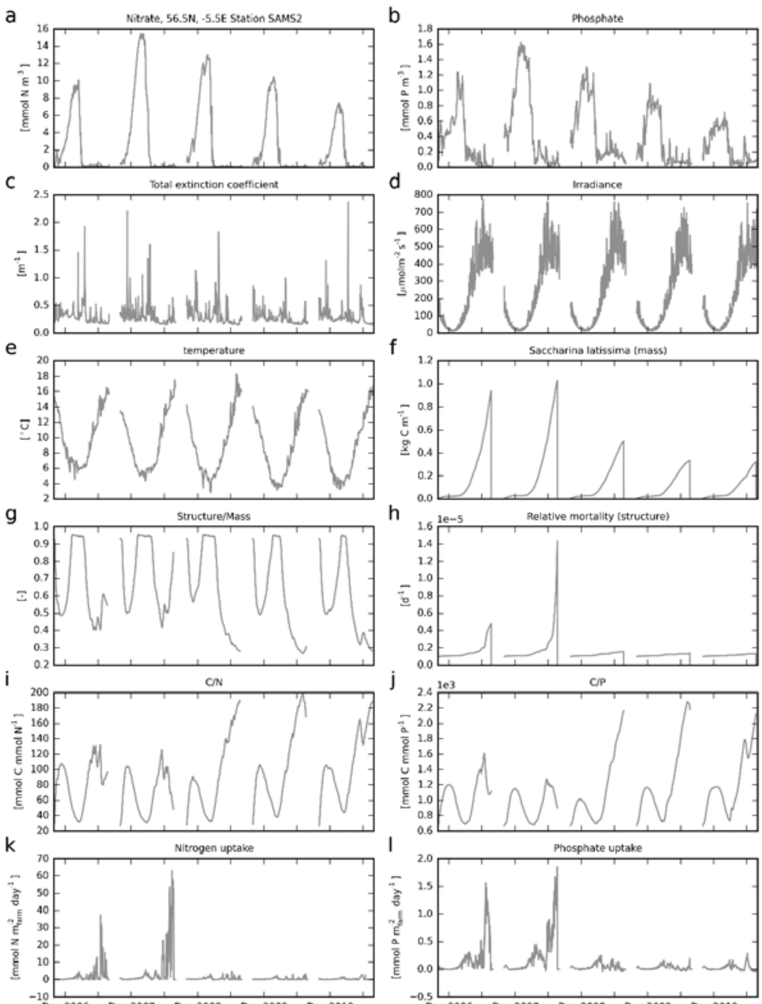

Figure 11. Model results for the Lynn of Lorne farm site. a) surface nitrate concentration; b) surface phosphate concentration; c) total extinction coefficient at the surface (excluding contribution by macroalgae); d) irradiance at the surface; e) surface water temperature; f) macroalgae carbon biomass per m of line; g) mass of macroalgae structure over total macroalgae mass ratio; h) relative mortality of macroalgae structure; i) C/N ratio of macroalgae; j) C/P ratio of macroalgae; k) farm net nitrogen uptake; l) farm net phospate uptake.

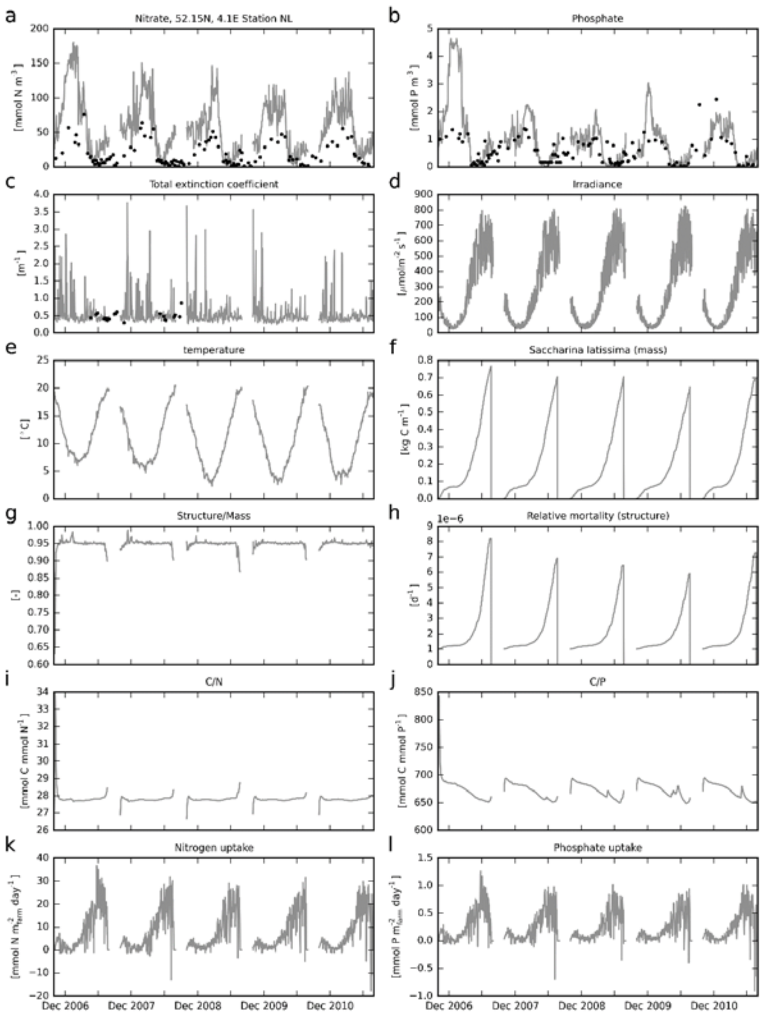

Figure 12. Model results for the Rhine plume farm site. a) surface nitrate concentration; b) surface phosphate concentration; c) total extinction coefficient at the surface (excluding contribution by macroalgae); d) irradiance at the surface; e) surface water temperature; f) macroalgae carbon biomass per m of line; g) mass of macroalgae structure over total macroalgae mass ratio; h) relative mortality of macroalgae structure; i) C/N ratio of macroalgae; j) C/P ratio of macroalgae; k) farm net nitrogen uptake; l) farm net phospate uptake. Black dots are observations from the near-by Noordwijk transect at 10 km offshore collected by RIKZ (live.waterbase.nl).

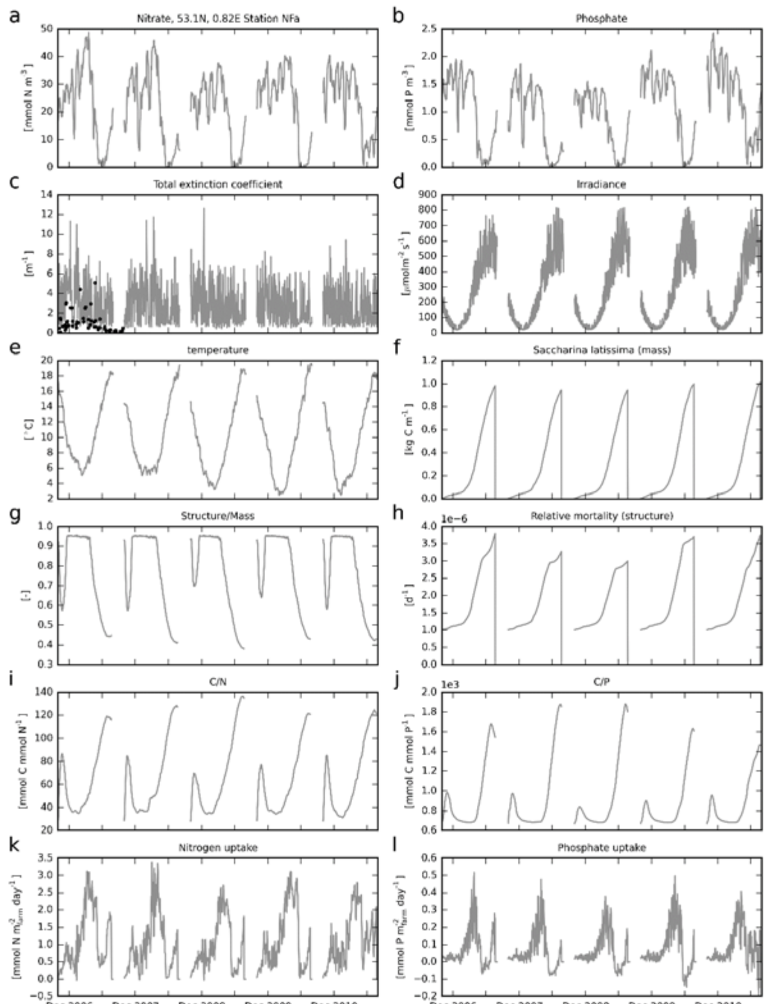

Figure 13. Model results for the western-most grid cell of the north Norfolk farm site. a) surface nitrate concentration; b) surface phosphate concentration; c) total extinction coefficient at the surface (excluding contribution by macroalgae); d) irradiance at the surface; e) surface water temperature; f) macroalgae carbon biomass per m of line; g) mass of macroalgae structure over total macroalgae mass ratio; h) relative mortality of macroalgae structure; i) C/N ratio of macroalgae; j) C/P ratio of macroalgae; k) farm net nitrogen uptake; l) farm net phospate uptake. Black dots in c) are the k_d contribution by SPM, calculated from in-situ SPM samples collected in the years 1996-2000 using the relationship derived by Devlin et al. (2009), and projected onto 2006-2007.

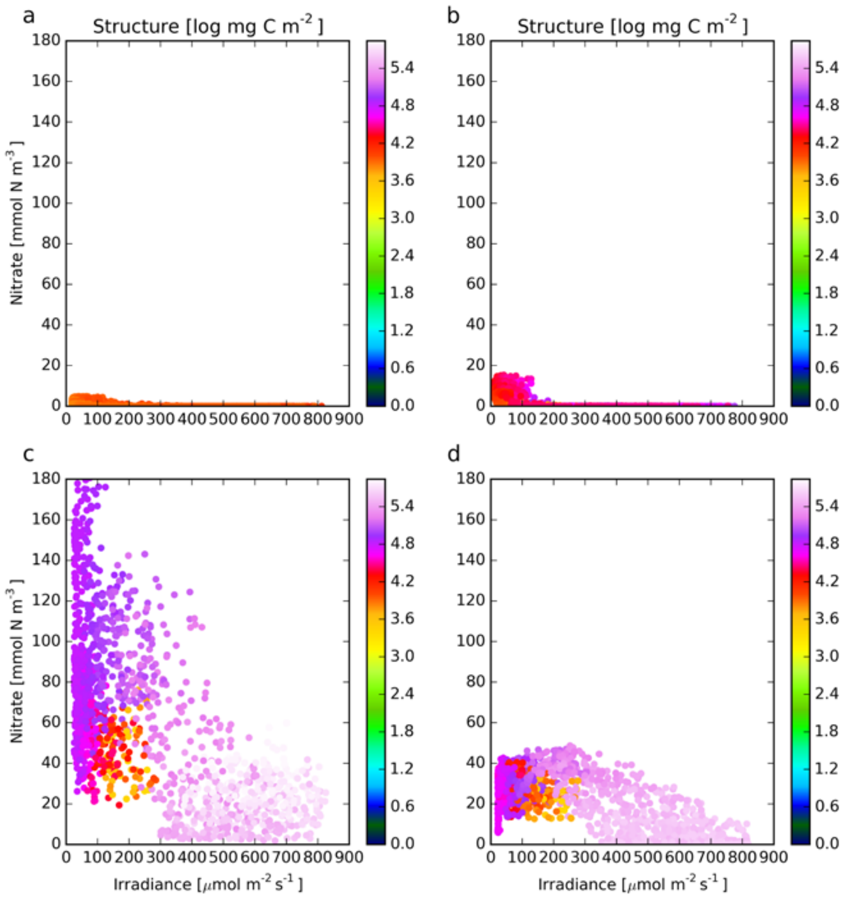

Figure 14. Logarithm of structural biomass as a function of irradiance and nitrate concentrations in the model. a) Strangford Lough farmRhine Plume farm, b) Sound of Kerrera farm, c) Rhine Plume farmStrangford Lough farm, d) Norfolk farm.

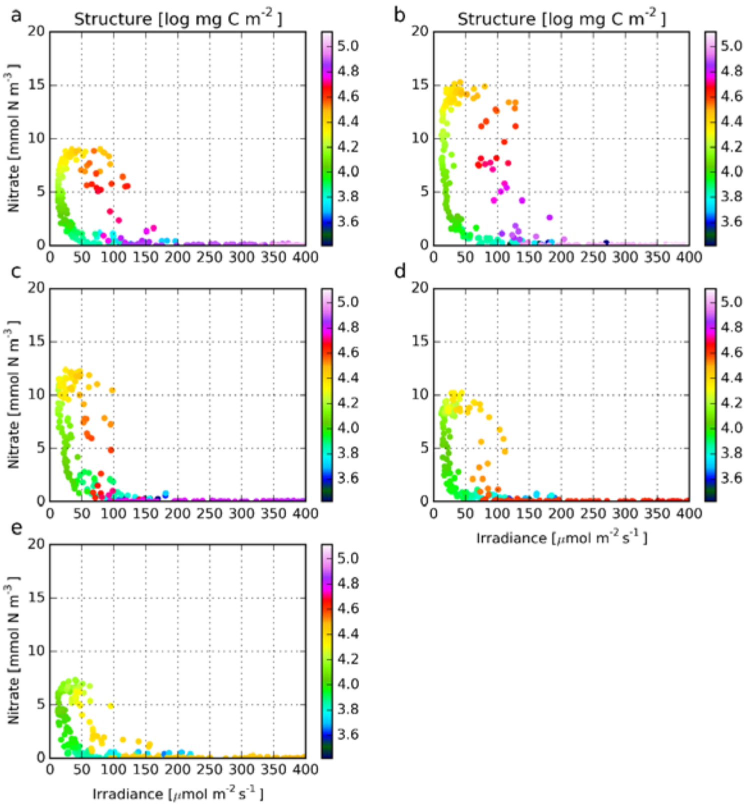

Figure 15. Logarithm of structural biomass as a function of irradiance and nitrate concentrations in the model for the Sound of Kerrera farm. a) 2006, b) 2007, c) 2008, d) 2009, e) 2010.