Additional salmon farms in Tory Channel

an assessment of effects on water-quality using a biophysical model (Oyster Bay, Tipi Bay & Motukina Point)

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Executive summary

The Ministry for Primary Industries (MPI) is investigating the possibility of introducing additional salmon farms into Tory Channel. They have commissioned NIWA to examine the effect of three potential new farms (sited around Oyster Bay, Tipi Bay and Motukina Point, Figure 0-1) on the trophic status of the Tory Channel/Queen Charlotte Sound system using an existing biophysical model (Hadfield, Broekhuizen et al. 2014; Morrisey, Anderson et al. 2015). The intent of the study is work is being carried out with the aim of determining whether the additional farm-derived nutrient will induce unwanted trophic changes to become a frequent/wide-spread [1]phenomenon within the Queen Charlotte/Tory Channel system. We were not provided with clear guidance as to what conditions might be deemed 'unwanted'. We elect to compare the simulation results with various published guideline values (e.g., ANZECC guidelines, and USA guidelines and consent conditions for three NZKS fish-farms which have recently been approved for Pelorus Sound and Tory Channel).

The assessment was made relative to a baseline scenario that includes all currently (2016) approved farms (mussel and fish). There are five such farms: Clay Point, Te Pangu, Ngamahau, Ruakaka and Otanerau. Of these, the first three are within Tory Channel whilst the remaining two are elsewhere in Queen Charlotte Sound. We will refer to this baseline as $baseline_{f2016}$. The $baseline_{f2016}$ is the same baseline adopted in an earlier report to MPI concerning other combinations of salmon farms within Queen Charlotte Sound (Broekhuizen & Hadfield 2015) but differs from the baseline ($baseline_{f2012}$) adopted in an earlier report to Marlborough District Council (Hadfield, Broekhuizen & Plew, 2014). The $baseline_{f2012}$ was a scenario that included only those mussel and fish farms which were operating (i.e., in the water) during 2012. In particular, the newly established Ngamahau salmon farm was not present in the earlier $baseline_{f2012}$ scenario.

[1] Nuisance blooms of toxic algae have occurred within Queen Charlotte/Tory Channel in the past (notably, within Onapua, Opua Bay).

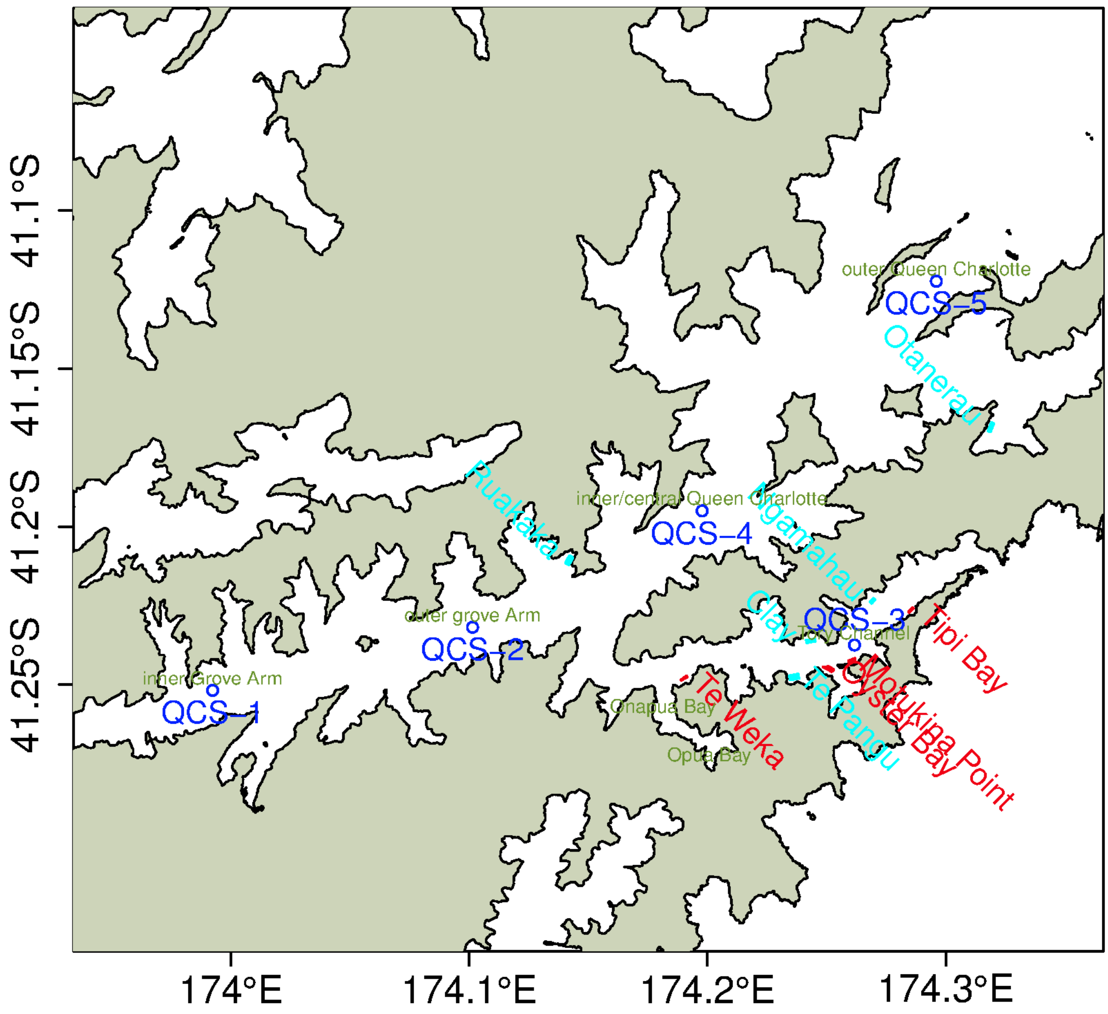

Figure 0-1: Location map for Queen Charlotte Sound and Tory Channel. The existing sites (Otanerau, Ruakaka, Clay Point, Te Pangu and Ngamahau) are shown in cyan. The three potential new sites (Tipi Bay, Oyster Bay and Motukina Point) are shown in red. The Marlborough District Council water-quality sampling sites are marked by blue circles and labelled QCS-1 to QCS-5. We will refer to site QCS-1 as being within 'inner Grove Arm', site QCS-2 as being in 'outer Grove Arm', QCS-3 as being in Tory Channel, site QCS-4 as being in 'inner/central Queen Charlotte' and site QCS-5 as being in 'outer Queen Charlotte'. Opua and Onapua Bays are also indicated.

The model we used to make our simulations is based upon the widely used, open-source ROMS framework and the specific implementation for the Queen Charlotte/Tory system has been subject to review by Marlborough District Council, Cawthron Institute and MPI's Aquatic Environment Working Group. The model has 200 m resolution in the horizontal and twenty layers in the vertical. It is designed to simulate the dynamics effects upon water-quality at the scale of large bays and the Sound as a whole, rather than effects at the scale of individual farms. It accounts for the influences of wind, tides and freshwater inputs on flow. The foodweb of the model contains ammonium, nitrogen, nitrate, phytoplankton (a single class), zooplankton (a single class) and particulate organic detritus (three classes). The phytoplankton are represented in terms of both nitrogen and chlorophyll abundance. A fixed fraction (75%) of any particulate organic detritus which settles to the seabed is assumed to be lost from the system through denitrification. The remainder (25%) returns to the bottom-most layer of the water-column as ammonium. Nitrogen is the only element considered within the foodweb. Our simulations focus upon the direct trophic effects of the fish-farm-derived nitrogen inputs upon the lower components of the planktonic foodweb.

The simulations presented in this report complement earlier work (Broekhuizen and Hadfield 2015), which examined the effect of adding farms in various combinations in the vicinities of Motukina Point, Tipi Bay and Te Weka Bay. In that earlier work, we were instructed to adopt annual feed loads of 2000 tonne for Tipi Bay and 5000 tonne for Motukina and Te Weka. We adopted those loads again for this new report. Following discussion between New Zealand King Salmon, NIWA and MPI we were instructed to adopt an annual feed load of 3000 tonne for the Oyster Bay farm that is introduced for the first time in this report.

We examined four different fish-farming scenarios:

- A 'baseline' scenario (scenario 0, baseline_{f2016}) which contained the five currently approved fish farms (Ruakaka, Otanerau, Clay Point, Te Pangu and Ngamahau) and all currently approved mussel farms. We will use the notation AM_AF_WD (Approved Mussels, Approved Fish farms, With benthic Denitrification).
- Scenario 1 (AM_AF_WD+Tipi2+Oyster3): as for the baseline_{f2016} scenario but also containing candidate fish farms in the vicinities of Tipi and Oyster Bays (respectively, operating at 2000 and 3000 tonne year^{-1} feed input).
- Scenario 2 (AM_AF_WD+Tipi2+Oyster3+Motu5): as for scenario 1 but also containing a fish farm in the vicinity of Motukina Point (operating at 5000 tonne feed year^{-1}).
- Scenario 3 (AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5). This scenario contains four candidate new sites (Tipi Bay, Oyster Bay, Motukina & Te Weka) but drops two existing sites (Ruakaka & Otanerau).

The baseline_{f2016} scenario is plausible in the sense that it includes all the farms that have a consent to operate at the present time, but it does not represent the pattern of farming that has taken place over the past two-three years. This is because the Ngamahau farm was only approved in 2012 and the first cohort of fish did not enter the water until a few months ago.

We made a single simulation for each farming scenario. Each simulation spanned a 500 day period (May 2012 to October 2013). We assessed the effects of the new farms by calculating:
(a) instantaneous differences between the new farm scenario and the baseline_{f2016} scenario; (b) time-averaged instantaneous and relative differences; and (c) by reference to water-quality standards.

The key findings from this work are:

- For ammonium, the largest farm-effects arise in the immediate farm vicinities. Nonetheless, even close to the fish-farms, ammonium concentrations will remain well below levels considered toxic to aquatic life.
- For nitrate and particulate detritus, the largest effects arise in Grove Arm and side bays of Tory Channel, especially Onapua Bay. The explanation is straightforward. Fish farms are net sources of ammonium (directly excreted by the fish), and of particulate organic

nitrogen (faeces and waste feed), which degrades into ammonium. It takes some time for the phytoplankton to fully incorporate the farm-derived ammonium into new biomass. During that time, the water (containing the additional ammonium and seed phytoplankton population) has been transported away from the source farm and subject to dispersive mixing. A similar argument holds with respect to conversion of ammonium into nitrate by bacterial activity. The combination of dispersive mixing and gradual uptake by phytoplankton and bacteria implies that ammonium concentration increases decline with increasing distance from the farm. Conversely, population increases by phytoplankton take time to develop, so phytoplankton and detritus concentration increases tend to be greatest at some distance away from the farms.

- The farms are predicted to have little effect upon phytoplankton, zooplankton and detritus during the winter-months. During those months, algal growth is limited by light rather than nutrients. Thus, the additional nitrogen can only be slowly incorporated into additional biomass. Much of it is exported from the system (to Cook Strait or to the atmosphere through denitrification) before it can be utilized.
- Regardless of which farms are added, the largest relative and absolute summertime changes in phytoplankton abundance tend to arise in Onapua Bay and Grove Arm. The changes in Onapua Bay tend to exceed those in Grove Arm.
- The changes (relative to $\text{baseline}_{\text{f2016}}$) induced by the AM_AF_WD+Tipi2+Oyster3+Motu5 are approximately twice as large as those induced by the AM_AF_WD+Tipi2+Oyster3 scenario.
- The smallest (by total annual feed load) scenario (AM_AF_WD+Tipi2+Oyster3) yields summertime chlorophyll and detritus concentration increases of 2 to 4% in Grove Arm and Onapua Bay. The larger scenario (AM_AF_WD+Tipi2+Oyster3+Motu5) induces chlorophyll and detritus increases of around 4-8% in Grove Arm (and a little more in Onapua Bay).
- Threshold chlorophyll concentrations of 3.5 mg m^{-3} and 5 mg m^{-3} are both relevant in the context of the existing NZKS farms in Queen Charlotte/Tory Channel. With the addition of new fish-farms, instantaneous chlorophyll concentrations will, perhaps, exceed 5 mg m^{-3} more often than they have over the past four years of monitoring, but we believe that such events will remain rare and short-lived. Indeed, we believe they will usually remain below 3.5 mg m^{-3}.

1 Introduction

For a number of years, Queen Charlotte Sound and Tory Channel have each supported two salmon farms (Ruakaka and Otanerau in Queen Charlotte Sound; Clay Point and Te Pangu in Tory Channel). A third farm in Tory Channel (Ngamahau) was approved in 2012 but did not come into operation until a few months ago.

The Ministry for Primary Industries is now seeking to determine whether the Queen Charlotte Sound/Tory Channel (QCS/Tory) system has a capacity to support additional salmon farms. The four proposed farms are all located within Tory Channel in the vicinities of Tipi Bay, Oyster Bay, Motukina Point and Te Weka Bay (Figure 1-1). As a part of their investigations, the Ministry commissioned NIWA to examine the effects that three proposed new farms may have upon the trophic-enrichment-status (water-quality status), using a slightly modified version of our biophysical model of the QCS/Tory system (Hadfield, Broekhuizen et al. 2014).

The crop-fish of the proposed (and existing) fish farms are fed with pelletized food which originates from material outside the Sounds. Whilst almost all of the feed that is delivered into the water is consumed by the crop-fish, much of the nutrient within the food is subsequently excreted into the environment in either solid- (faeces) or dissolved form (e.g., ammonium-nitrogen). Once released into the environment, this nutrient has the potential to fertilize the system – stimulating greater growth of algae and zooplankton etc. This modelling work is being carried out with the aim of determining whether the additional nutrient will induce unwanted trophic changes to become a frequent/wide-spread [2]phenomenon within the Queen Charlotte/Tory Channel system. We were not provided with clear guidance as to what conditions might be deemed 'unwanted'. We elect to compare the simulation results with various published guideline values (e.g., ANZECC guidelines, and USA guidelines and consent conditions for three NZKS fish-farms which have recently been approved for Pelorus Sound and Tory Channel).

The classical description of plankton dynamics in temperate waters (such as the Marlborough sounds) is as follows. During the winter, plant (notably phytoplankton) growth is constrained by low light inputs and low water temperatures. Nutrients that regenerate from (naturally present) decaying (rotting) organic matter tend to accrue because the regeneration rate exceeds the rate at which the slowly growing plants are able to accrue nutrients. As the days lengthen, individual growth rates begin to rise. This is accelerated as the surface waters warm (causing stratification that 'traps' the phytoplankton in the light-rich surface layers). As phytoplankton growth rates (esp. those in the surface layer) rise and their population biomass expands, the total rate of nutrient uptake comes to exceed the rate of regeneration from decaying material. Thus, the pool of readily available inorganic nutrient becomes depleted (esp. in the surface layers). Once the initial pool of nutrient is depleted, further plant growth becomes nutrient-limited and can proceed only as rapidly as additional inorganic nutrient is imported into the location (by means of: slow regeneration from local organic matter, vertical import from the light-poor deeper layers and by horizontal import of nutrient nitrogen from elsewhere (if such nutrient nitrogen is actually available)).

Once incorporated into particulate matter, nitrogen can influence the attenuation of light – hence potential phytoplankton growth rates. Of necessity, significant quantities of nitrogen can only be incorporated into particulate matter when light is plentiful. Thus, during the light-limited winter period, farm-derived nutrient cannot readily be incorporated into plant biomass and there can be

[2] Nuisance blooms of toxic algae have occurred within Queen Charlotte/Tory Channel in the past (notably, within Onapua, Opua Bay).

little effect upon light attenuation. During the summer, phytoplankton can assimilate the nutrient and any biomass increase will influence light attenuation. Whilst this may not materially influence (suppress) depth-integrated primary production, it can lead to suppression of production in deeper water in favour of production in shallower parts.

For farm-derived nitrogen to have a material influence upon the food-web at any given location:

a) The local system must be sensitive/responsive to the additional nitrogen. As noted above, this implies that the system will be more responsive during spring/summer than during late autumn/winter.

b) The farm-derived nitrogen must reach the location/region in question. Material released into Tory Channel tends sweeps up-and-down the channel under the influence of tides, but on longer time-scales there is a tendency to move clockwise into Queen Charlotte. Some of the material entering Queen Charlotte moves toward the head of the Sound (Grove Arm) whilst the remainder movers outward past Long Island and onward to Cook Strait.

c) The farm-derived nutrient must be a significant component of the local system's nutrient budget.

d) The farm-derived nitrogen must remain 'resident' within the region for sufficiently long for the system to be able to respond to it.

There is a tension between (b) and (d). Transport tends to be dominated by currents. Flows into a region are rapidly balanced by outflows Thus, processes which transport nutrient into a region also tend to induce nutrient export. Where import is rapid, the local system may show little trophic response to the imported nutrient – because the nutrient (and any plankton which have grown in response to the nutrient) will be rapidly exported to elsewhere. Where import is very slow, too little nutrient will enter the system over relevant time-scales (days to months) for it to represent a significant component of the local system's budget. Our biophysical model explicitly represents both hydrodynamic transport and biogeochemical transformations. Thus, it provides a tool to examine the net result of the processes and tensions outlined in the preceding text.

The reader should consult Hadfield, Broekhuizen et al. (2014) for a description of the original QCS/Tory model. The minor modifications made since that report are summarized in section 2 of this report and, in more detail, in Broekhuizen, Hadfield et al. (2015), which is a companion report (of Hadfield, Broekhuizen et al. (2014)) describing the corresponding Pelorus Sound model and Broekhuizen,Hadfield (2015). The Queen Charlotte/Tory and Pelorus biophysical models were developed with support from Marlborough District Council, MPI and Government CORE funding. They represent the best tools currently available to determine the water-column effects of aquaculture in these water bodies. They have been subject to external peer review through Council and Aquatic Environment Working Group processes.

The simulations presented in this report complement a preceding work (Broekhuizen and Hadfield 2015), which examined the effects of adding farms (in various combinations) in the vicinities of Motukina Point, Tipi Bay and Te Weka Bay (but not Oyster Bay). The model which we use for this new work remains structurally and parametrically identical to the one that was used for Broekhuizen,Hadfield (2015).

The only changes are: (a) introduction of one new farm (Oyster Bay) and (b) removal of one of the candidate farms that was considered in the previous report (Te Weka Point) from some of the scenarios that we consider in this report. For this report, the Motukina, Tipi and Te Weka farms were assumed to have the same characteristics (temporal patterns of feed load etc.,) as in the preceding report.

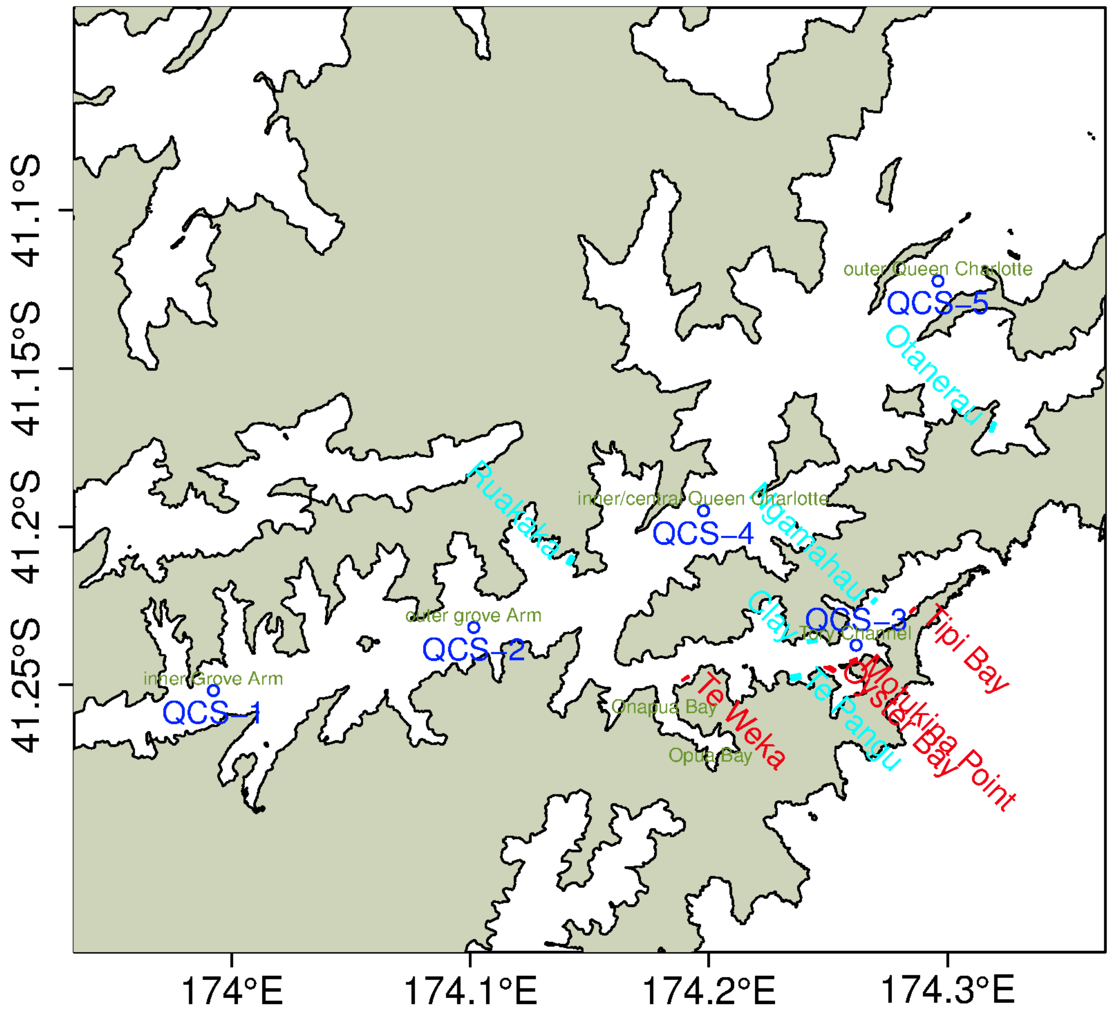

Figure 1-1: Location map for Queen Charlotte Sound and Tory Channel. The existing sites (Otanerau, Ruakaka, Clay Point, Te Pangu and Ngamahau) are shown in cyan. The four potential new sites (Tipi Bay, Oyster Bay, Motukina Point and Te Weka) are shown in red. The Marlborough District Council water-quality sampling sites are marked by blue circles and labelled QCS-1 to QCS-5. We will refer to site QCS-1 as being within 'inner Grove Arm', site QCS-2 as being in 'outer Grove Arm', QCS-3 as being in Tory Channel, site QCS-4 as being in 'inner/central Queen Charlotte' and site QCS-5 as being in 'outer Queen Charlotte'. Opua and Onapua Bays are also indicated.

1.1 Scenarios

For this work, we simulated four different farming scenarios (Table 1-1). In all scenarios, we adopted the 'with denitrification' assumption. That is, we assumed that 75% of any particulate organic nitrogen which settles to the seabed is lost from the system (denitrified). The remaining 25% is instantaneously mineralized to ammonium and returned to the water immediately above the seabed.

Table 1-1: Summary of the four farming scenarios that were simulated. The short-hand codes are as follows: "AM_AF-WD": approved mussels_approved_fish_with_denitrification; "AM_SF_WD": approved mussels_swapped_fish_with_denitrification; "Tipi2": A Tipi Bay fish farm with an annual feed input of 2000 tonne; "Oyster3": an Oyster Bay fish farm with an annual feed input of 3000 tonne: "Motu5": a Motukina Point farm with an annual feed input of 5000 tonne; "Weka5": a farm at Te Weka with an annual feed input of 5000 tonne.

Scenario name	Scenario short-hand code	Description
Baseline$_{f2016}$	AM_AF_WD[3]	Currently allocated mussel- and salmon farm space. In this scenario, all water-space that has already been allocated[4] for mussel farming was assumed to be occupied. Similarly, in addition to the four already operating salmon farms, the newly approved salmon farm in Tory channel (Ngamahau) was assumed to be operating, with an annual feed input of 4000 tonne.
Baseline$_{f2016}$+Tipi2+Oyster3	AM_AF_WD+Tipi2+Oyster3	As for the baseline$_{f2016}$ scenario, but with the proposed Tipi Bay and Oyster Bay farms added (respectively, with an annual feed inputs of 2000 and 3000 tonne).
Baseline$_{f2016}$ +Tipi2+Oyster3+Motu5	AM_AF_WD+Tipi2+Oyster3+Motu5	As for Baseline$_{f2016}$ +Tipi2+Oyster3, but with the proposed Motukina Point farm added (with an annual feed input of 5000 tonne).
Reduced baseline$_{f2016}$ +Tipi2+Oyster3+Motu5	AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5	As for Baseline$_{f2016}$ +Tipi2+Oyster3+Motu5 but with an additional farm at Te Weka Point (5000 tonne annual feed input) and without the present-day Ruakaka & Otanerau farms.

Relative to the AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 scenario, the AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 has fewer farms (it gains the Te Weka farm but loses the Ruakaka & Otanerau ones), but greater nominal total annual feed loads. The AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 has a very similar annual feed load to that of the AM_AF_WD_+Tipi2+Motu5+Weka5 scenario considered within our earlier report (Broekhuizen and Hadfield 2015). Whilst that earlier scenario lacked the proposed Oyster Bay farm, it retained the Otanerau and Ruakaka farms.

[3] AM: approved mussels; AF: approved fish.
[4] Based upon GIS maps provided to us by Marlborough District Council in February 2014.

It is worth noting that whilst the $baseline_{f2016}$ scenario is realistic in the sense that it includes all the farms that presently hold consent to operate, it over-estimates the feed inputs that have been applied within Queen Charlotte Sound/Tory Channel in the recent (or more distant) past. This is because the Ngamahau farm has only received a consent to operate in 2012 and did not introduce any fish into the water until early 2016. Thus, results from the $baseline_{f2016}$ scenario simulation are not directly comparable with the majority of the existing water quality monitoring data. Rather, the $baseline_{f2016}$ scenario is intended to provide an indication of the future water-quality of the system if no further farms are added[5] and existing farms continue to be operated in much the same manner as they have been in the past three-four years.

Table 1-2: Total feed inputs (tonne) associated with the farms of each scenario. The unbracketed figures are totals for the period 1 May 2012 - 31 October 2013. The bracketed figures are those numbers rescaled to 365 days. The values for Otanerau, Ruakaka, Clay Point and Te Pangu are based upon historical data supplied by New Zealand king Salmon. The values for the remaining farms are based upon annual total feed inputs stipulated by the Ministry for Primary Industries (refer to section 2.1 for additional explanation).

	Scenario			
Farm	**AM_AF_WD ($baseline_{f2016}$)**	**AM_AF_WD +Tipi2+Oyster3**	**AM_AF_WD +Tipi2+Oyster3+Motu5**	**AM_SF_WD+Tipi2 +Oyster3+Motu5+Weka5**
Otanerau	2430 (1616)	2430 (1616)	2430 (1616)	
Ruakaka	3124 (1904)	3124 (1904)	3124 (1904)	
Clay Point	6569 (4368)	6569 (4368)	6569 (4368)	6569 (4368)
Te Pangu	6146 (4086)	6146 (4086)	6146 (4086)	6146 (4086)
Ngamahau	6016 (4000)	6016 (4000)	6016 (4000)	6016 (4000)
Tipi Bay		2740 (2000)	2740 (2000)	2740 (2000)
Oyster Bay		4100 (3000)	4100 (3000)	4100 (3000)
Te Weka Point				6849 (5000)
Motukina			6849 (5000)	6849 (5000)
Total	**24285 (15974)**	**31125 (20974)**	**37974 (25974)**	**39269 (27454)**

[5] In earlier work (Hadfield, M., Broekhuizen, N., Plew, D. (2014) A biophysical model of the Marlborough Sounds: part 1: Queen Charlotte & Tory Channel. *NIWA Client Report (for Marlborough District Council)*: 183. http://www.marlborough.govt.nz/Environment/Coastal/Coastal-Reports.aspx#Hydrodynamic
, Broekhuizen, N., Hadfield, M. (2015) Additional salmon farms in Tory Channel - an assessment of effects on water-quality using a biophysical model. *National Institute of Water & Atmospheric Research Ltd. (Client Report)*, HAM2015-039: 95.) it has been shown that a simulation that excludes the Nagamahau farm (such that it better approximates the farming practices that have prevailed whilst MDC have been sampling) tends to over-predict summertime phytoplankton abundances. This over-prediction must be born in mind when interpreting the 'with extra farms' results. Broekhuizen & Hadfield (2015) provide an extensive discussion of the matter.

2 Methods

We used a spatially explicit, three dimensional, coupled biophysical model to simulate the hydrodynamics and water-quality of the QCS/Tory system. The model is an updated version of the one described by Hadfield, Broekhuizen et al. (2014). With the exception of the changed combinations of fish-farms, it is structurally and parametrically identical to the one used in the prior work that examined some of the ramifications of adding fish-farms at Tipi Bay, Te Weka Bay and Motukina Point (Broekhuizen and Hadfield 2015).

Relative to Broekhuizen,Hadfield (2015), the modifications are as follows:

- Revised Cook Strait tidal boundary data.
- An improved representation of the fact that the waste organic matter from mussel farms (faeces and pseudo-faeces) and from fish farms (faeces and uneaten feed) sink very much more [6]rapidly than does the organic detritus that stems from dead phytoplankton etc.

The reader should consult Broekhuizen,Hadfield (2015) for a more detailed description of the changes.

2.1 Farm characteristics

Mussel-farm perimeters were derived from GIS maps provided to us in February 2013 by Marlborough District Council. Fish farm perimeter locations were provided to us by New Zealand King Salmon (Ruakaka, Otanerau, Clay Point, Te Pangu, Ngamahau) and the Ministry for Primary Industries (Tipi Bay, Motikina Point, Oyster Bay). For most of the fish-farms, the prescribed perimeters correspond to the outer-most corners of the pen-arrays but for Oyster Bay we were provided with a shape-file that included the coordinates of the perimeter points for the proposed fish-farm area as described in figure 11 of Anderson,Grange (2013). It is our understanding that these perimeter points represent the perimeter of a proposed licensed area. As such, they approximate the perimeter points of the anchor-field rather than those of a (smaller) polygon drawn around the pen-structures.

Details of mussel farm stocking characteristics and fish-farm stocking characteristics are provided in Hadfield, Broekhuizen et al. (2014). That report also describes the manner in which fish-farm stocking and feed input characteristics were derived. In brief, New Zealand King Salmon Ltd. provided monthly records for their existing farms (Ruakaka, Otanerau, Clay Point, Te Pangu) spanning the calendar period of interest. Data included: estimates of the numbers of living fish and average size of those fish within each cohort in each farm at the beginning and end of each calendar month together with an accompanying cohort-and-farm specific total feed input over the course of the month. We used those data directly (for the existing farms) and also used them as a basis for synthesizing plausible characteristics for the newly established farm (Ngamahau) and for the proposed additional farms (Tipi Bay, Motukina Point, and Oyster Bay). Specifically, we assumed that Ngamahau and Oyster Bay would have stocking characteristics like Clay Point, whereas Tipi Bay and Motukina would have stocking characteristics like Te Pangu. We therefore took the relevant 'template-farm' (Clay or Te

[6] The majority of measured sinking speeds for fish faeces and uneaten feed have been reported to fall within the range 1-10 cm s^{-1} (864 – 8640 m d^{-1}). In contrast, the sinking speed of natural marine particulate organic detritus ranges from 0-several hundred m d^{-1} (Smayda, T.J. (1970) The suspension and sinking of phytoplankton in the sea. *Oceanography and Marine Biology Annual Review*, 8: 353-414.). Within the model, the sinking speeds of the two 'natural' detrital classes are 0.1 m d^{-1} and 1 m^{-1}. In the model, the (implicit) sinking speed of the uneaten feed and fish faces is sufficiently high that all such material will sink to the seabed within the 200 m x 200 m water-column in which the material is generated by the farm.

Pangu) characteristics and rescaled the monthly fish numbers and feed-inputs, so that the implied annual feed-loads would match the maximum feed input rates for the four farms (per annum: Ngamahau: 4000 tonne; Tipi Bay: 2000 tonne; Oyster Bay: 3000 tonne; Motukina Point: 5000 tonne). Those proposed annual total feed inputs for the potential new farms (Tipi, Oyster and Motukina) were provided by the Ministry for Primary Industries in consultation with New Zealand King Salmon Ltd.

2.2 Analysis and presentation of results

We carried out our biophysical simulations on a 200 m resolution horizontal grid. At this resolution, the detailed structures of individual fish farms and mussel farms cannot be not resolved[7]. Similarly, the very steep but rapidly changing concentration gradients that may occur along the outer perimeter of the pen-system cannot be resolved. However beyond, say, a few hundred meters from any farm, we believe that natural mixing will have eroded any steep gradients induced by the farms to a sufficient degree that the grid spacing will resolve spatial gradients adequately. Thus, in the far-field the simulated concentration patterns will be much less subject to model bias.

Simulation results at the locations of each of the five Marlborough District Council sampling sites (Figure 1-1) were stored at approximately 6 minute resolution. In addition, the 12-hour averaged concentrations for every control-volume were stored.

We treat the AM_AF_WD scenario as our 'baseline$_{f2016}$' scenario. We present simulation results in two manners. Firstly, as time-series of (a) near-surface concentration measured at each of the five Marlborough District Council monitoring stations, (b) concentration relative to the baseline$_{f2016}$ at these stations and (c) concentration difference (from the baseline$_{f2016}$) at these stations. Secondly, we illustrate the predicted influences which the various alternative scenarios have upon water-quality (relative to the baseline$_{f2016}$ one), by means of false colour maps that illustrate time-averaged spatial patterns. We define two time-averaging periods: "spring/summer" (2012-09-15 – 2013-02-28, days 114-280 of the simulation period) and "winter" (2013-05-01 – 2013-08-31, days 342-464 of the simulation period).

Each figure will contain six rows and each row will contain three panels (maps). Each panel is a map of the model's horizontal domain. Pixel colour at any location within the map is indicative of the numerical value of the property[8] in question at the pixel-location (yellow/red being 'high', and blue being 'low'). The colour-scheme is designed to yield 'pleasing' colours that allow differences to be distinguished readily. **The colours should not be interpreted as indicative of whether or not the magnitude of change might be deemed 'acceptable'. For example, 'green' should not be deemed to imply 'safe/acceptable' and 'red' should not be interpreted as meaning 'unsafe/unacceptable'.** The numerical range spanned by the colour-scale differs for each variable that we plot. Thus, when comparing maps of different properties, one must recognise that any specific colour does not necessarily equate to the same numerical value in both maps.

Each row corresponds to a different model state-variable (i.e., ammonium, nitrate, etc., – as indicated in the title above the left-hand-most panel of each row). Specifically, the left-hand most

[7] That is, individual mussel lines or fish pens are not explicitly present within the model. The total mussel (or fish) crop associated with each marine farm license is apportioned across those 200 x 200 m water-columns that contain any part of the water-space contained within the consented perimeter of the farm. A farm's crop is distributed across the grid-cells which contain any part of the farm in proportion to the ratio of (farm-area-within-grid-cell/total-area-enclosed-within-grid-cells-that-are-partially-or-wholly-occupied-by-this-farm).

[8] In this context, *property* is used as a convenient short-hand to refer to the time-averaged absolute or relative concentration for a particular state-variable.

panel will show a time-averaged concentration for the state-variable under a reference scenario (usually, the baseline$_{f2016}$ scenario, AM_AF_WD). The panels within the central column illustrate the time-averages of relative concentration R_{p} for other scenarios. For example, the central column may show results from the baseline$_{f2016}$+Tipi2+Oyster3 scenario relative to the baseline$_{f2016}$ one. The time-average of relative concentration is calculated as:

Equation 2-1: Definition of relative concentration

$$R_p = 1 + \frac{1}{N}\sum_{n=1}^{N}\frac{P_{\mathrm{n}}^{\mathrm{a}} - P_{\mathrm{n}}^{\mathrm{ref}}}{\varepsilon + P_{\mathrm{n}}^{\mathrm{ref}}}$$

where *N* is the number of time-levels involved in the time-average, ε=10^{-100} (present to avoid the possibility of a division by zero), while P_n^{ref} and P_n^{a} represent the simulated 12-hour average concentration P at time-level n in the reference (P_n^{ref}) and alternative (P_n^{a}) scenarios. In other words, the relative concentration is 1 plus the average fractional difference from the reference. If, on average, the alternative scenario gives lower concentrations than the reference one, the relative concentration will be less than 1; if higher it will be greater than 1. Note that the percentage change can be derived from the relative concentration, by subtracting 1.0. Thus, $R_p = 1.1$ implies that the concentration in the 'alternative scenario' exceeds that in the 'reference scenario' by 10%. Conversely, $R_p = 0.9$ implies that the concentration in the alternative scenario is 90% of that of the reference scenario (ie a 10% reduction relative to the reference scenario).

The right hand column of panels presents maps of the time-average of the instantaneous concentration differences. Zero indicates no change, negative values indicate that the alternative scenario is yielding lower concentrations than the reference simulation (left-hand most image) and positive values indicate the alternative simulation is yielding larger concentrations. Header text above each figure serves as a reminder to the reader of what each of the three panels within each row represent. Concentration difference is calculated as:

$$D_p = \frac{1}{N}\sum_{n=1}^{N}\left(P_{\mathrm{n}}^{\mathrm{a}} - P_{\mathrm{n}}^{\mathrm{ref}}\right)$$

A positive difference implies that, in the time-average, the alternative scenario yields a higher concentration than the reference scenario.

As defined above, both the relative concentrations and the concentration differences are calculated by comparison to a reference simulation rather than by comparison to a reference condition that has been established from field measurements. One implication is that if the model over-predicts the concentration of a property in the reference (relative to defined by field data from a corresponding real-world field situation), then the magnitude of any resultant relative change associated with an alternative scenario will be under-estimated (assuming that the model correctly predicts the magnitude of concentration change induced by the farms of the alternative scenario). Conversely, if the model under-predicts the concentration of a property in the reference simulation, then the magnitude of any resultant relative change associated with an alternative scenario will tend to be under-estimated.

Marlborough District Council have sampled water quality in Queen Charlotte/Tory on a monthly basis since July 2011. Our baseline$_{f2016}$ scenario includes a newly established fish farm at Ngamahau. For most of the time that MDC have sampled, that farm has not operated. Thus, the simulation results from the 'baseline$_{f2016}$' simulation should not be compared directly with the MDC field data. In earlier work (Hadfield, Broekhuizen et al. 2014; Broekhuizen and Hadfield 2015) it has been shown that a simulation which excludes the Ngamahau farm (such that it better approximates the farming practices that have prevailed whilst MDC have been sampling) tends to over-predict summertime phytoplankton abundances. This over-prediction must be borne in mind when interpreting the 'with extra farms' results. Broekhuizen & Hadfield (2015) provide an extensive discussion of the matter.

3 Results

Within the sub-sections of this section, we show results from the three candidate 'future scenarios' in comparison with the baseline$_{f2016}$ scenario. Specifically, within Section 3.1 we show the predicted time-series of state-variable concentrations at each of the five Marlborough District Council water-quality monitoring stations (Figure 1-1). Within section 3.2, we show maps of the time-averaged relative concentration change and time-averaged concentration differences associated with each scenario.

3.1 Time-series at the Marlborough District Council stations

Figure 3-1 to Figure 3-5 illustrate the time-series of simulated concentrations of each model state-variable in the upper-most layer of each water-column at each of the five Marlborough District Council water-quality sampling stations. They show results for the baseline$_{f2016}$ scenario and the two alternative scenarios. The same simulation results are plotted as time-series of relative concentration in Figure 3-6 to Figure 3-10 and as concentration difference in Figure 3-11 to Figure 3-15.

The key messages are:

- There is marked high-frequency (tidal), medium-frequency (weather-scale) and low-frequency (seasonal-scale & farm-production time-scale) variability in all simulations and for all scenarios. The amplitudes and phases of these variations remain similar in all scenarios. The tidally induced variability is most marked in Tory Channel and least evident in inner Grove Arm (compare, for example, Figure 3-1a and Figure 3-3a).
- The concentrations changes (absolute and relative) induced by the AM_AF_WD+Tipi2+Oyster3+Motu5 scenario are approximately twice as large as those induced by the AM_AF_WD+Tipi2+Oyster3 (compare the elevations of the yellow and pink lines in any of the images within Figure 3-6 - Figure 3-10).
- It is the AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 scenario that tends to induce greatest enrichment throughout Tory Channel (QCS-3), inner- and central Queen Charlotte (QCS-1, QCS-2, QCS-4). Within outer Queen Charlotte (QCS-5), the situation is less clear-cut. Ammonium and nitrate concentrations are often less than those of even the baseline$_{f2016}$ scenario. Phytoplankton concentrations are sometimes less than those of the baseline$_{f2016}$ scenario but sometimes greater than in any other scenario). Concentrations of detritus and zooplankton are almost always greatest in the AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 scenario.
- For ammonium, the largest relative changes arise within Tory channel (compare Figure 3-8a, with other 'a' panels in Figures 3-6, 3-7, 3-9 & 3-10). There, the dominant time-scale of fluctuation appears to be the tidal one. At the monitoring station in Tory Channel, it is the AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 scenario that tends to induce the greatest ammonium enrichment. Peak ammonium concentration increases in this scenario frequently exceed 30% of the baseline$_{f2016}$ concentration (and, on rare occasions are more than double those of the baseline$_{f2016}$ scenario). (Figure 3-8a).

- For the remaining state-variables, the largest absolute and relative changes tend to occur at more distant (from the farms) monitoring stations. Tidally induced variability is of lesser magnitude than longer time-scale variability (compare, for example, the chlorophyll increments arising at any of the four Queen Charlotte stations (QCS-1, 2, 4 & 5) with those arising in Tory Channel (QCS-3) – as evident in Figure 3-11d - Figure 3-15d.
- For nitrate, phytoplankton, chlorophyll, detritus and zooplankton, the stations which tend to show the largest changes are QCS-1 & QCS-2 (inner & outer Grove Arm). There, during the summer months, nitrate concentrations are predicted to rise by 10-20% (sometimes more) in the AM_AF_WD+Tipi2+Oyster3+Motu5+Weka5 scenario (Figure 3-6b, Figure 3-7b). Phytoplankton concentrations are predicted to rise by up to about 15% Figure 3-6c,d, Figure 3-7c,d, detrital concentrations by around 5% (Figure 3-6e,f, Figure 3-7e,f) and zooplankton concentrations by up to about 40% (Figure 3-6g, Figure 3-7g).
- The three alternative scenarios induce concentration changes that are small in comparison with the seasonal scale variability and the baseline$_{f2016}$ standing stocks (Figure 3-1a - Figure 3-10g).
- The concentration changes induced by the two alternative scenarios are of similar magnitude to the weekly-scale variability in the baseline$_{f2016}$ scenario, but unlike the weekly scale variability, the farm-induced change is almost invariably in one direction (a concentration increase).

3.1.1 Time-series of concentration

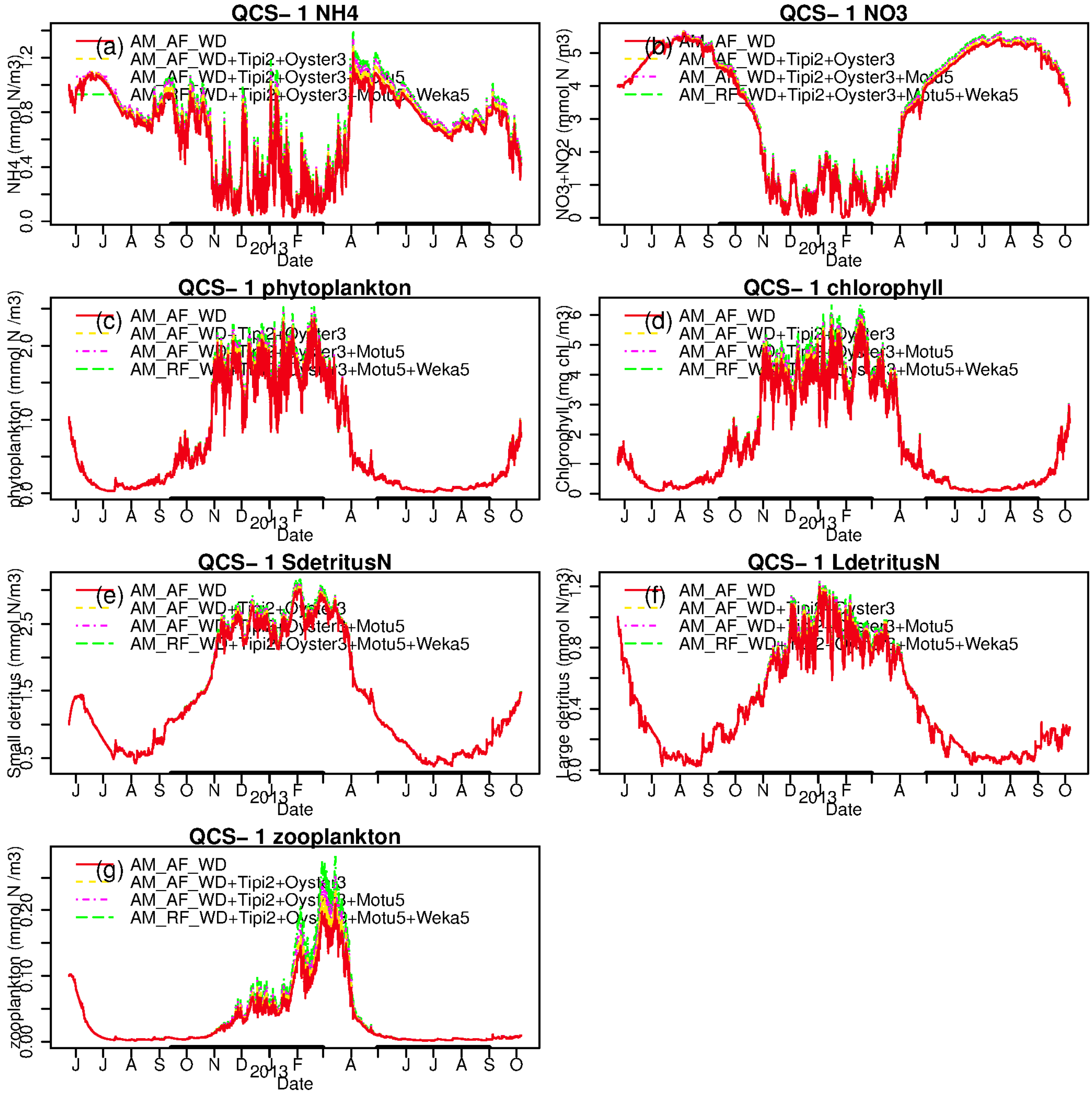

Figure 3-1: Simulated dynamics of water-quality state-variables in the uppermost layer at station QCS-1 (inner Grove Arm) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

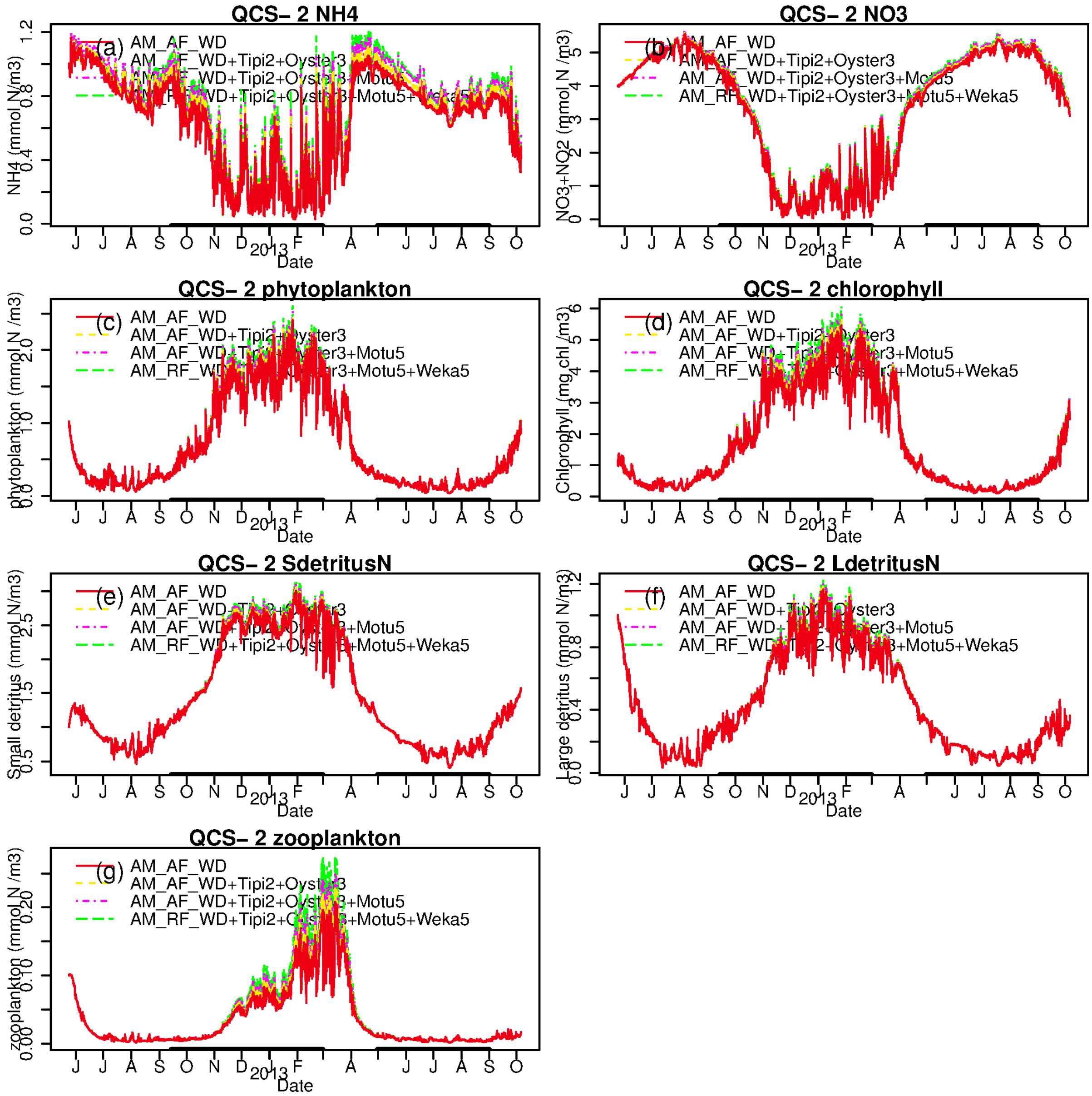

Figure 3-2: Simulated dynamics of water-quality state-variables in the uppermost layer at station QCS-2 (outer Grove Arm) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

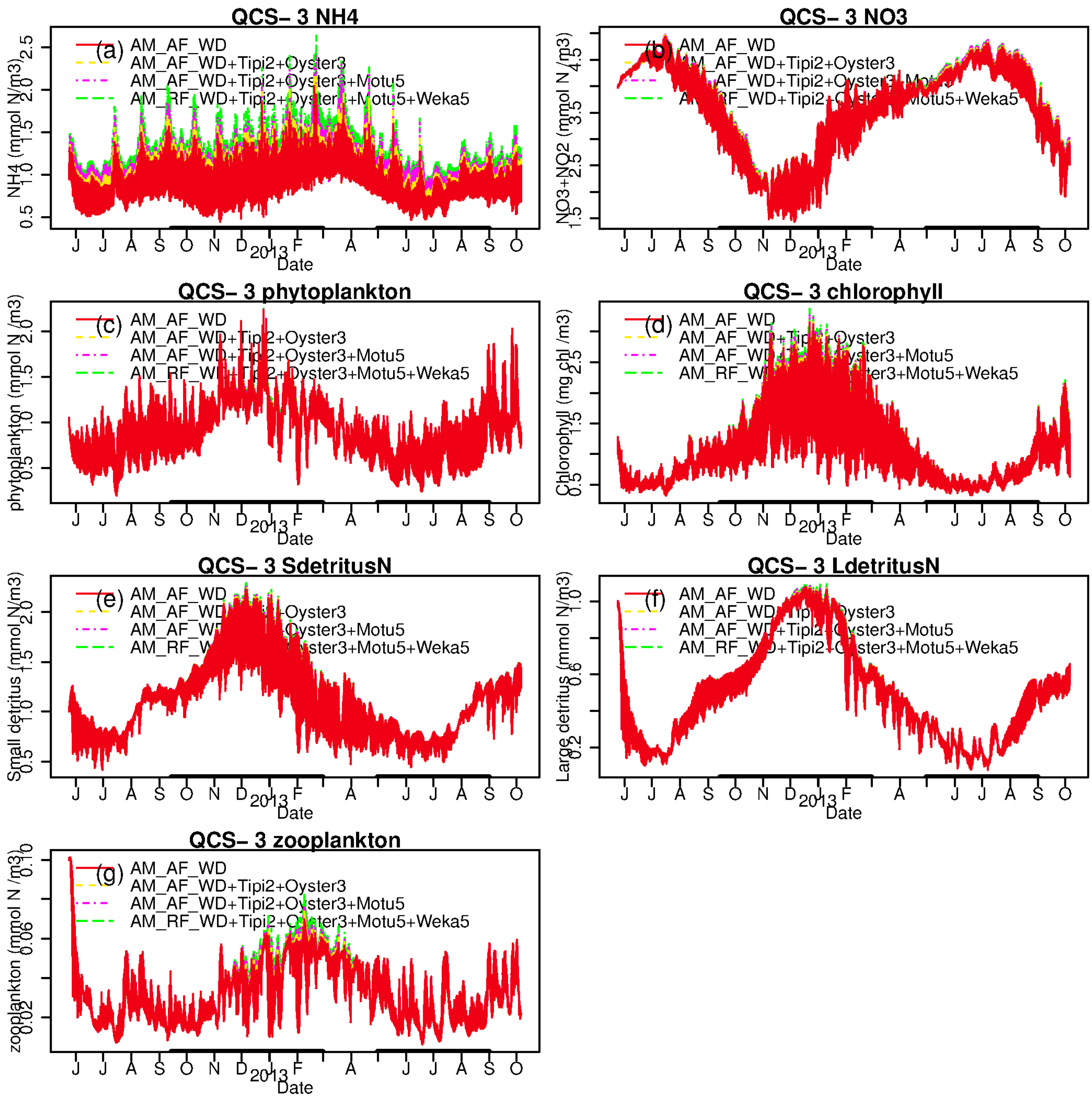

Figure 3-3: Simulated dynamics of water-quality state-variables in the uppermost layer at station QCS-3 (Tory Channel) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

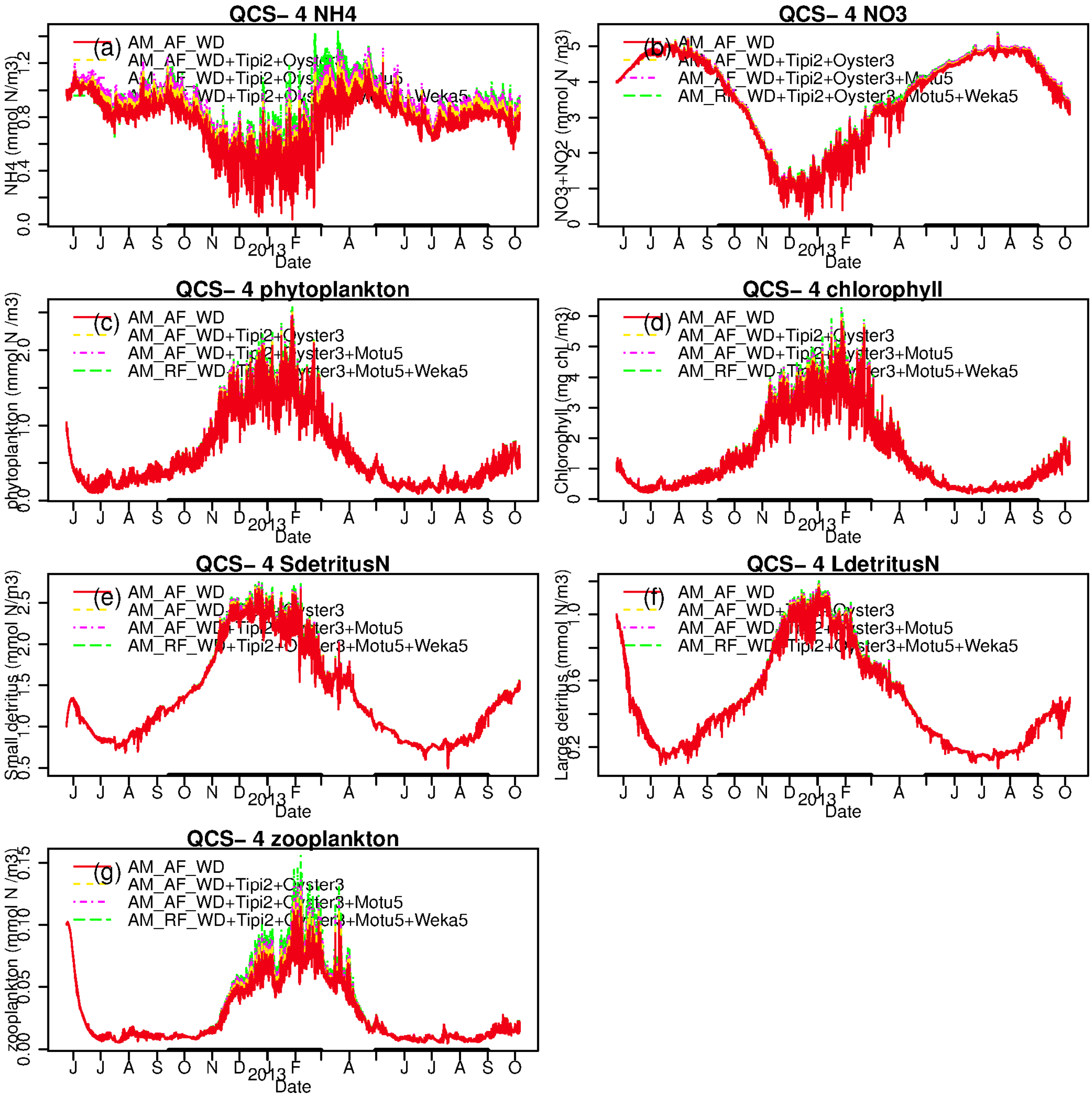

Figure 3-4: Simulated dynamics of water-quality state-variables in the uppermost layer at station QCS-4 (central Queen Charlotte) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

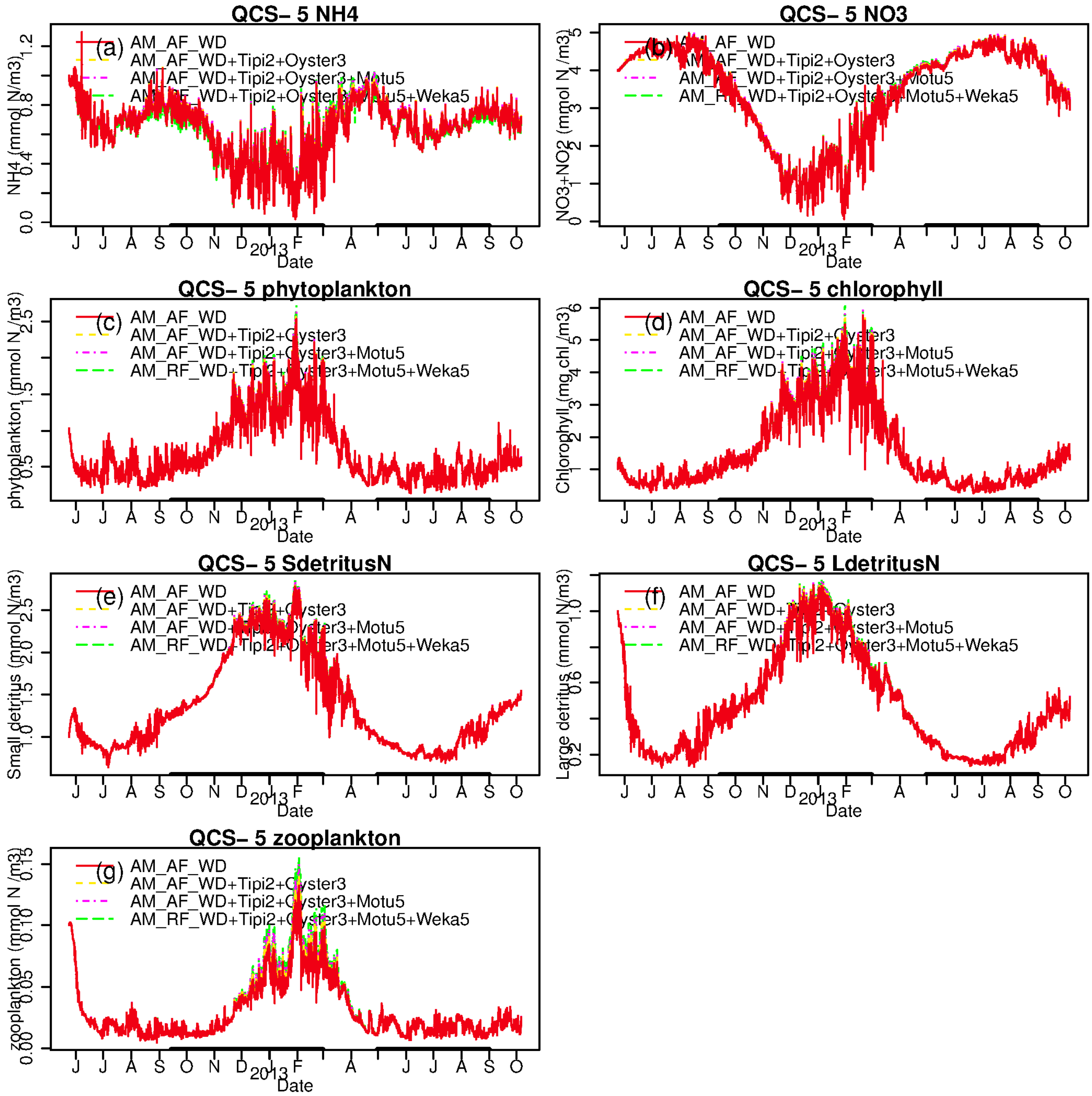

Figure 3-5: Simulated dynamics of water-quality state-variables in the uppermost layer at station QCS-5 (outer Queen Charlotte) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

3.1.2 Time-series of relative concentration

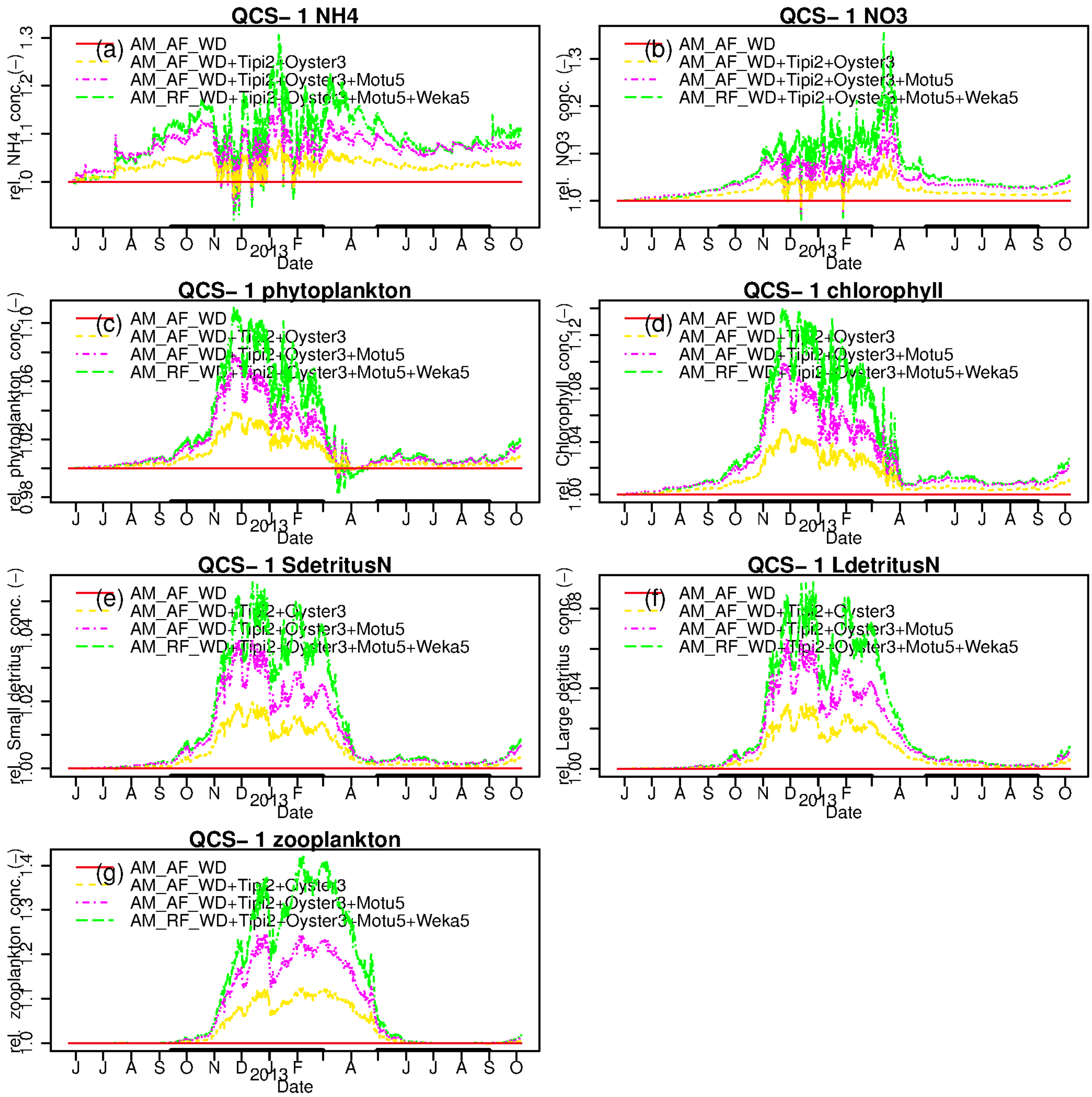

Figure 3-6: Simulated dynamics of water-quality (relative concentration) in the uppermost layer at station QCS-1 (inner Grove Arm) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

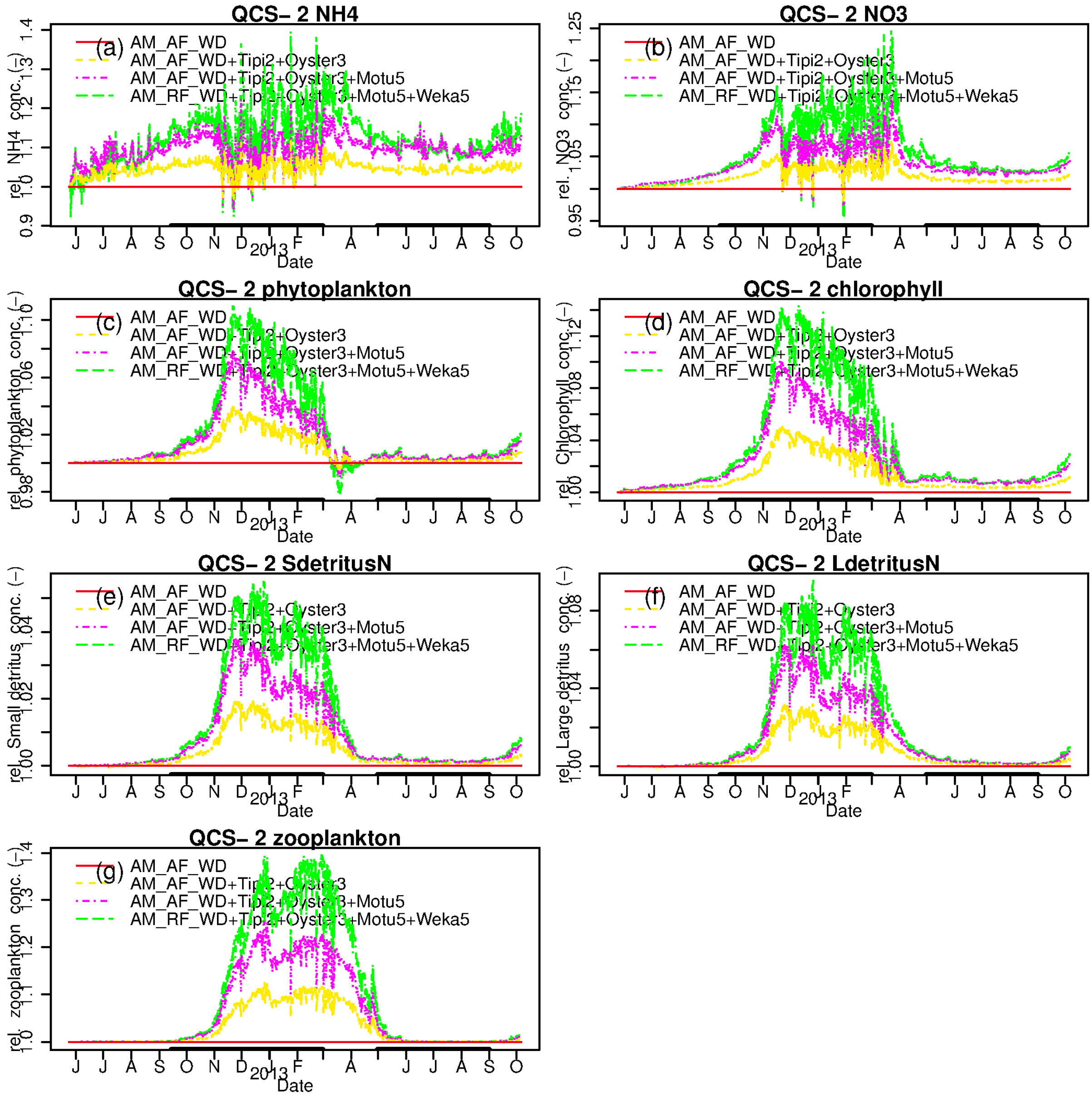

Figure 3-7: Simulated dynamics of water-quality (relative concentration) in the uppermost layer at station QCS-2 (outer Grove Arm) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

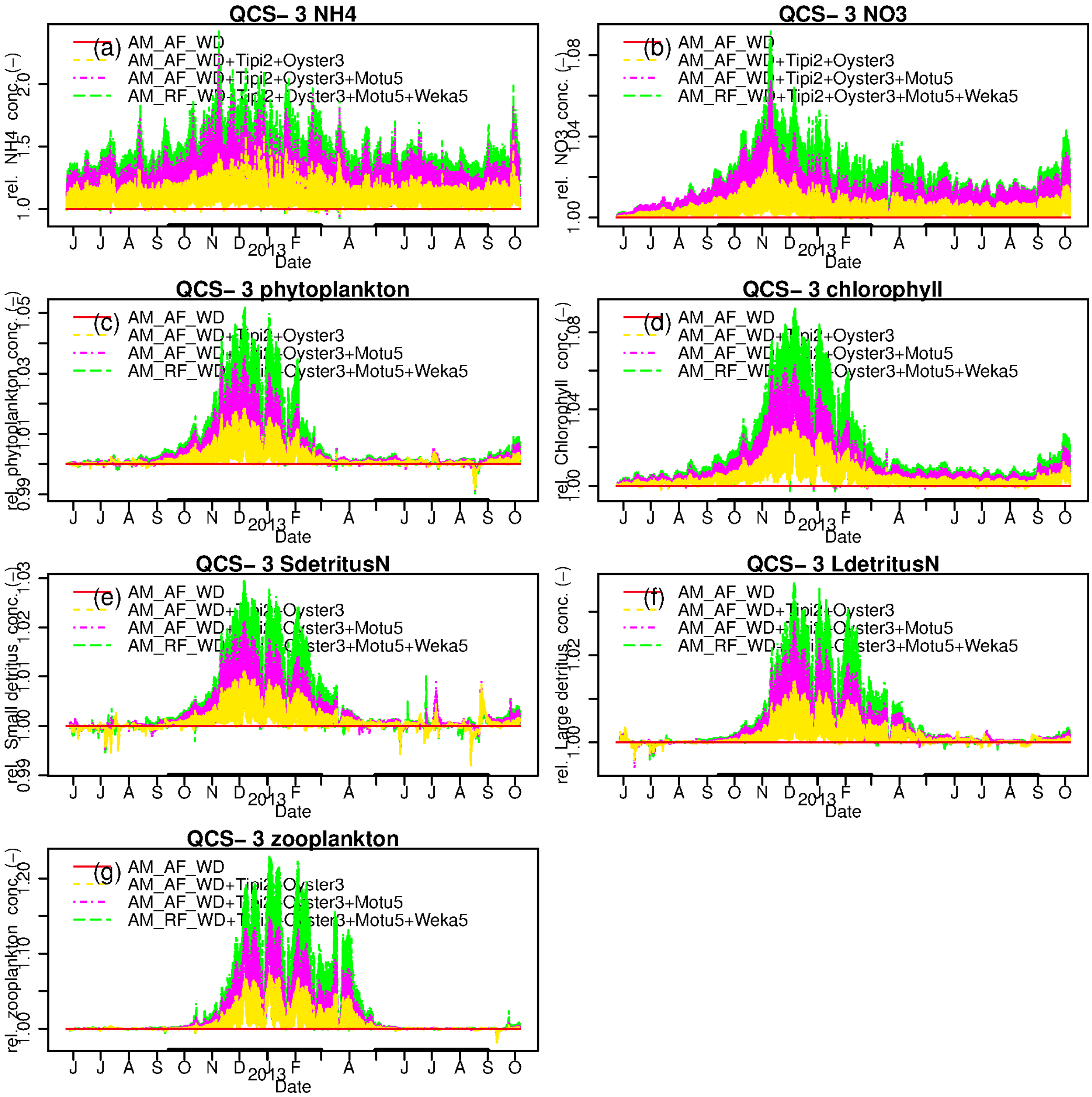

Figure 3-8: Simulated dynamics of water-quality (relative concentration) in the uppermost layer at station QCS-3 (Tory Channel) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

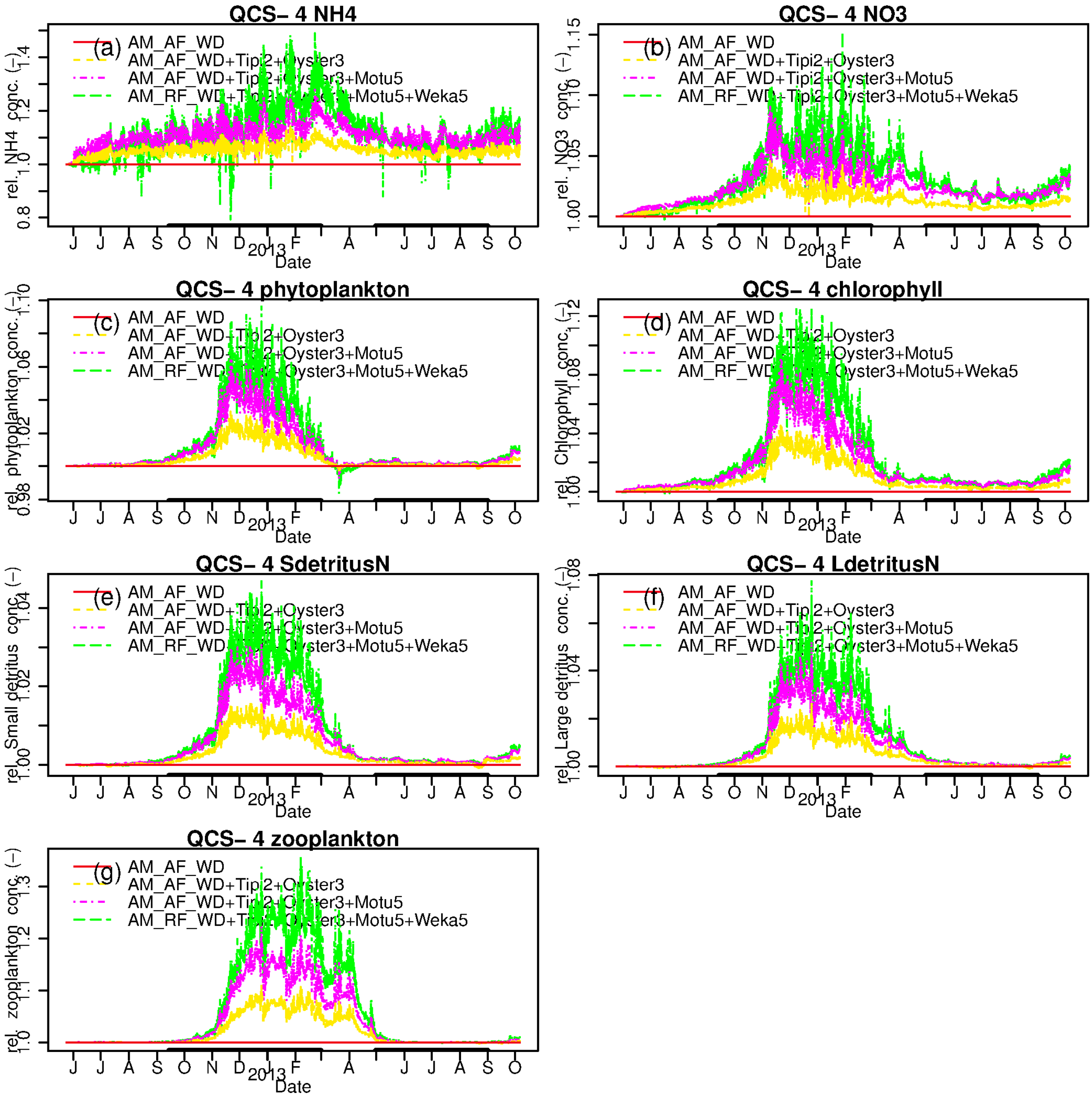

Figure 3-9: Simulated dynamics of water-quality (relative concentration) in the uppermost layer at station QCS-4 (central Queen Charlotte) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

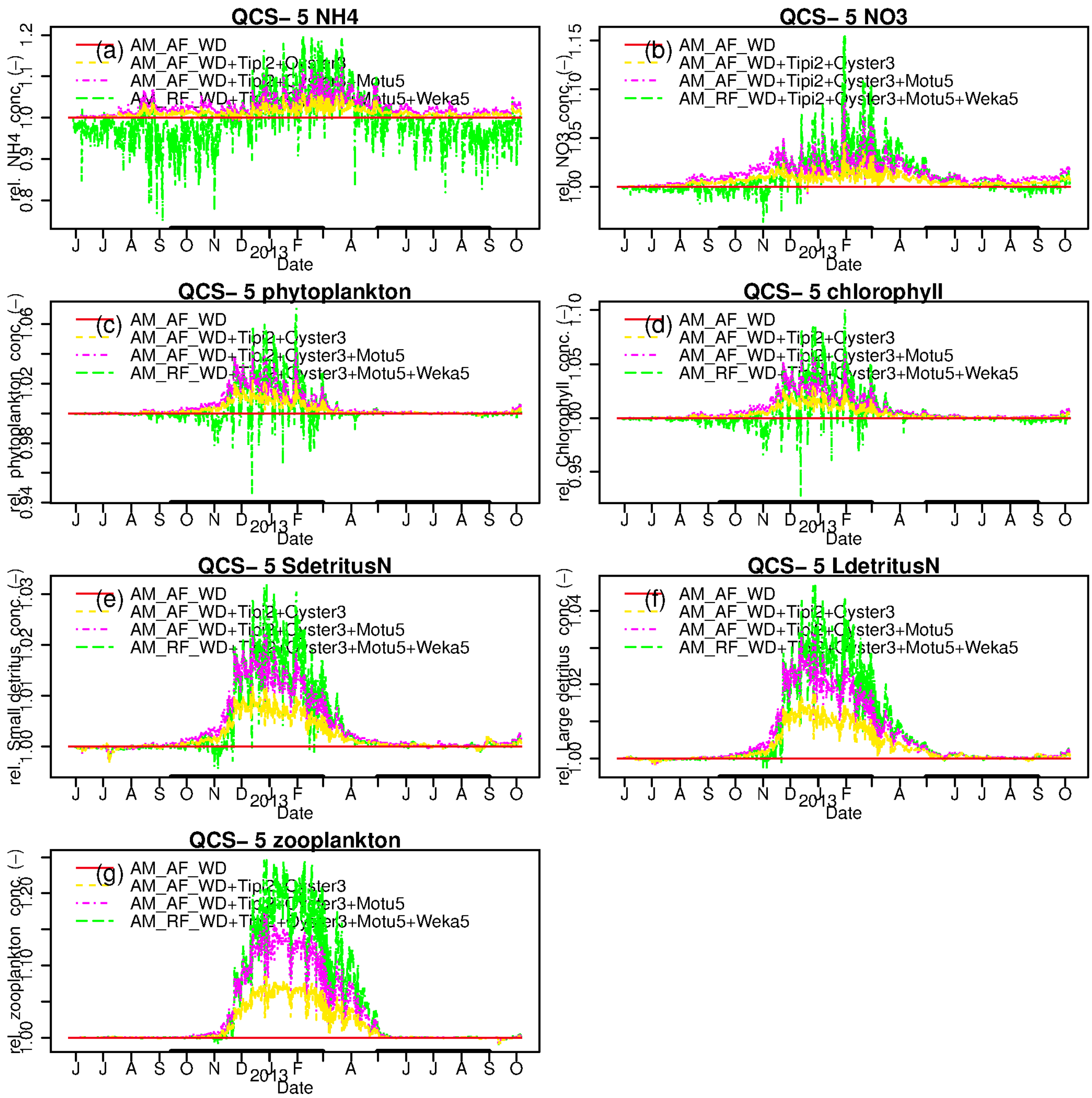

Figure 3-10: Simulated dynamics of water-quality (relative concentration) in the uppermost layer at station QCS-5 (outer Queen Charlotte) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

3.1.3 Time-series of concentration difference

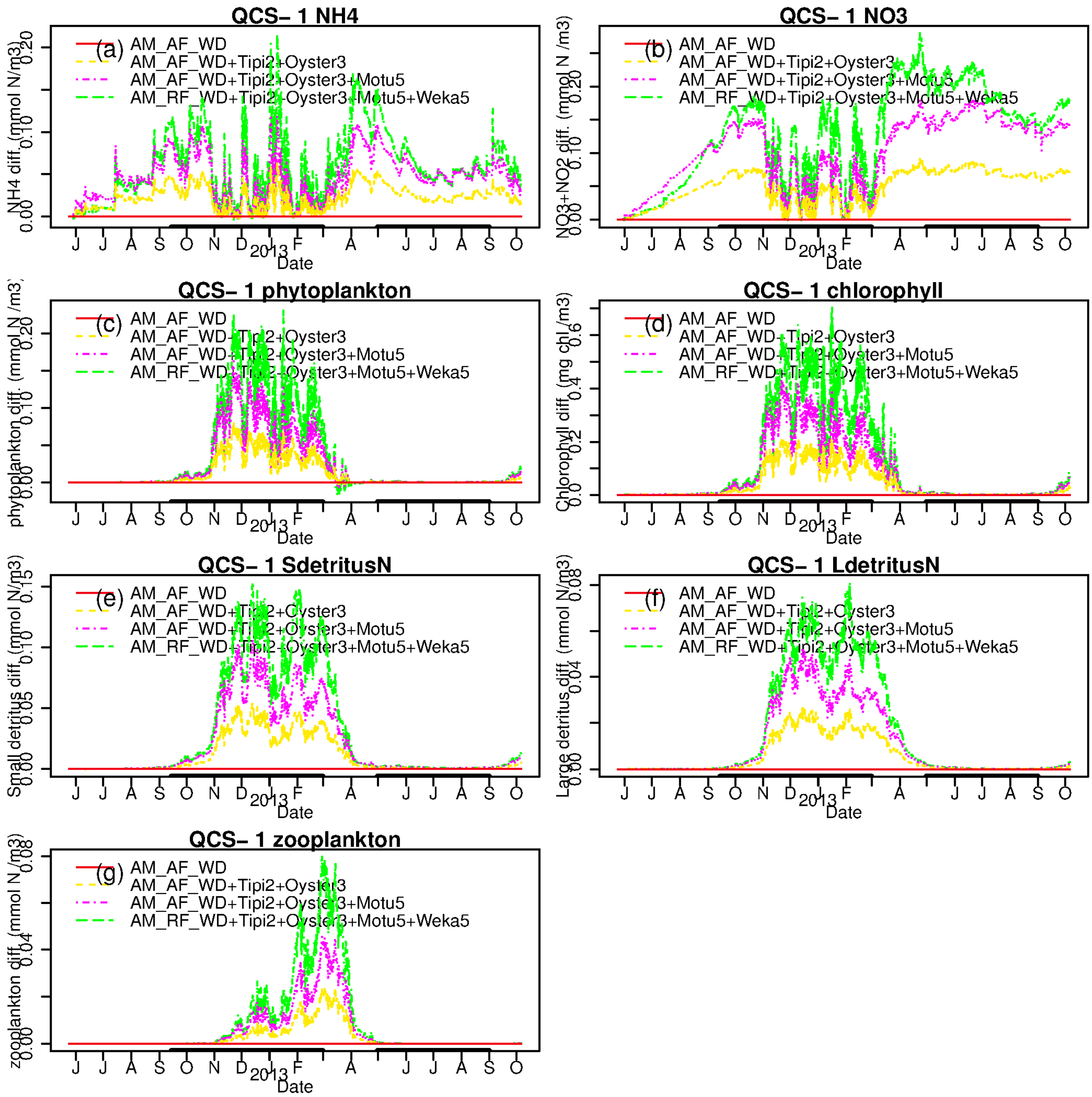

Figure 3-11: Simulated dynamics of water-quality concentration differences in the uppermost layer at station QCS-1 (inner Grove Arm) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

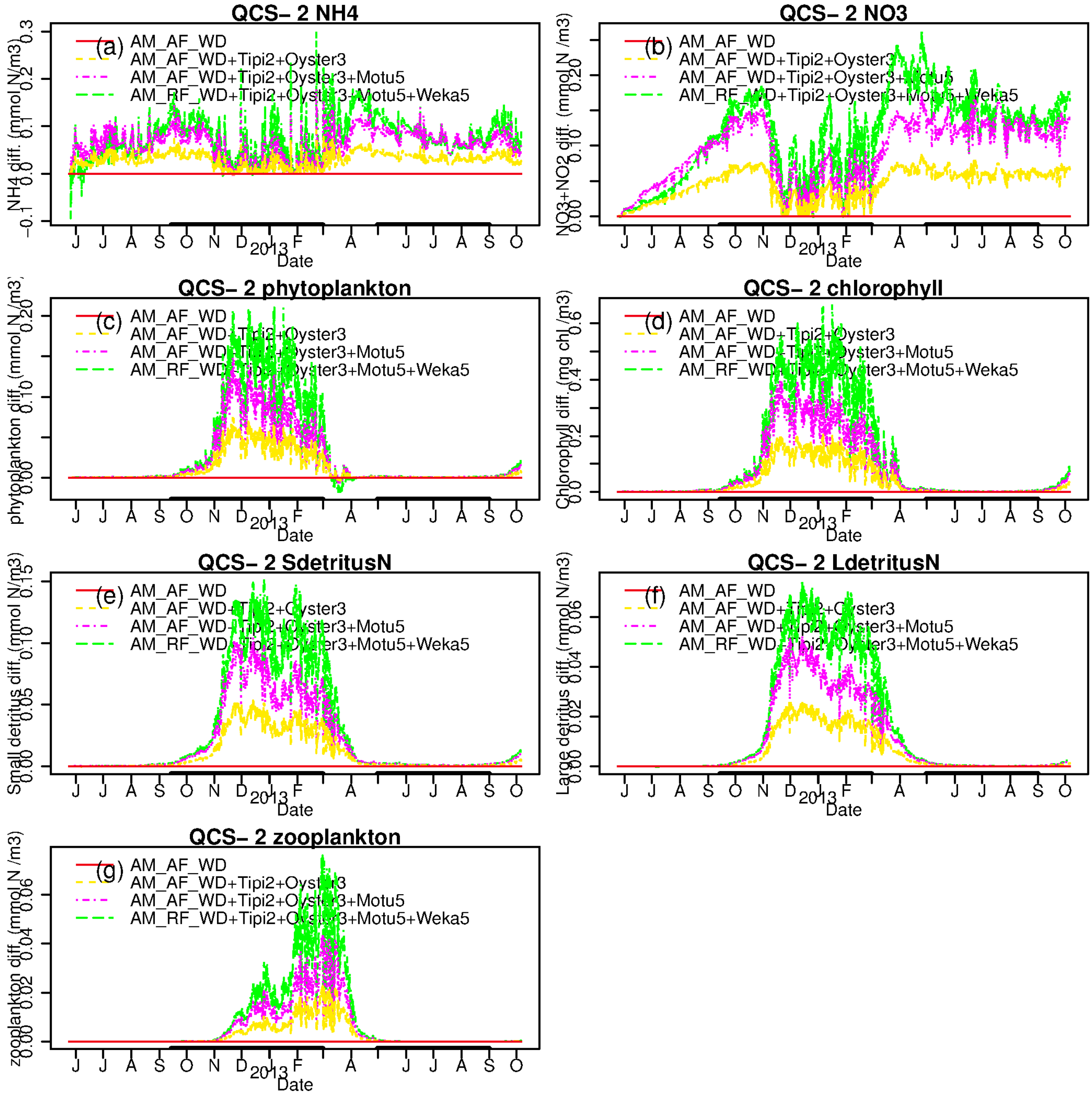

Figure 3-12: Simulated dynamics of water-quality concentration differences in the uppermost layer at station QCS-2 (outer Grove Arm) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

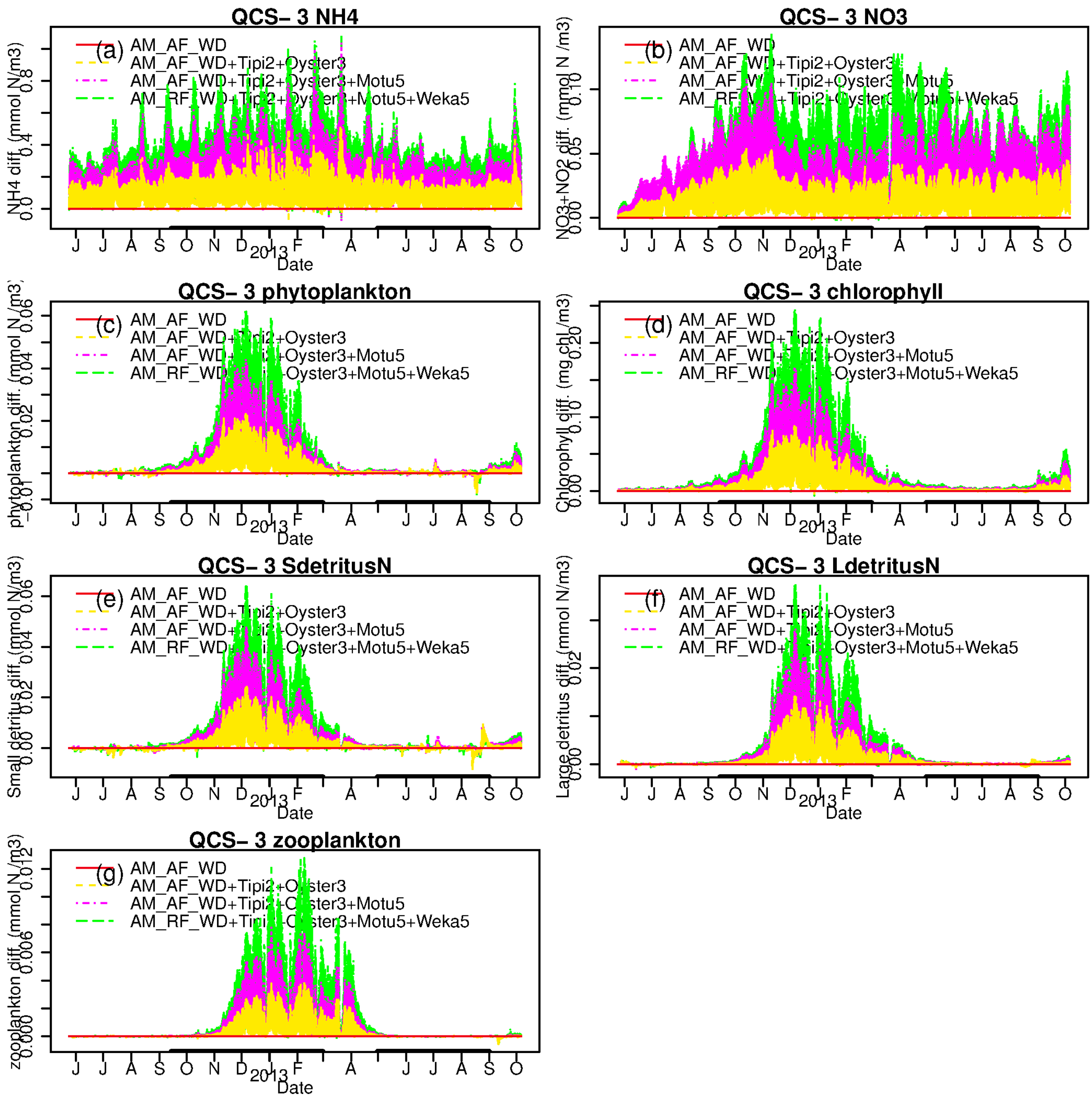

Figure 3-13: Simulated dynamics of water-quality concentration differences in the uppermost layer at station QCS-3 (Tory Channel) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to thef2016scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

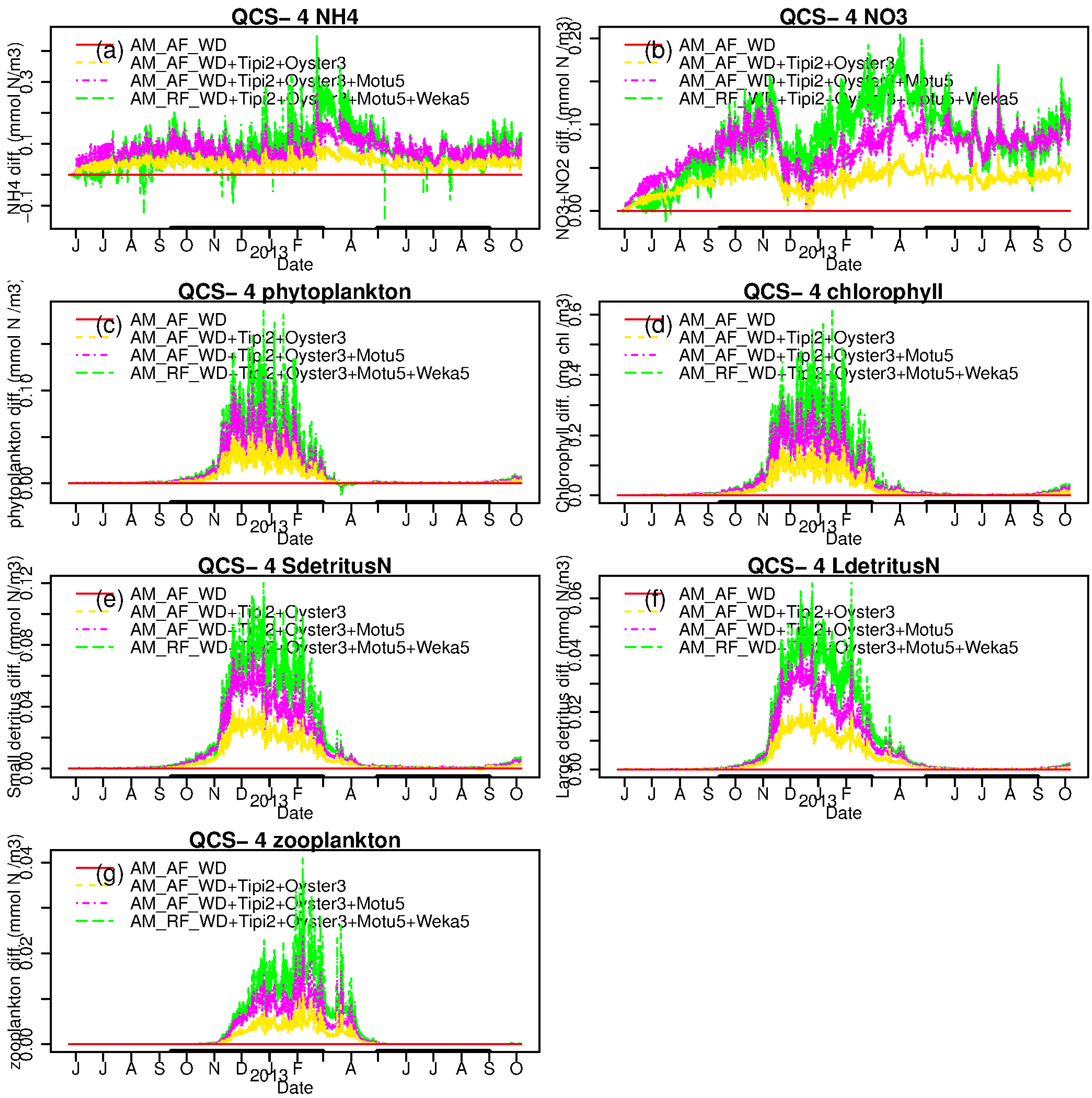

Figure 3-14: Simulated dynamics of water-quality concentration differences in the uppermost layer at station QCS-4 (central Queen Charlotte) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

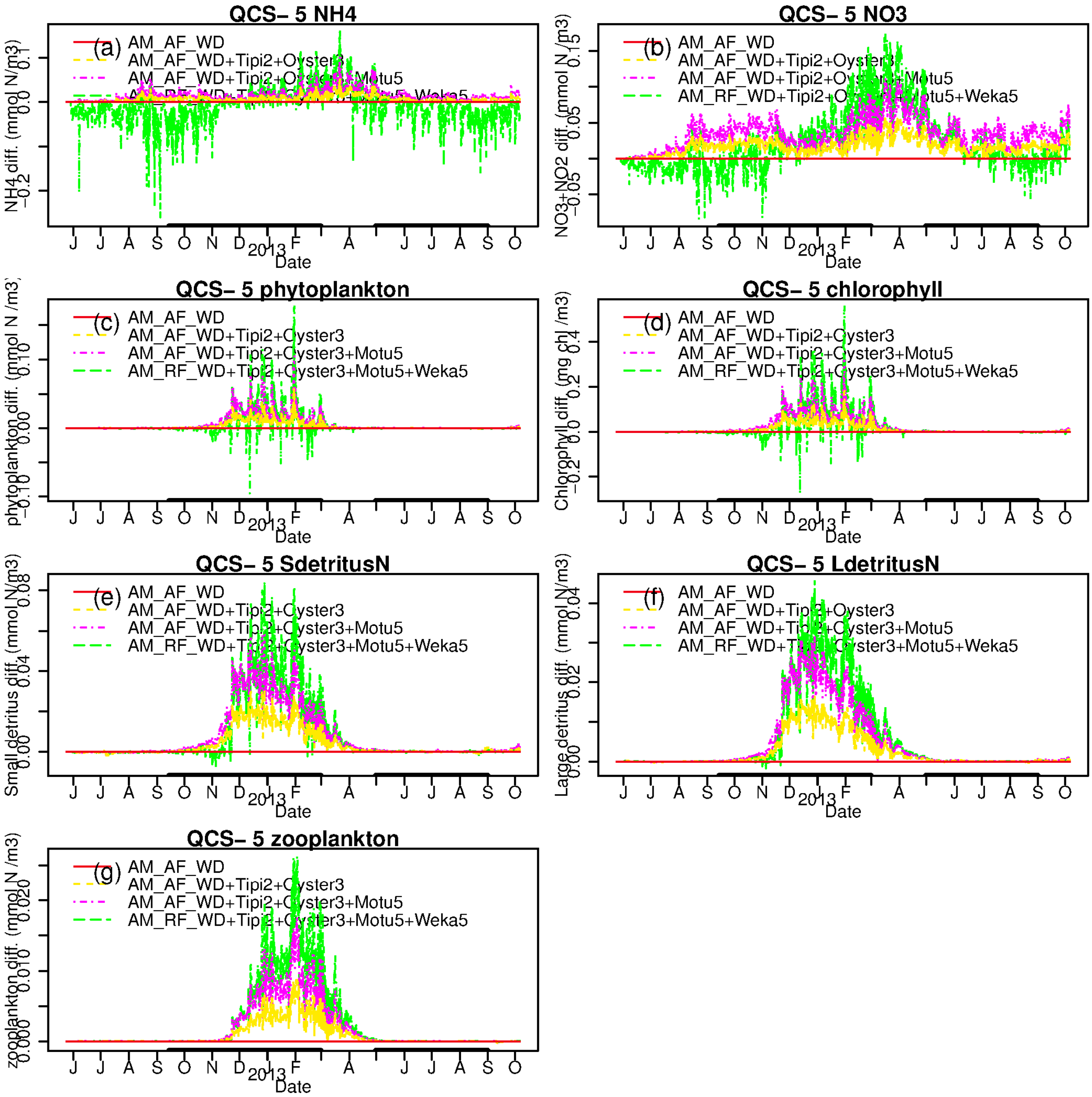

Figure 3-15: Simulated dynamics of water-quality concentration differences in the uppermost layer at station QCS-5 (outer Queen Charlotte) under differing fish-farm scenarios. The thick, black horizontal lines denote the winter (May-Aug. incl.) and spring/summer (Mid Sept. - end Feb.) time-averaging periods. The red line corresponds to the baseline$_{f2016}$ scenario (AM_AF_WD), the dashed orange line to the 'baseline$_{f2016}$ farms plus Tipi & Oyster Bays' scenario, the dotted pink line to the 'baseline$_{f2016}$ plus Tipi & Oyster Bays plus Motukina' and the green to the 'reduced baseline$_{f2016}$+Tipi+Oyster+Motukina+Te Weka' scenario.

3.2 Spatial maps of time-averaged change

We show results for two different time-averaging period: a winter period (May-Aug 2013) and a summer period (mid-September 2012 to end of March 2013) and two different depth horizons (the layer immediately below the surface and the layer immediately above the seabed). The near surface results are presented within this section. Section 3.2.1 presents comparisons of the baseline$_{f2016}$ and Baseline$_{f2016}$+Tipi2+Oyster3 scenarios. Section 3.2.2 presents comparisons of the baseline$_{f2016}$ and Baseline$_{f2016}$+Tipi2+Oyster3+Motukina5 scenarios. Appendix A presents corresponding figures for the near-bed layer.

3.2.1 AM_AF_WD versus AM_AF_WD+Tipi2+Oyster3

The false-colour maps for the winter time and summer time-averages (respectively,

Figure 3-16 and Figure 3-17) reveal that:

- As one might anticipate, the largest absolute and relative near-surface ammonium concentration changes arise close to the new farms (within Tory Channel and especially along the southern side of the channel, where the proposed new farms are). During both the summer and winter, increases of 5–15% are evident though much of Tory Channel. In the immediate vicinity of the farms, increases of 20–30% are seen. The absolute concentration increments are around 0.05–0.1 mmol N m^{-3} in Tory Channel (rising much higher in Oyster Bay). During the winter months, the plume of elevated ammonium extends into Grove Arm.
- The largest nitrate concentration increases tend to be seen in the inner parts of Queen Charlotte (Grove Arm). They amount to 2–4% in relative terms, or in absolute terms to 0.05–0.1mmol N m^{-3} in the winter and 0.02–0.04mmol N m^{-3} in the summer).
- The various seston groups (small & large detritus, phytoplankton (as chlorophyll) and zooplankton) also tend to show the greatest changes in the Onapua–Opua Bay side-arm of Tory Channel. In those areas, chlorophyll concentrations are predicted to increase by around 1% (0.02 mg chl m^{-3}) in the winter and around 4% (0.08 mg chl m^{-3}) in the summer. In the summer (but not winter), chlorophyll concentrations also rise (by less than 10%) in Oyster Bay. More wide-spread, but lesser-magnitude, increases are also evident throughout inner Queen Charlotte/Grove Arm. The changes become gradually smaller as one moves seaward through Queen Charlotte from the junction with Tory Channel.

Baseline$_{f2016}$ concentration	Relative concentration	Concentration change

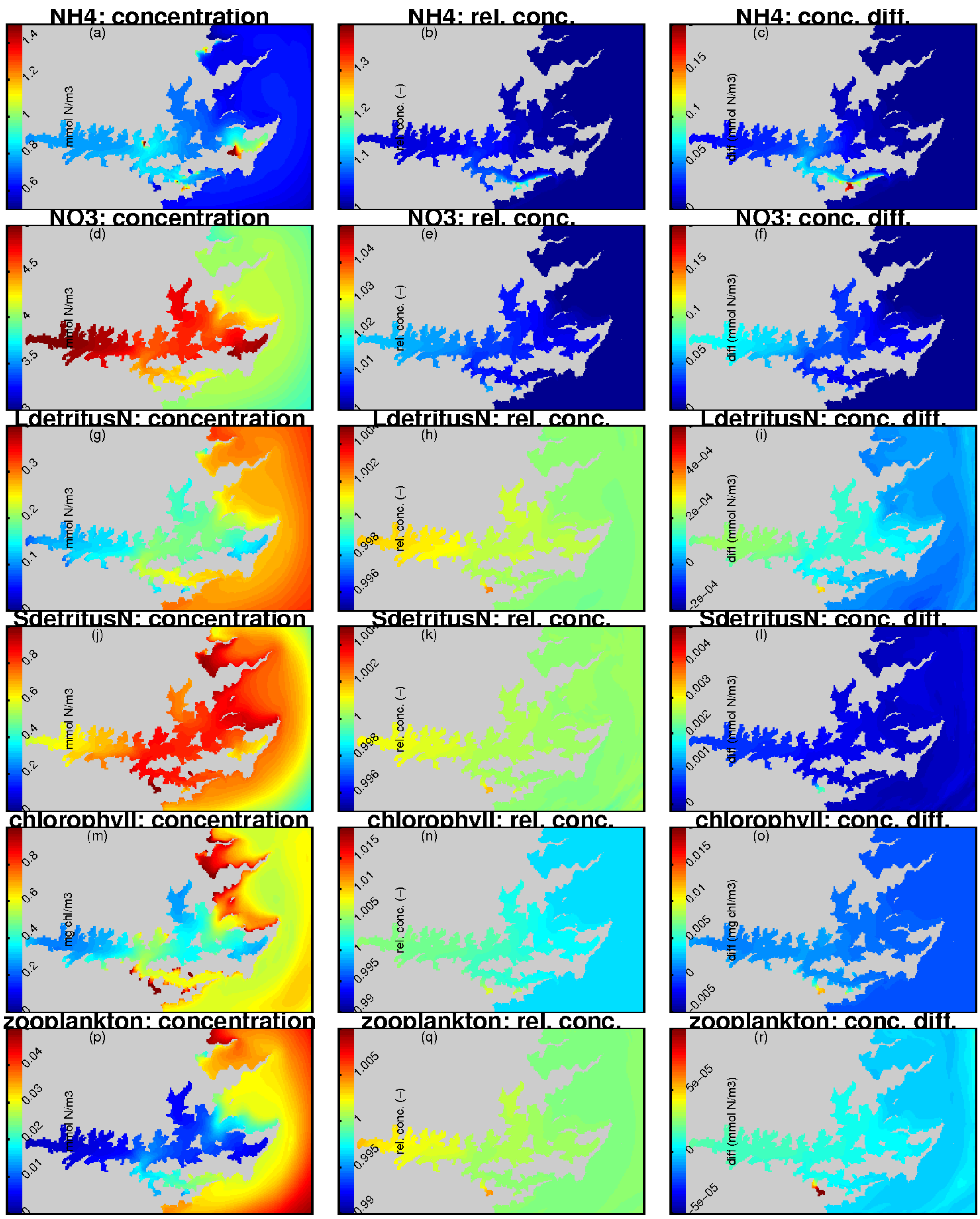

Figure 3-16: False colour maps of time-averaged, winter-time, near-surface water-quality characteristics for the AM_AF_WD and AM_AF_WD+Tipi2+Oyster3 scenarios. Left-hand images: time-average concentration in the AM_AF_WD scenario. Central images: relative concentration (AM_AF_WD+Tipi2+Oyster3 relative to AM_AF_WD). Right-hand images: concentration change (AM_AF_WD+Tipi2+Oyster3 minus AM_AF_WD). Each row shows results for a different state-variable (as indicated in the title of the left-hand-most image of each row).

Baseline$_{f2016}$ concentration	Relative concentration	Concentration change

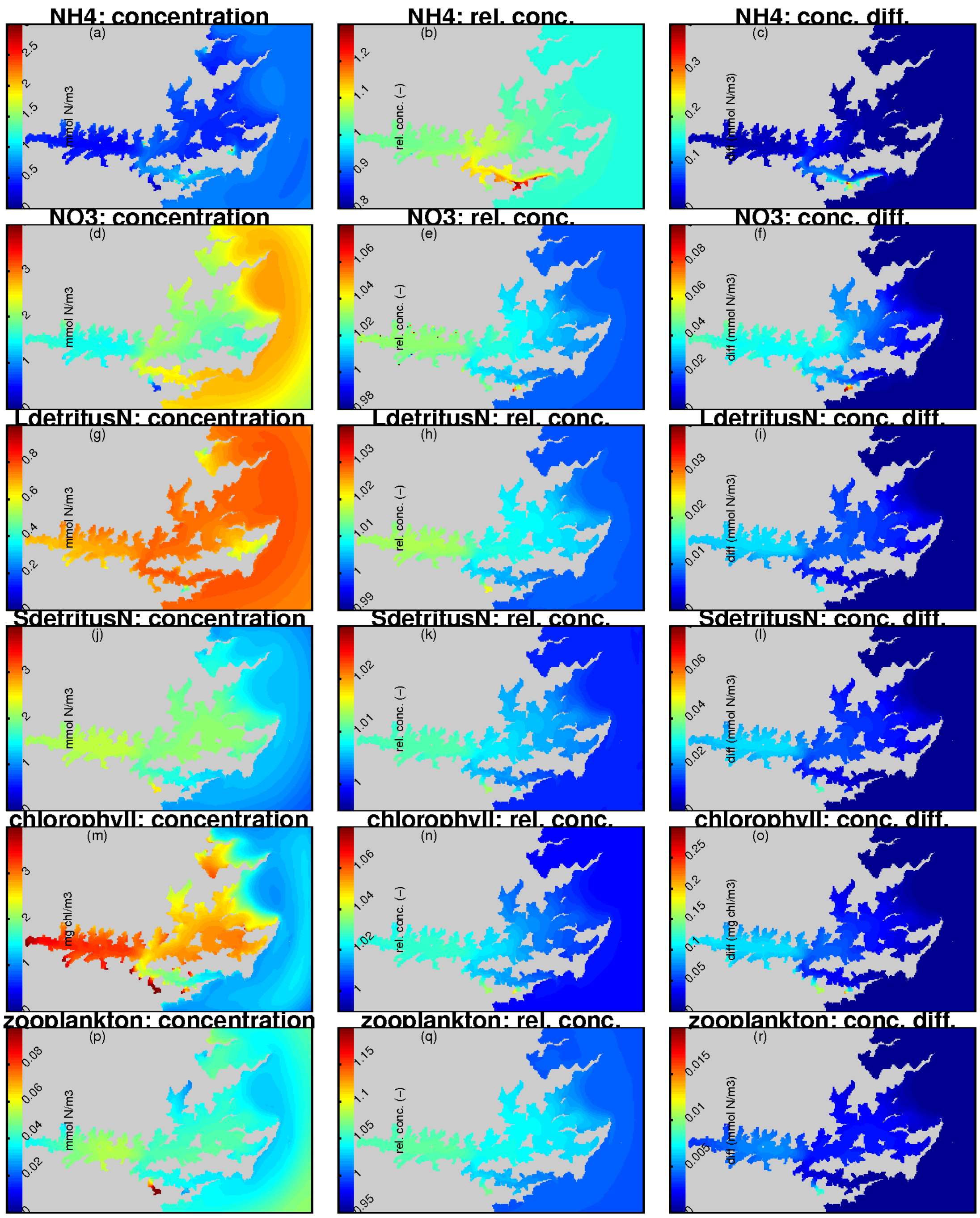

Figure 3-17: False colour maps of time-averaged, summer-time, near-surface water-quality characteristics for the AM_AF_WD and AM_AF_WD+Tipi2+Oyster3 scenarios. Left-hand images: time-average concentration in the AM_AF_WD scenario. Central images: relative concentration (AM_AF_WD+Tipi2+Oyster3 relative to AM_AF_WD). Right-hand images: concentration change (AM_AF_WD+Tipi2+Oyster3 minus AM_AF_WD). Each row shows results for a different state-variable (as indicated in the title of the left-hand-most image of each row).

3.2.2 AM_AF_WD versus AM_AF_WD+Tipi2+Oyster3+Motu5

The temporal and spatial changes (relative to baseline$_{f2016}$) arising in the AM_AF_WD_Tipi2+

Oyster3+Motu5 are roughly double the size of the ones arising in the AM_AF_WD_Tipi2+Oyster3 scenario.

Baseline$_{f2016}$ concentration	Relative concentration	Concentration change

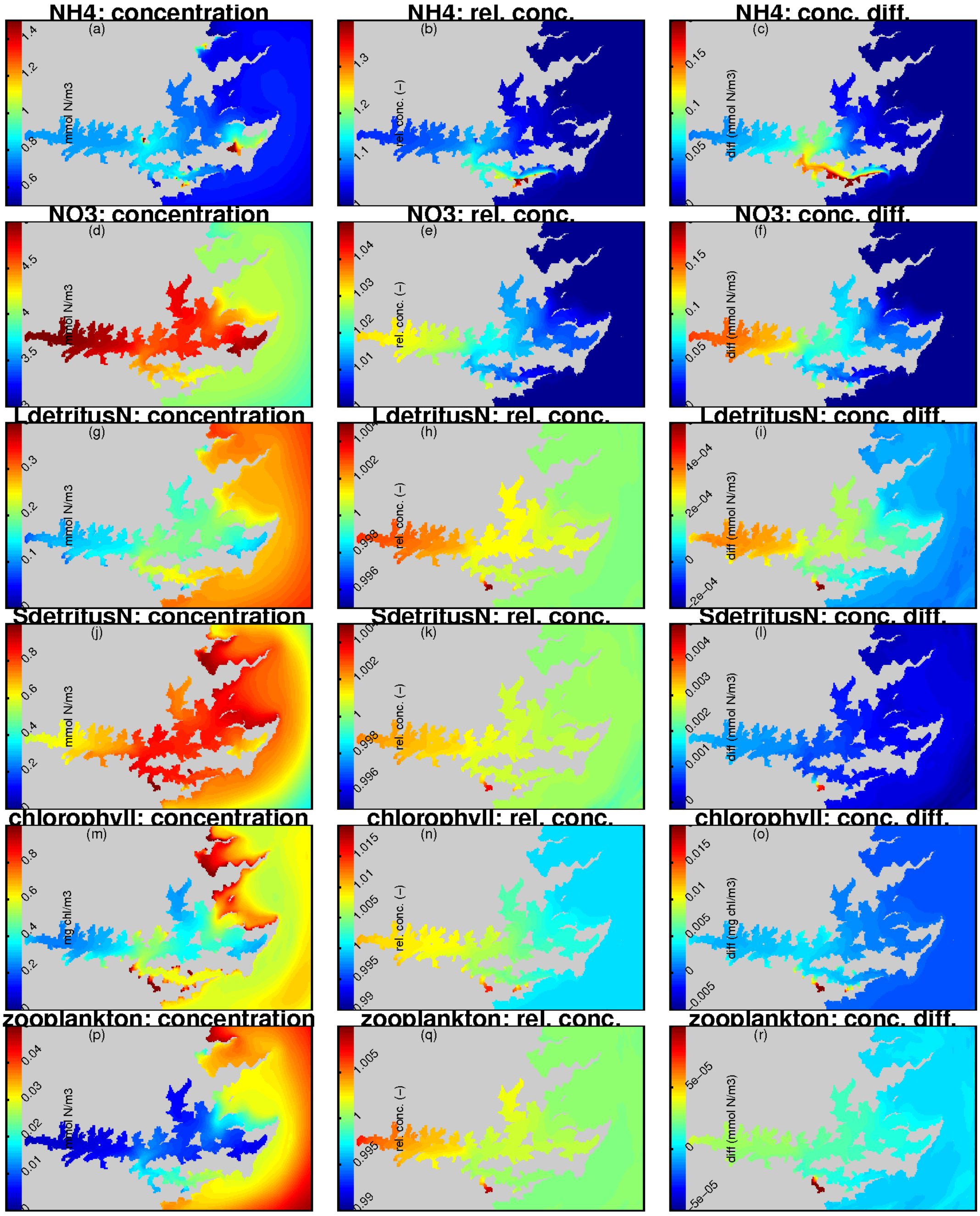

Figure 3-18: False colour maps of time-averaged, winter-time, near-surface water-quality characteristics for the AM_AF_WD and AM_AF_WD+Tipi2+Oyster3+Motu5 scenarios. Left-hand images: time-average concentration in the AM_AF_WD scenario. Central images: relative concentration (AM_AF_WD+Tipi2+Oyster3+Motu5 relative to AM_AF_WD). Right-hand images: concentration change (AM_AF_WD+Tipi2+Oyster3+Motu5 minus AM_AF_WD).

Baseline$_{f2016}$ concentration	Relative concentration	Concentration change

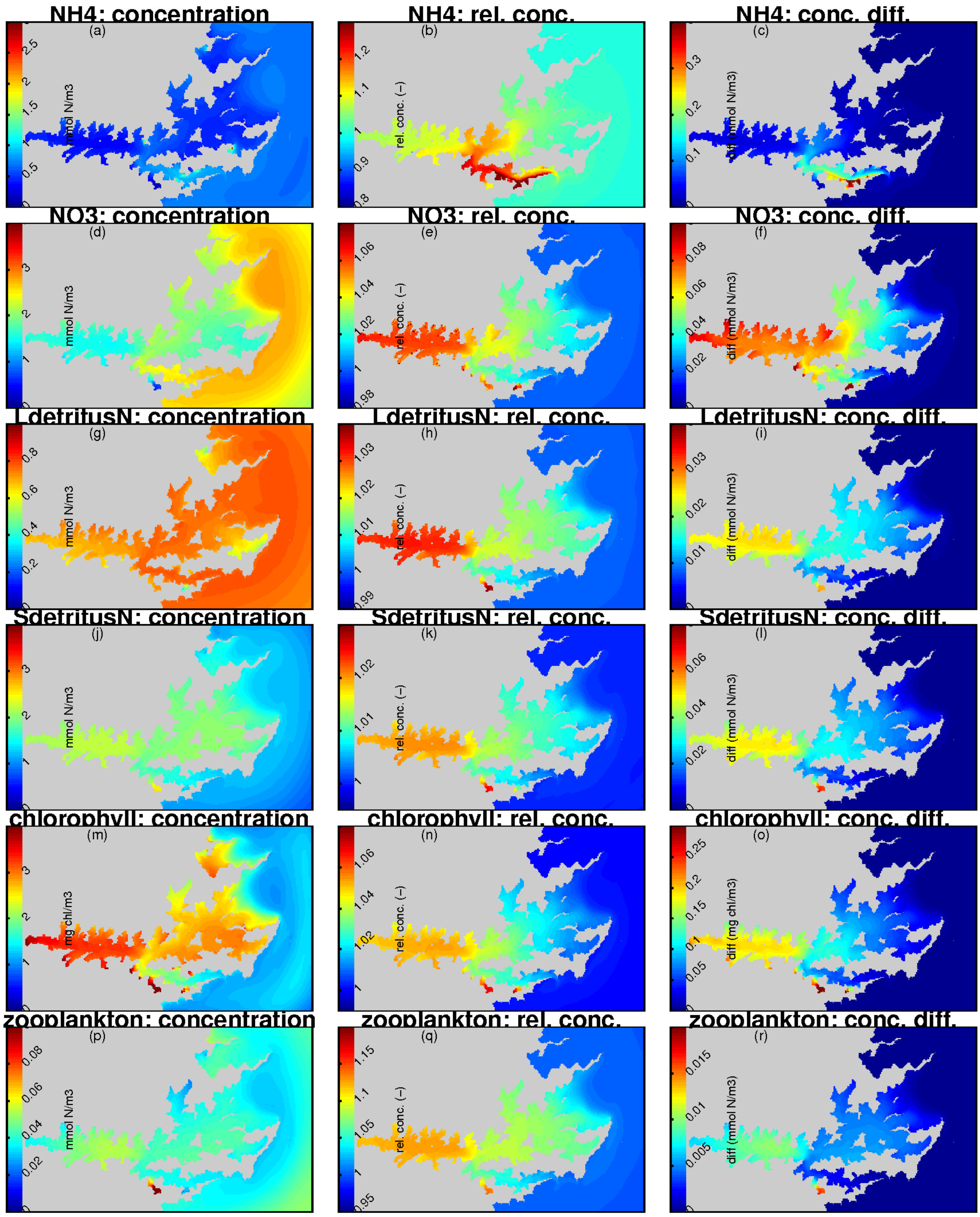

Figure 3-19: False colour maps of time-averaged, summer-time, near-surface water-quality characteristics for the AM_AF_WD and AM_AF_WD+Tipi2+Oyster3+Motu5 scenarios. Left-hand images: time-average concentration in the AM_AF_WD scenario. Central images: relative concentration (AM_AF_WD+Tipi2+Oyster3+Motu5 relative to AM_AF_WD). Right-hand images: concentration change (AM_AF_WD+Tipi2+Oyster3+motu5 minus AM_AF_WD). Each row shows results for a different state-variable (as indicated in the title of the left-hand-most image of each row).

3.2.3 AM_AF_WD versus AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5

The AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 lacks the Ruakaka & Otanerau farms that exist at present. As one might anticipate, simulated ammonium concentrations in the immediate vicinities of these (absent) farms are lower in the AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 than in the baseline_{f2016} scenario. Nonetheless, in the medium and far-fields the time-average concentrations of nitrate and particulate materials tend to exceed those found in the baseline_{f2016} scenario. The temporal and spatial changes (relative to baseline_{f2016}) arising in the AM_SF_WD_Tipi2+Oyster3+Motu5+Weka5 are roughly two-three times greater than the ones arising in the AM_SF_WD_Tipi2+Oyster3 scenario. As with the other two 'future scenarios' of this report, the greatest far-field seston changes (increases) arise within Onapua/Opua Bay and the inner parts of Queen Charlotte Sound.

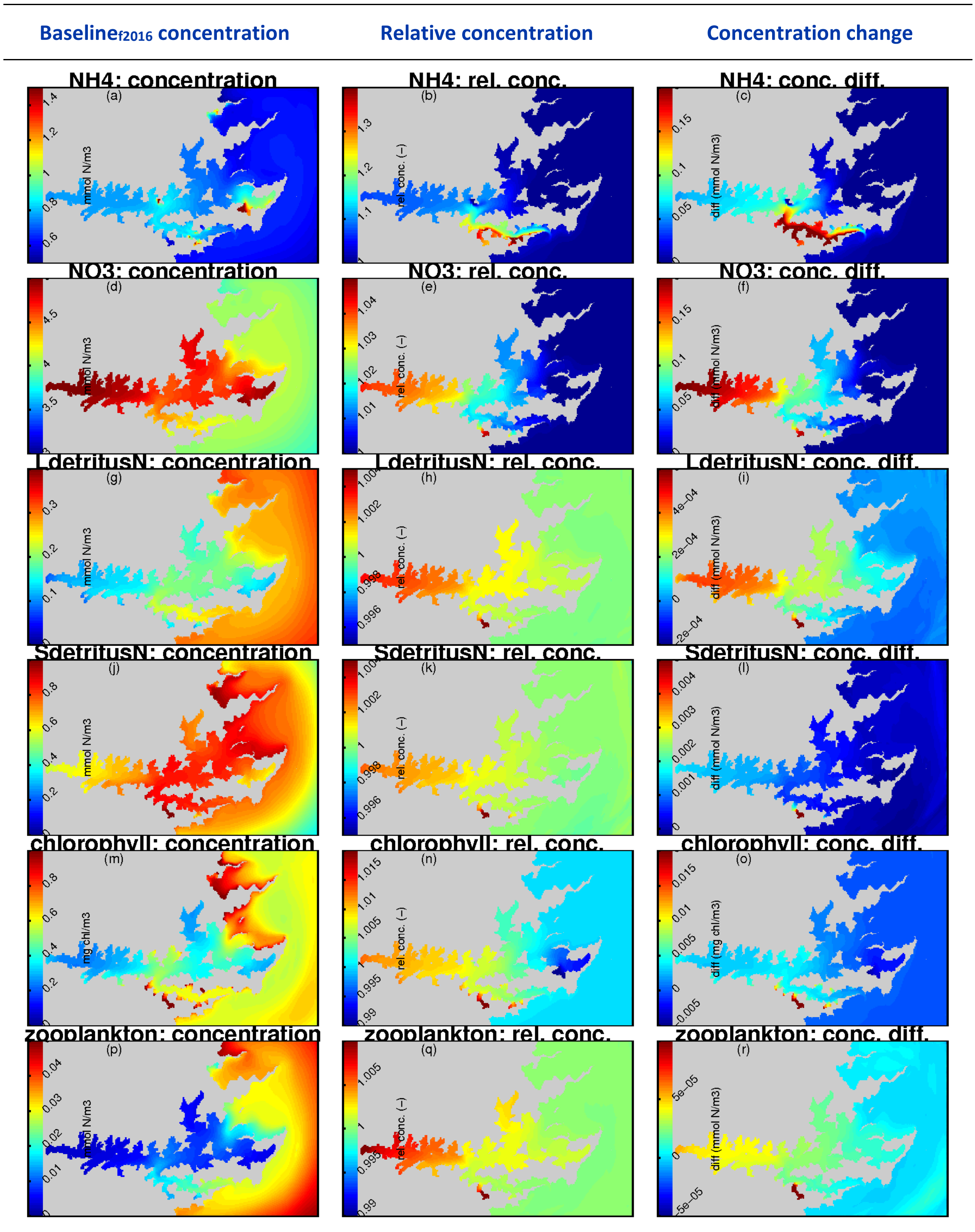

Figure 3-20: False colour maps of time-averaged, winter-time, near-surface water-quality characteristics for the AM_AF_WD and AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 scenarios. Left-hand images: time-average concentration in the AM_AF_WD scenario. Central images: relative concentration (AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 relative to AM_AF_WD). Right-hand images: concentration change (AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 minus AM_AF_WD). Each row shows results for a different state-variable (as indicated in the title of the left-hand-most image of each row).

Baseline$_{f2016}$ concentration	Relative concentration	Concentration change

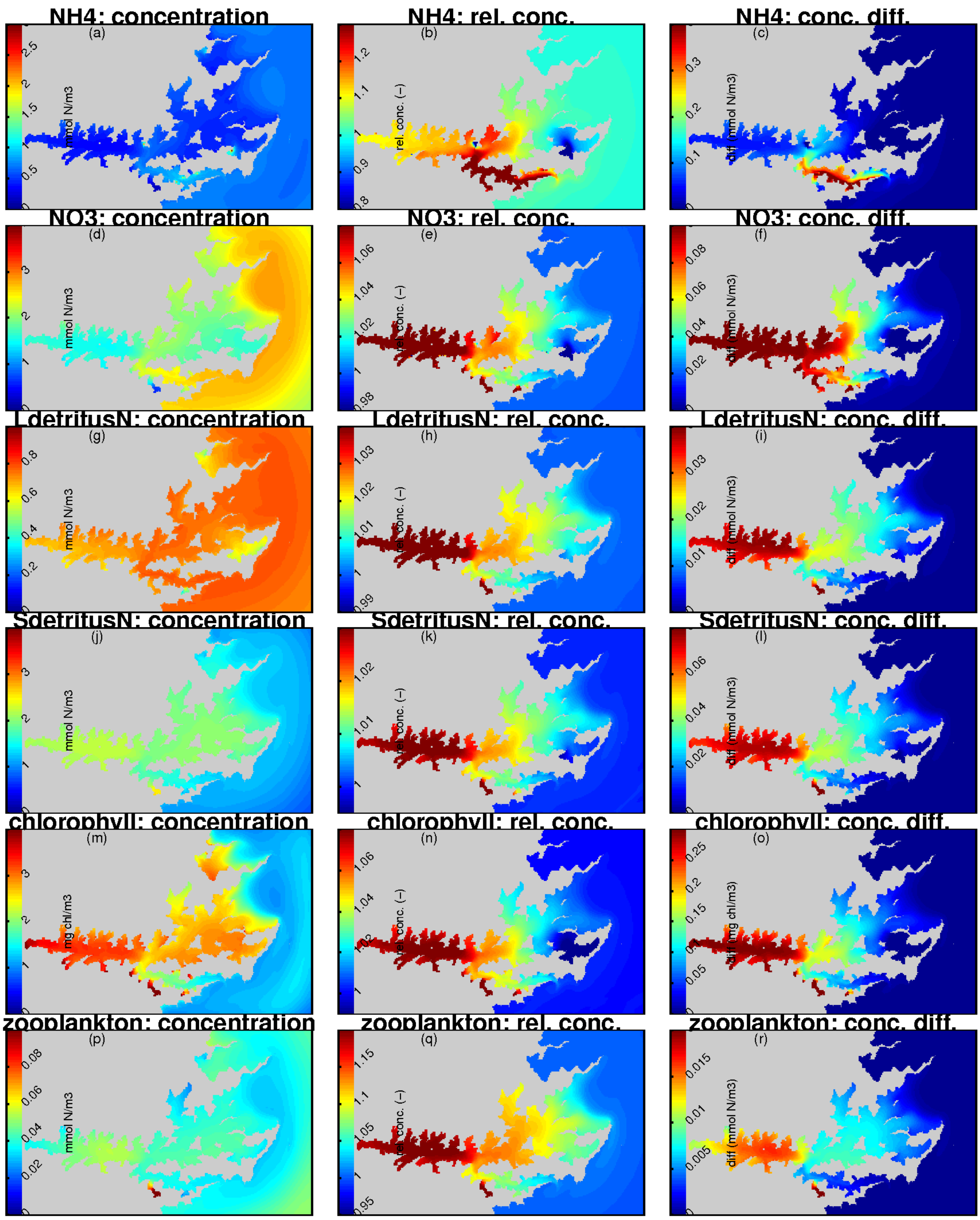

Figure 3-21: False colour maps of time-averaged, summer-time, near-surface water-quality characteristics for the AM_AF_WD and AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 scenarios. Left-hand images: time-average concentration in the AM_AF_WD scenario. Central images: relative concentration (AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 relative to AM_AF_WD). Right-hand images: concentration change (AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 minus AM_AF_WD). Each row shows results for a different state-variable (as indicated in the title of the left-hand-most image of each row).

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3.3 Near bed changes

The predicted magnitudes of change in near-bed water quality characteristics are shown in Appendix A. The spatial and temporal patterns are very similar to those evident in the near-surface layer, but the near-bed changes tend to be of lesser magnitude. During the winter months, the model yields "speckled"/"oscillatory" (with respect to geographic location) changes in the bottom-right corner of the domain for some water-quality properties (eastern Cook Strait, e.g., Figure A-1(q)). We believe these are numerical artefacts of the boundary condition and do not contaminate the rest of the solution.

4 Discussion

Much of the material presented within this section (Section 4) is adapted from an earlier report concerning possible additional fish farms within Tory Channel (Broekhuizen and Hadfield 2015). Indeed, this section is a near-duplicate of material first presented within Broekhuizen,Hadfield (2015). The adaptations are minor. Most changes can be attributed to the facts that: (a) we considered a smaller and differing suite of farming scenarios in this latter report. In addition to changes related to the differing geographic locations, we have also introduced some entirely new material into the discussion. To facilitate comparison across reports, paragraphs containing new material are indicated with the following preceding text: "[*New Material*]".

Two other reports (Broekhuizen 2015; Broekhuizen, Hadfield et al. 2015) also discuss model limitations. Most of the limitations discussed in those reports were also brought up in (Broekhuizen and Hadfield 2015).

Our modelling has examined the influence which nitrogen stemming from three proposed new fish-farms may have upon the lower food-web components of the pelagic zones of the Queen Charlotte Sound and Tory Channel system. The modelling focusses upon direct trophic effects of the nitrogen. Nitrogen is a key nutrient that phytoplankton (and other plants and animals) require in order to grow. Indeed, it is often (but not invariably, see below) the factor that constrains realizable growth rates in New Zealand coastal waters.

In the simulations, Tory Channel shows moderately large ammonium increases – because it is the direct recipient of the farm-derived ammonium. On the other hand, even during summer, it shows only small changes in seston. This is because the ammonium is exported from Tory Channel (some, directly out into Cook Strait, some to Queen Charlotte) before the phytoplankton have sufficient time to incorporate much of the ammonium. Some of the ammonium which enters Queen Charlotte from Tory Channel moves seaward (out toward Long Island and beyond). During the summer, it does engender a phytoplankton (hence, detrital and zooplankton) response – but this is muted by dilution with 'unmodified' Cook Strait water entering the seaward end of Queen Charlotte on each tide (i.e., the farm nutrient is not an overwhelming component of the nitrogen budget for that region). In contrast, ammonium which enters Grove Arm tends to remain there for sufficient time to enable phytoplankton to respond to it. Furthermore, the farm nutrient represents a non-trivial additional component of that sub-region's nitrogen budget. A similar story holds for some side-bays (such as Onapua).

4.1 Modelling limitations

Biogeochemical models (like that used here) typically produce relatively crude representations of the complex bio-geophysical systems under study. Some components of reality are entirely excluded (whether explicitly, or implicitly). Other aspects of reality are included, but only in simplified form. A model will not reproduce all details of reality accurately. Despite their imperfections, such models remain one of the few ways for us to describe and analyse spatially and temporally diverse real world systems.

Our model considers the effects that nitrogen emissions from fish-farms may have upon the lower food-web. It explicitly ignores the possibility that elements other than nitrogen may limit phytoplankton growth. The so-called *Redfield ratio* (Redfield 1934; Redfield, Ketchum et al. 1963) is a suite of empirically determined elemental molar ratios (C:N:P=106:16:1) in particulate organic matter collected from deep oceans. That ratio is also characteristic of phytoplankton cells when they are growing under conditions of plentiful nutrient (i.e., when they are not nutrient-limited). Broadly speaking, when the molar ratio of dissolved inorganic nitrogen:dissolved inorganic phosphorus falls below about 16, a growing phytoplankton population can be expected to exhaust the pool of readily-available nitrogen before it exhausts the pool of readily available phosphorus. Conversely, when the ratio exceeds approximately 16, they will exhaust the phosphorus pool first. Once one or other nutrient pool is exhausted, further phytoplankton growth will be limited by the rate at which that pool can be replenished. Note, the emphasis upon what will happen if the concentration of one (or both) dissolved organic nutrients become low. When nutrients are plentiful, neither nutrient will limit the present, instantaneous growth rate. In this situation, the ratio of dissolved inorganic N:dissolved inorganic P may depart substantially from 16 yet have no influence upon the present, short-term growth rate of the phytoplankton population.

Of course, all living matter is composed of more than nitrogen and phosphorus. In particular, some phytoplankton (notably diatoms) require silicon. Unlike nitrogen and phosphorus, silicon is not a significant component of fish-feed. Thus, in waters that are silicon-limited (or close to being silicon limited), nutrients from fish-feed may favour the growth of non-silaceous algae over that of silaceous ones. The Redfield-Brzezinski ratio is an empirically-determined approximate molar composition for diatoms (Brzezinski 1985). The molar ratio is 106:15:16:1 (C:Si:N:P). The molar ratio of dissolved inorganic silicon:dissolved inorganic nitrogen may be compared with the ratio 15:16 to determine whether diatoms are more likely to be(come) silicon or nitrogen limited, and an analogous comparison can be used to determine whether Si or P limitation is the more likely.

The Marlborough District Council data indicate that N:P ratios are almost invariably less than 16 (in five years' worth of monthly monitoring at five stations and two depths per station, the N:P ratio has exceeded 16 on only thirteen occasions). We infer that nitrogen is more limiting that phosphorus throughout Tory Channel and Queen Charlotte Sound). Similarly, the Marlborough District Council monitoring data reveal that DRSi:DIN ratios almost invariably exceed 15:16 within Grove Arm (i.e., diatoms will be nitrogen-limited). In Tory Channel, the DRSi:DIN ratio has usually been less than 15:16 (i.e., the diatoms would become silicon limited before becoming nitrogen-limited). At the central and outer Queen Charlotte monitoring stations (Figure 1-1), DRSi:DIN ratios have exceeded 15:16 on about 50% of occasions and fallen below 15:16 on the other 50%. The implication is that fish-feed inputs are unlikely to dramatically change the abundance of diatoms (relative to non-silaceous phytoplankton taxa) in Grove Arm but we cannot entirely rule out the possibility that the relative diatom content of the phytoplankton community might decline in Tory Channel and the central/outer parts of Queen Charlotte. That said, we believe that is unlikely to happen. The Marlborough District Council monitoring data indicate that, though the diatom content of the phytoplankton community fluctuates dramatically through time at any one station, it also shows some consistent between-station differences. Despite the DRSi:DIN ratios being consistently less than 15:16 in Tory Channel, that station almost always exhibits the most strongly diatom dominated community (median approx. 70% diatom by biomass, range approx. 30%-approx. 85%), whereas stations QCS-1 (inner Grove Arm, nitrogen-limited) and QCS-5 (outer Queen Charlotte, frequently silicon limited) tend to exhibit relatively lower diatom contents. Diatoms are renowned for performing well in vigorously mixed systems (such as Tory Channel, and, to a lesser extent, outer Queen Charlotte). Together with the spatial patterns of community composition evident in the Marlborough District Council data lead us to infer that spatial variations in the phytoplankton community of the Queen Charlotte/Tory system are more strongly influenced by spatial variations in hydrodynamic conditions than they are by spatial variations in biogeochemical conditions. We speculate that changes in the taxonomic composition of the phytoplankton community will be small in comparison with the temporal variations evident at any of the Marlborough District Council stations and in comparison with the persistent differences across the stations.

Comparison of the concentrations of dissolved reactive phosphorus and dissolved inorganic nitrogen in Queen Charlotte Sound with the so-called Redfield ratio[9] suggest that nitrogen (N) is more limiting than phosphorus (P), but comparison of dissolved reactive silicon and dissolved inorganic nitrogen concentrations with the so-called extended Redfield ratio[10] suggest that the diatom community may sometimes be silicon (Si) (rather than nitrogen) limited within Queen Charlotte (notably in Tory Channel and the central/outer parts of Queen Charlotte[11]). Fish feed contains N and P, but little or no Si. Thus, the nutrient-stream emanating from a fish-farm will tend to increase the N:Si nutrient ratio in the water. All phytoplankton require nitrogen, but only some (notably, diatoms) require silicon. During periods of Si-limitation, nitrogen inputs (such as those from fish farms) may be disproportionately incorporated into taxa that do not require silicon in order to grow (e.g., dinoflagellates and many small flagellates etc.). Loosely speaking, larger forms (such as dinoflagellates and diatoms) are believed to be more likely to be grazed by larger grazers (copepods etc.,) and hence pass upward through the foodweb into fish and the like. In contrast, smaller forms are believed to be more likely to be consumed by protozoal grazers. Their energy and biomass may not pass up into higher parts of the foodweb (Richardson 1997). There is some evidence that the different phytoplankton taxa are of differing nutritional value to grazer populations (Cloern 2001). It is therefore conceivable that some grazers may benefit (and others may be disadvantaged) if farm-derived nitrogen inputs were to be large enough to substantially reduce the probability (in space and/or time) that the system will be N-limited. Since our model lacks silicon as a state-variable and makes no distinctions between differing algal or grazer taxa, we cannot make any quantitative statements about how individual taxa might change.

Much of our discussion has focussed upon chlorophyll. This is primarily because chlorophyll is one of the few variables for which a water-quality threshold has been set with respect to fish farming in the Sounds. Chlorophyll is a molecule that is found within all photosynthetic organisms (incl. phytoplankton). This is the pigment which is responsible for most photosynthetic production. Thus, chlorophyll is important in its own right. In practice, however, it is also routinely measured as a proxy indicator of phytoplankton abundance – because chlorophyll is easy/cheap to measure in comparison with counting and measuring phytoplankton cells! Note however, that chlorophyll concentration provides only a rough indication of phytoplankton biomass concentration. Even within a single phytoplankter, the chlorophyll:total biomass ratio can vary markedly through time[12] and some taxa tend to maintain markedly higher chlorophyll:carbon ratios than others.

In reality, phytoplankton abundance is determined by much more than mere nitrogen input rates (or even nitrogen concentrations). To varying degrees, the concentrations of other [13]nutrients, the instantaneous (and historical) light intensities (and spectral composition), water temperature,

[9] An empirical ratio summarising the elemental composition of seston in the deep ocean: 106:16:1 (C:N:P by atoms). Redfield, A.C. (1934) On the proportions of organic derivatives in sea water and their relation to the composition of plankton. *James Johnstone Memorial Volume*. Liverpool University Press, Liverpool.

[10] An extension of the original Redfield ratio to include other elements – notably silicon: 106:16:15:1 (C:N:Si:P, by atoms) Brzezinski, M.A. (1985) The Si:C:N ratio of marine diatoms: interspecific variability and the effect of some environmental variables. *Journal of Phycology*, 21: 347-357.

[11] The model does not carry any representation of Si, or Si-limitation. The consequent absence of intermittent Si-limitation may partially explain the model's tendency to over-estimate summertime phytoplankton concentrations.

[12] Being influenced by factors such as recent ambient light, temperature and nutrient experiences.

[13] For example, far out into oceans, iron is sometimes the limiting element. In coastal waters, iron inputs from dust blown off the land are sufficient to preclude iron limitation. In coastal waters, nitrogen (or, less commonly, silicon or phosphorus) are the elements which are most likely to be limiting.

strength of vertical mixing, taxonomic composition of the initial phytoplankton community, time-course of grazing pressure etc., can all influence the evolution of total phytoplankton biomass. Similar complexities apply within all the other components of the real-world food-web. The model represents only some of these factors, and even those are only represented in simplified form. In the model (as in the real world), it is the rate coefficients (specific mortality rate, specific ingestion rates, maximal photosynthetic rates, mineralization rates etc.,) which will help to determine where (geographically, and within the food web) farm-derived nitrogen will tend to accrue. Unfortunately, many of these important coefficients are poorly known. In part this is because most are not fundamental physical constants (such that they may differ across taxa and across space and time within taxa). The dynamics that any model produces are influenced by the chosen coefficient values (as well as the functional forms/equations chosen to represent each process). In this report, we have not investigated the model's sensitivity to any coefficient values or to any changes in the equations that are used within the model to approximate the structure and function of the real-world food-web. Indeed, to date, we have made only very few such investigations. Such analyses that we have conducted have tended to focus upon 'baseline$_{f2016}$-like' farming scenarios only. In earlier work (Broekhuizen, Hadfield et al. 2015)we made some simulations to examine sensitivity to assumptions regarding benthic denitrification (which will influence how long fish-farm-derived nitrogen remains bio-available for), but we have not examined the model's sensitivity to the coefficients governing uptake of nutrient by phytoplankton.

The model does not consider oxygen. Fish farming will increase the system's demand for oxygen. The fish themselves require oxygen. Furthermore oxygen will be consumed by the biogeochemical processes that convert fish-derived ammonium to nitrate, mineralizing organic matter stemming from the farms (faeces, uneaten food). Similarly, should the fish-farm-derived nutrients stimulate a net increase in organic matter production, then this additional organic matter will create a new oxygen demand when (and where) it decays – perhaps at some distance away from the farms. Marlborough District Council hold about two years' worth of monthly dissolved oxygen data from the Queen Charlotte system, but those data indicate that oxygen concentrations remain high (>85% saturation) throughout most of the water column and throughout the year. The only exceptions have occurred within Grove Arm - where near-bed concentrations have dropped to 60-70% saturation during some summer months. Those concentrations are above the sub-lethal effects threshold of the vast majority of marine taxa that have been studied (Vaquer-Sunyer and Duarte 2008). Clearly, it would not be in the fish-farmers' interest to run their farms at stocking rates which would induce local (to the farm) hypoxia. Such direct self-interest does not entirely preclude the possibility that fish-farming might contribute to the induction of far-field hypoxia, but the need to maintain adequate near-field dissolved oxygen does make it less likely that far-field hypoxia will arise. Indeed, to the best of our knowledge, there are no cases where far-field hypoxia has been attributed to fish-farms operating in a nearby area.

The model does not consider the effects that the biofouling community (encrusting macro-algae and invertebrates) associated with the farm may have. Fish farm nets are cleaned regularly, and, at the regional-scale, they are likely to represent only a small proportion of the already-available hard-surface onto which encrusting organisms could settle.

The model does not consider the effects that farm structures will have upon patterns of flow. They certainly do influence flow, but this occurs mostly at the local/bay-scale. Plew (2011) reports results from a simulation model of Pelorus Sound (cf Queen Charlotte/Tory Channel) currents that included the effects of the (approximately 600) mussel farms within that system upon flow. He focussed upon Waihinau Bay and Port Ligar (where mussel farms occupy about 10% of each bay). He reported that farms within each bay may have caused bay-scale average current speeds to drop by circa 7-8% in Port Ligar and circa 3% in Waihinau. At finer scales, changes were larger: the model suggested that current speeds would often drop several tens of percent amongst the lines within some individual farms. Conversely, addition of the farms yielded higher (approximately doubled) current speeds immediately outside some of the added farms. For Port Ligar, inclusion of the effects of all the farms within Pelorus (as well as those of the bay itself) reduced current speeds by a further 3%. The location of farms was important with regard to effects on currents with greater bay scale (and beyond) reductions in flows caused by farms located in regions of faster currents. Many of the farms in Pelorus are located in side bays where flows are less than in the main channel. It has been estimated that the effect on current speeds over Pelorus as a whole is likely to be around 5% (D. Plew, NIWA, pers. comm.). In total, the pens of the proposed three new farms within Tory Channel would occupy approximately 4 ha. Tory Channel has a surface area of approximately 1800 ha. Thus, the proposed new fish farms would occupy <1% of the area of Tory Channel. Despite the fact that the proposed new farms will be exposed to relatively high current speeds, we speculate that their incremental effect upon large-scale flow in Tory Channel will be very small (<1% reduction) [D. Plew, NIWA, pers. comm].

[*New Material*] In a similar vein, we note that wind-forcing (which drives short-term fluctuations in surface currents and vertical mixing) comes from a wind model that has insufficient resolution to properly resolve near-sea-surface winds within the topographically complex Marlborough Sounds region. This is unlikely to have an adverse influence upon long-term transport patterns (which are dominated by estuarine circulation and tidal features), but may imply that the simulated instantaneous locations of farm plumes could sometimes be wrong. In particular, simulated phytoplankton (etc.,) concentration fluctuations occurring across the weather time-scale (days) may be less reliable than longer-tem changes. In particular, animations of chlorophyll concentrations (not shown) often reveal that the highest chlorophyll concentrations 'oscillate' between the bays on either side of inner Queen Charlotte on a time-scale of days. We suspect that these oscillations are induced by changing patterns of wind-driven near-surface flow and upwelling. Those may not be accurately reproduced in the hydrodynamic model. Conceivably, the discrepancies between the seasonal phases of simulated- and observed seasonal phases of phytoplankton might indicate that the magnitudes of wind-driven vertical mixing are incorrectly reproduced by the hydrodynamic model (at least at some locations and times of the year). This hypothesis remains untested.

As noted in Hadfield, Broekhuizen et al. (2014) and Broekhuizen, Hadfield et al. (2015), benthic denitrification rates can become suppressed when organic loadings to the seabed become too high. If this occurs over a sufficiently large fraction of the region, this can induce a positive feed-back loop that exacerbates the progression towards eutrophy. Hadfield, Broekhuizen et al. (2014) examined an (implausibly) worst-case scenario – in which denitrification did not operate anywhere in the model domain. A more plausible (but still unlikely) scenario would be to assume that denitrification efficiency might become suppressed (such that a smaller percentage of ammonium stemming from decay of organic matter becomes converted to relatively inert nitrogen gas) in immediate environs of the farms. We have not examined that possibility. We note that New Zealand King Salmon Ltd. and Marlborough District Council have recently agreed upon a set of best practice management protocols aimed at precluding the most extreme adverse benthic effects that can be associated with fish farming. If these protocols work as intended, they should limit the extent to which denitrification processes under the existing fish-farms can become suppressed. In the same way, the water-quality monitoring & response protocols (Morrisey, Anderson et al. 2015, see also next sub-section) that have been agreed between NZKS and Marlborough District Council should preclude serious enrichment of the Sounds by the existing farms [but note, that if the proposed new farms were not operated by NZKS, these protocols would not automatically apply to those new farms].

[*New Material*] Some of the salmon physiology coefficients are based upon Atlantic salmon rather than King salmon. The nature of the fish-growth model is such that it was never expected to conserve mass (Broekhuizen, Hadfield et al. 2015) but a recent analysis (Broekhuizen 2015) suggests that the growth model yields output fluxes (of ammonium and faeces) which are too large to permit the fish to grow at the rates implied by the forcing data (time-series of feed input rates and fish stock numbers-at-size). This suggests that the emergent rates of ammonium excretion and faecal production may be too high – despite the fact that Atlantic salmon are said to have lower energy expenditures than King salmon of similar size.

Given the approximations that are introduced in these biogeochemical models, and the uncertainties concerning many of the model's coefficients, it is conceivable that, in reality, the farms will induce larger (or smaller) phytoplankton (chlorophyll) changes than those suggested by the model. We are inclined to believe that the real world changes will be smaller. The fact that the 'operating farms' scenario variant of the model over-predicts summertime phytoplankton concentrations (whilst getting other explicit components of the model food web 'about right'[14]) suggests that the model may have a tendency to 'capture' too much farm-derived nitrogen within an explicit phytoplankton population during the summer. This excess capture must be at the expense of a deficit of capture of a real-world component that is either: (a) implicitly present within the model system (i.e., 'subsumed' within a state-variable whose name does not fully convey its nature) or, (b) absent from the model system (i.e., none of the model's state-variables adequately account for the material in question). Since the model gets the dynamics of the other explicit food web components 'about right' (Hadfield, Broekhuizen & Plew, 2014), it seems probable that the implicit deficit (that we believe must be occurring somewhere) arises in some real-world component that is absent from the model. In reality, benthic detritus, organic solutes (open-water and pore-water) and pore-water inorganic solutes all represent significant nitrogen stores that are absent from this model. In this model, farm-derived nitrogen which 'should' accrue into those pools is falsely forced to accrue within one of the model's explicit components (in our case, seemingly, in the phytoplankton). Unfortunately, there have been comparatively few measurements of benthic nutrient dynamics in Queen Charlotte and Pelorus. This makes it difficult to reliably gauge the spatial and temporal variability in the sizes of the various benthic nutrient pools.

4.2 Influence of the seaward boundary condition

[*New Material*] We have adopted a so-called Orlanski boundary condition. Loosely speaking, in this boundary condition, the water which flows into the domain from outside retains a (decaying) memory of the state of the water at this location upon the last occasion when there was an outflow at the location. This 'memory' decays – such that the assumed state of the incoming water slowly reverts to a user-prescribed boundary condition value. Nonetheless, if water only rarely flows outward at a given location, then the boundary condition can retain an implausibly long memory of earlier water conditions (rather than adequately reflecting the state of the water that has more recently flowed towards the boundary from elsewhere). In such situations, close to the Cook Strait boundaries, what should have been short-lived differences between two simulations may persist for too long – such that they become too large in the time-average. We believe that this is a greater

[14] Though, at some stations, there is a tendency for deep water nitrate concentrations to remain 'low' for too long during the mid/late summer period and for ammonium concentrations to be toward the lower end of the observed range.

problem along the NE boundary of the domain (the side that does not intersect a coastline) than along the NW and SW boundaries.

Whilst the boundary conditions can retain a memory of earlier model conditions, they are also influenced by time-series supplied by the model-user. In the absence of good field data from the vicinities of the model's seaward boundaries, we have used field data from the seaward mouth of Port Gore to prescribe the requisite biogeochemical time-series. It is unclear how well these approximate the real-world conditions at the boundaries of the present model domain.

4.3 Spatial resolution and possible systematic bias

Section 2.2 notes that, whilst the model has a nominal horizontal resolution of 200 m, it is likely to be best able to reproduce system dynamics only at scales somewhat larger than this. There are several reasons for this. Below, we mention three.

Firstly, as noted in section 2.2, the 200 m resolution precludes accurate reproduction of the very steep ammonium and detritus concentration profiles that are likely to exist in the immediate environs of each farm.

Secondly, (probably, more importantly), the winds (which influence vertical mixing and day-to-day variations in near-surface current flows) that drive the hydrodynamic model stem from a 12.5 km resolution wind-model. Given the steep topography around the Sounds, it is very likely that the real-world winds felt at the sea-surface in some parts of the model's domain would not similar to those generated by the wind-model (and felt by the hydrodynamic model) on at least some occasions. The wind-errors are likely to become progressively smaller as one retreats further offshore. Thus, they will probably be greatest in small bays/side-arms, intermediate (but perhaps still large) in the main channels and smallest out in Cook Strait. At any given location, the magnitude and direction of any wind-discrepancies probably fluctuates day-to-day.

Thirdly, the model has no explicit benthic store of nutrients (particulate or solute). A fraction of any particulate material which settles to the bed is instantaneously mineralized and returned to the bottom-most layer of the water-column as ammoniacal nitrogen. In reality, sedimented organic material will mineralize at a variety of time-scales (time-scale of days to months – all of which are much slower than instantaneous). Consequently, short-term (and seasonal-scale) fluctuations in the rate of sedimentation to the seabed are unlikely to yield correspondingly abrupt fluctuations in ammonium efflux rates in the real-word – but they will do so in the model. In deep water, much of the detrital seston will mineralize (gradually) before hitting the seabed, but in shallow waters a much larger portion will sink to the seabed before mineralizing (hence, suffer from false, instantaneous mineralization). This implies that model performance probably degrades in poorly flushed shallow areas (e.g., the side-arms of inner Queen Charlotte).

In short, the model has been designed with the intent that it be used to derive an understanding of the regional (and large-bay scale) influences of farming rather than the farm-scale/small bay-scale influences.

4.4 Water-quality thresholds

A formal review of water-quality standards relating to aquaculture (or anything else) is outside the scope of our contract. Nonetheless, we offer a brief commentary to provide context that will help with interpretation of our simulation results.

[*Expanded Material within next four paragraphs*] If the proposed new farms were to be granted, they would undoubtedly be governed by consent conditions. Those may well include water-quality limits. As an example, the consent conditions governing the three recently consented NZKS salmon farms (two in Pelorus Sound, one in Tory Channel) include both seabed health and water-quality standards. The following text is extracted from the consent conditions for the Waitata[15] farm in Pelorus Sound as defined in Appendix 9 of the Board of Inquiry decision (Whiting, Beaumont et al. 2012):

Environmental Quality Standards (EQS) – Water Column

43. The marine farm shall be operated at all times in such a way as to achieve the following Water Quality Objectives in the water column:

a To not cause an increase in the frequency, intensity or duration of phytoplankton blooms (i.e. chlorophyl *a* concentrations ≥5 mg/m^3) [Note: water clarity as affected by chlorophyl *a* concentrations is addressed by this objective];

b To not cause a change in the typical seasonal patterns of phytoplankton community structure (i.e. diatoms vs. dinoflagellates), and with no increased frequency of harmful algal blooms (HAB's) (i.e. exceeding toxicity thresholds for HAB species);

c To not cause reduction in dissolved oxygen concentrations to levels that are potentially harmful to marine biota [Note: Near bottom dissolved oxygen under the net pens is addressed separately through the EQS – Seabed Deposition];

d To not cause elevation of nutrient concentrations outside the confines of established natural variation for the location and time of year, beyond 250m from the edge of the net pens;

e To not cause a statistically significant shift, beyond that which is likely to occur naturally, from a oligotrophic/mesotrophic state towards a eutrophic state;

f To not cause an obvious or noxious build-up of macroalgal (eg sea lettuce) biomass [Note to be monitored in accordance with Condition 66h].

On the assumption that the water-quality consent conditions for the Waitata farm may serve as prototypes for those that will govern any new (replacement) farms, we note that our modelling can be viewed as having some relevance[16] to conditions (a) and (e) of the Waitata farm's consent conditions.

The Waitata consent conditions leave some important details unclear. For example, different phytoplankton species are of differing sizes. The smallest taxa have cell sizes < 1 µm. The largest are > 100 µm. The term microplankton is often used to refer to phytoplankton >20 µm. Those in the 2 - 20 µm range are often referred to as nanoplankton. Those in the < 2 µm size-class are referred to as picoplankton. In coastal waters, chlorophyll concentrations are usually measured using glass-fibre (GF) filters having a nominal pore-size of 0.8 µm (GF-F filter) or 1.2 µm (GF-C filter), but the consent conditions contain no discussion of whether they refer to total chlorophyll (all size fractions) or just the chlorophyll caught on a GF-C filter (which is what has usually been used in the Sounds over many years). In a similar vein, the consent conditions state only that the frequency of algal blooms should not change without commenting upon what time-scales and space-scales (how many samples)

[15] The conditions for the Richmond farm are not materially different.

[16] Some might argue that it is also relevant to condition (d), but we disagree for two reasons. The horizontal spatial resolution of the model (200 m) is such that it cannot resolve near-farm concentration gradients well. This is compounded by the fact that the model makes no attempt to account for the effect of farm-induced drag upon flow patterns in the immediate vicinities of farms.

should be considered when calculating the concentration or upon how chlorophyll should be measured.

Perhaps as an acknowledgement that some details remained to be resolved, the conditions required that provisional water-quality standards and management response protocols be nominated and agreed upon by an independent review panel. A suite of provisional standards have been negotiated and approved by the review panel (Morrisey, Anderson et al. 2015)[17]. The standards and protocols will be reviewed periodically (and may change as a result). The present versions include provision for assessment and possible intervention should monitoring reveal chlorophyll concentrations (as measured on a GF-C filter[18]) in excess of 3.5 mg m^{-3} in three successive months (at any one station, or across several stations). Note however, that whilst each exceedance of 3.5 mg m^{-3} triggers a process aimed at determining whether the exceedance was driven by farms, further interventions aimed at reducing farm-effects will only be required in the event that the farms are deemed to be the cause of the exceedance. The reader is referred to Morrisey, Anderson et al. (2015) for a more detailed description of the protocols.

By way of comparison, the NOAA Assessment of Estuarine Trophic Status (ASSETS) is a USA-derived protocol for evaluating eutrophication based on the National Estuarine Eutrophication Assessment (NEEA) database (Bricker, Ferreira et al. 2003). Bricker et al. conclude that chlorophyll concentrations that are in excess of 5 mg chl m^{-3} during the 'annual bloom period' are considered indicative of at least a moderate impact[19]. Systems in which chlorophyll concentrations do not exceed 5 mg chl m^{-3} during the annual bloom period are deemed to be unimpacted.

In MDC's water-quality sampling in Queen Charlotte Sound (monthly at five stations since July 2011 up to and including March 2015), 5 mg chl m^{-3} (measured using a GF-C filter) has been exceeded in four water samples. All were near-surface (rather than near bed) samples. Two stemmed from station QCS-1 (April 2013, August 2013) and two from station QCS-2 (May 2013, August 2013). Both stations are within inner Queen Charlotte. In total, there have been more than 90 near-surface water samples collected at stations QCS-1 and QCS-2. Thus, 5 mg m^{-3} has been exceeded in about 5% of the near-surface sampling records from inner Queen Charlotte. The vast majority (79 of 90 records) of near-surface measurements from inner Queen Charlotte have been below 3 mg chl m^{-3}.

4.5 Assessment relative to water-quality standards

We acknowledge the fact that the model suggests that (even in the baseline$_{f2016}$) the 5 mg m^{-3} threshold will be broken from time to time (see, for example, Figure 3-1d), but we re-iterate that: (a)

[17] In a separate process, NZKS and MDC have also negotiated a set of protocols to manage seabed health around the NZKS farms Keeley, N., Gillard, M., Broekhuizen, N., Ford, R., Schuckard, R., Urlich, S. (2015) Best Management Practice guidelines for salmon farms in the Marlborough Sounds: Benthic environmental quality standards and monitoring protocol (Version 1.0 January 2015). *MPI Technical Paper*. Ministry of Primary Industries, Wellington: 47. http://www.mpi.govt.nz/news-and-resources/publications/.

[18] GF-C filters have a nominal pore-size of approx. 1.2 µm. GF-C or, more commonly, GF-F (0.7 µm) are commonly used to measure phytoplankton Moran 1999. In practice, both capture very similar quantities of phytoplankton, and both fail to capture very small cells Moran, X.A.G., Gasol, J.M., Arin, L., Estrada, M. (1999) A comparison between glass fiber and membrane filters for the estimation of phytoplankton POC and DOC production. *Marine Ecology - Progress Series*, 187: 31-41. Knefelkamp, B., Carstens, K., Wiltshire, K.H. (2007) Comparison of different filter types on chlorophyll-a retention and nutrient measurements. *Journal of Experimental Marine Biology and Ecology [J. EXP. MAR. BIOL. ECOL.]*, 345: 61-70. The consent conditions do not discuss what size-fractions of phytoplankton should be considered when calculating chlorophyll abundance but we note that Marlborough District Council data stem from GF-C filters. The majority of NIWA's own data from the region (Pelorus Sound) stem from GF-C filters and we believe that the majority of other data-sets (e.g., those of the Cawthron Institute) will also have used GF-C or, perhaps, GF-F filters.

[19] We discuss Bricker et al. analysis and the 5 mg m^{-3} threshold because it is broadly consistent with the mandated consent conditions for the three recently approved NZKS farms in the Sounds. The reader should not infer that we are advocating in favour (or against) applying the NOAA classification scheme to the Marlborough Sounds within this report. The NOAA scheme is but one of several in the literature. Unfortunately, whilst most offer chlorophyll thresholds, many are vague in important details (e.g., degree of spatial-temporal averaging to apply to field data before comparing measurements with thresholds, size-fraction of the phytoplankton community to consider etc.).

this is already happening (infrequently) in reality but we do not believe that it is indicative that the system is in imminent danger of ‘collapse’, (b) there is evidence to suggest that the model is over-estimating time-averaged chlorophyll concentration using farming conditions more representative of those during the majority of the time that MDC have sampled[20]. If, (i) the model were generating more realistic summertime chlorophyll concentrations in the ‘historical operating conditions’ scenario, and (ii) the predicted chlorophyll increments arising from the various alternative (increased) farming scenarios remain of the same magnitude (same excursion size, but over-and-above the true present-day time-average), we believe that the model would yield fewer breaches of the 5 mg chl m^{-3} threshold than the present variant does. Elaborating further: since, (i) the vast majority of historical chlorophyll measurements in the surface waters of inner Queen Charlotte have been less than 3 mg m^{-3}, (ii) the simulated time-averaged total chlorophyll increase in the inner Sound is circa 0.2 mg m^{-3} (relative to the existing operating conditions scenario; note that the time-averaged increase in Onapua Bay is larger than this), and (iii) the maximum instantaneous increment within inner Queen Charlotte is predicted to be circa 0.4 mg m^{-3}, we consider it unlikely that values >5 mg m^{-3} (GF-C chlorophyll) will become a frequent occurrence (i.e., we suspect that the system is unlikely to shift from Bricker’s ‘unimpacted’ category into the ‘moderately impacted one’). Nonetheless, values in excess of 5 mg chl m^{-3} may become a little more common. Similarly, breaches of the precautionary 3.5 mg chl m^{-3} threshold that has been agreed for the three new NZKS fish farms: Ngamahau (Tory Channel), Waitata and Richmond (Pelorus Sound) may come to be exceeded more frequently than it has been the case in the recent past.

The difference between the simulated chlorophyll concentrations in the $\text{baseline}_{\text{f2016}}$+Tipi2+Oyster3+Motu5 and existing approved farms (AM_AF_WD) scenarios suggests that time-averaged summertime-concentrations of total chlorophyll may increase by circa 0.4 mg m^{-3} in inner/central Queen Charlotte relative to present day conditions. If we assume that all of that additional chlorophyll accrues into cells that are large enough to be captured on a GF-C filter, we can calculate an upper bound upon the extent to which GF-C filterable chlorophyll concentration will increase.

Broekhuizen,Hadfield (2015) reported that, at that time, the average of GF-C filtered spring summertime chlorophyll from the two Marlborough District Council stations that are within inner Queen Charlotte (QCS-1 & 2) was 1.24 (standard deviation=0.66) mg chl m^{-3} (Broekhuizen and Hadfield 2015). Adding 0.4(ish) to 1.24, we infer that summertime average GF-C filterable chlorophyll concentration may rise to a maximum of approximately 1.6 - 1.7(ish) mg chl m^{-3} (an increase of approximately 37-45%). Those magnitudes of change are similar to coefficient of variation (standard deviation/mean =0.66/1.24 =0.53). This implies that the change is not especially extreme relative to the variation in summertime measurements. Nonetheless, as a persistent (chronic), summertime change it does feel large enough to be note-worthy (indicative that some other aspects of system function/behaviour may change). It is not clear what (if any) additional changes may occur in response to the increased phytoplankton (and zooplankton) or how large they would be but we suspect that they would be subtle. We note that mussel yields in Beatrix Bay varied by approximately 25% over the 1995-2005 period seemingly driven by a (approximately) three-fold (300%) variation in particulate nitrogen concentrations (Zeldis, Howard-Williams et al. 2008). On

[20] An earlier piece of work (Hadfield, Broekhuizen & Plew, 2014) adopted a different baseline ($\text{baseline}_{\text{f2012}}$) that did not contain the recently constructed Ngamahau farm. The simulated chlorophyll concentrations in the $\text{basseline}_{\text{f2012}}$ scenario also tend to exceed the chlorophyll concentrations that have been measured in the Marlborough Distrcit Council monitoring during the summer months.

that basis, we speculate that a 45% change in phytoplankton/chlorophyll is unlikely to drive major changes through direct trophic linkages.

In the preceding paragraph, we suggest that the direct trophic consequences of any phytoplankton increase will be small, but it is important to note that there may be other (perhaps, larger) effects. The increased detrital concentrations will exert an additional oxygen demand as it decays. This may increase the extent to which the seawater becomes under-saturated with oxygen. The oxygen data from the Marlborough District Council monitoring are scarce (< two years' worth) in comparison with the data on nutrients etc., but dissolved oxygen levels have usually exceeded 7.5 mg O_2 L^{-1} (roughly 85-90% saturation) throughout the water-column. The lowest oxygen concentrations have been recorded in the near-bed waters at sites QCS-1 and QCS-2 (around 6-6.5 mg L^{-1} (60-70% saturation) during the summers of 2013/14 and 2014/15). 6 mg O_2 m^{-3} is well above the lethal concentrations for the majority of taxa that are most sensitive to hypoxia (such as fish and crustacean). Indeed, 6 mg O_2 m^{-3} is also well above the median concentrations for sub-lethal effects for members of these taxa (approx. 4 mg O_2 m^{-3}, Vaquer-Sunyer and Duarte 2008). Whilst the ROMS/Fennel model does offer dissolved oxygen as an optional state-variable, we have not yet turned this variable on. Thus, we can make no quantitative statements about changes in oxygen levels in response to additional fish-farm inputs.

4.6 Onapua Bay

Onapua Bay has developed harmful algal blooms in the past, particularly blooms of the toxic dinoflagellate *Alexandrium catenella* (a Paralytic-Shellfish-Poisoning species) (MacKenzie, Harwood et al. 2013). The conditions that enabled those blooms are not well understood. Our model does not explicitly represent toxic algae as independent component(s) of the phytoplankton community. Rather, it has only one phytoplankton class, representing total phytoplankton. Thus, we cannot use our model to make any quantitative statements about how the magnitude or frequency of toxic algal blooms would change in response to additional farms. Nonetheless, in all of our additional farms scenarios, we note that the addition of farms led to increased concentrations of ammonium and phytoplankton within Onapua Bay. Indeed, during summer, that inlet generally showed the largest magnitude increases in phytoplankton concentration. We have not sought to determine whether the (simulated) high phytoplankton populations which accrue within Onapua Bay sometimes become transported elsewhere (i.e., whether Onapua Bay can act as a 'seed area' for blooms which spread elsewhere). Whilst we speculate that the farms are unlikely to influence the probability of physical conditions that favour export, they clearly influence the probability of a bloom developing within Onapua bay. If (a) Onapua bay does occasionally act as a seed area from which blooms spread, and (b) the abundance of the 'bloom population' at the time that it exits from Onapua Bay influences the subsequent size and/or life-time of the exported bloom, then it seems reasonable to infer that both of the 'additional farms' scenarios will make such 'exported blooms' more probable.

4.7 Degrees of enrichment – a between scenario ranking

We have been asked to make recommendations "*for/against farm placement/relocation sites with respect to simulated water-quality impacts*". Our modelling considers only a limited sub-set of water-quality indicators and we have been given no guidance as to what measures of water-quality to use, or what parts of the Sound system (incl. Cook Strait waters outside the Sounds) are considered most 'valuable'. Ultimately, issues of acceptability and relative value are societal questions to which we cannot provide unilateral or definitive answers. Nonetheless, we offer the following thoughts.

In the absence of any other guidance, we have elected to compare our simulation results with trigger thresholds that reflect some of the water-quality consent conditions which have been applied to three newly approved New Zealand King Salmon Ltd. farms (see section 4.4). In particular, these triggers prescribe maxima chlorophyll levels and minimum dissolved oxygen concentrations.

This report presents results from a 'baseline$_{f2016}$' scenario and three different 'future farming scenarios'. An earlier report (Broekhuizen and Hadfield 2015) considered a further six 'future farming scenarios' for the Queen Charlotte/Tory Channel system. Whilst we do not intend to discuss any of those earlier scenarios in detail within this report, but we consider it relevant to make a brief comparison (ranking) of all nine 'future farming scenarios' (those of this report and those of the preceding one). We chose to rank the simulations according to the degree of summer-time relative chlorophyll enhancement induced within inner Queen Charlotte Sound and Onapua/Opua Bay (ie the vicinities of Marlborough District Council sampling sites 1 & 2) because:

- Marlborough District Council monitoring data indicate that chlorophyll concentrations within the main-stem of inner Queen Charlotte Sound tend to be greater than those in the main-stem of Tory Channel or central/outer Queen Charlotte. Similarly, the lowest dissolved oxygen concentrations tend to arise in the deeper waters of inner Queen Charlotte.
- Onapua/Opua Bay has a history of toxic algal blooms and Cawthron monitoring data indicate that it is sometimes home to chlorophyll abundances which are high relative to the main stem of Tory Channel and central/outer Queen Charlotte.
- All of the scenarios suggest that the greatest seston changes (concentration increases) will arise within inner Queen Charlotte Sound and Onapua/Opua bays.
- Our model does not consider dissolved oxygen, but it does consider chlorophyll and organic detritus (which will consume oxygen as it decays). Interestingly (and probably not by coincidence), the model also suggests that chlorophyll and detrital concentrations tend to be higher in the inner part of Queen Charlotte and Opua Bay than in most other bathymetrically similar parts of the system.
- It seems probable that any future farms will be governed by consent conditions that place an upper bound upon acceptable chlorophyll and oxygen concentrations (see sections 4.4 & 4.5).

Whilst neither the chlorophyll maxima, nor the oxygen minima within inner Queen Charlotte are sufficiently extreme to warrant immediate concern, the collective facts outlined above indicate that inner Queen Charlotte and Opua/Onapua bays may be the most enriched[21] parts of the Sound at present. Furthermore, modelling suggests they are the regions which are most susceptible to further enrichment by the proposed additional/relocated farms. The fact that the model predicts the largest farm induced changes will arise in areas that already show some characteristics of a (very mildly) enriched system makes it easy to justify choosing to address the farm-placement-favourability

[21] Note that we use the term phrase 'most enriched' only in a relative sense. In freshwater systems, the scale of trophic enrichment ranges across the spectrum oligotrophic-mesotrophic-eutrophic-hypertrophic. Different authors adopt differing means of defining the thresholds between each category. Furthermore, some authors feel that the classification scheme is less applicable to estuarine systems {Bricker, 2003 #2510}. Nevertheless, we suggest that Inner Queen Charlotte would probably fall into the upper part of the oligotrophic/lower part of the mesotrophic categories whilst Onapua/Opua Bay might creep a little higher into the mesotrophic category.

question by ranking the farming scenarios in accordance with the magnitudes of water-quality enrichment they induce within inner Queen Charlotte Sound and Opua Bay.

Table 4-1: The Future Farming scenarios considered within this report and (Broekhuizen and Hadfield 2015) ranked by degree of spring/summer chlorophyll enrichment induced within inner Queen Charlotte Sound (vicinities of MDC sites QCS-1 & QCS-2). Higher ranking (higher numerical score) implies greater quantum of induced chlorophyll change.

Scenario	Source report	Ranking
AM_AF_WD	Both reports	0
AM_AF_WD+Tipi2	(Broekhuizen and Hadfield 2015)	1
AM_AF_WD+Motu5	(Broekhuizen and Hadfield 2015)	2
AM_AF_WD+ Weka5	(Broekhuizen and Hadfield 2015)	3
AM_AF_WD+Tipi2+Oyster3	This report	4
AM_AF_WD+Tipi2+Motu5	(Broekhuizen and Hadfield 2015)	5
AM_SF_WD+Tipi2+Oyster3+Motu5	This report	6
AM_SF_WD+Tipi2+Motu5+Weka5	(Broekhuizen and Hadfield 2015)	7
AM_AF_WD+Tipi2+Motu5+Weka5	(Broekhuizen and Hadfield 2015)	8
AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5	This report	9

Any recommendation as to the most (un)favourable combination of farm locations hinges upon the relative weights which one places upon minimising water-quality changes versus enhancing the perceived economic value of fish-farming operations within the Sounds.

If the sole criterion for site selection is that adverse changes in water-quality within the inner part of Queen Charlotte and Onapua/Opua bay should be minimized then we conclude that all of the alternative scenarios are unacceptable (relative to the baseline, they all induce a small degree of enrichment within inner Queen Charlotte).

If, however, one is prepared to accept a small degree of enrichment within inner Queen Charlotte and locations such as Onapua Bay, then at least some of the alternative scenarios may become acceptable. It is our opinion that none of the alternative scenarios will lead to frequent breaches of the water-quality thresholds that govern present NZKS farms in the Sounds – however, we believe that the probability of a breach will increase as one moves downward through Table 4-1. An individual's decision as to the favoured scenario may depend upon where (s)he chooses to strike the balance between enrichment (risk that a mandated water-quality threshold is breached within inner Queen Charlotte & Onapua/Opua Bay) and any anticipated increased economic value accruing to one or more of: (a) themselves, (b) fish-farm owners, (c) farm-employees and (d) the wider economy[22].

Broadly speaking, those who seek to minimise the risk of a breach of environmental standard will favour scenarios with a smaller rank-score within Table 4-1. The risk of triggering a water-quality breach is minimized by favouring scenarios which:

[22] For simplicity, we focus upon a possible trade-off between water-quality and perceived economic benefits, but we acknowledge that there are other factors that individuals may consider (benthic effects, free navigation, land-scape value etc.).

(i) minimize the net increase in feed loads to the system (implying a favourability ranking: Tipi > Oyster > Motukina = Te Weka), and

(ii) place the new/relocated farms closer towards the Cook Strait end of Tory Channel (implying a favourability ranking: Tipi > Motukina > Oyster > Te Weka).

Both criteria favour adoption of the Tipi Bay site (because it is the smallest candidate site and the closest to Cook Strait). Conversely, both criteria select against the Te Weka site (it is one of the largest and it is the closest to the Queen Charlotte end of Tory Channel). The Motukina and Oyster sites are of intermediate favourability. The modelling implies that farm combinations involving Oyster Bay but not Motukina induce slightly lesser enrichment than those involving Motukina but not Oyster.

We were asked to make recommendations about favoured farm placements with respect to water-quality impacts. We have chosen to focus upon impacts within inner Queen Charlotte and Opua/Onapua bay because these appear to be most 'at risk' but we acknowledge that there are many parts of the Sound for which there are no data - so we have no definitive way of knowing that inner Queen Charlotte and Opua/Onapua Bays genuinely are the most enriched parts of the system at present. We also acknowledge that some individuals may have legitimate reasons to prefer minimising water-quality effects elsewhere in the Sound. For example, whilst the swapped farm scenarios do not rank amongst the more favourable ones by our chosen criterion, some may choose to favour them because they place greater value upon reducing aquaculture impacts within Otanerau and/or Ruakaka Bay at the expense of increasing enrichment within inner Queen Charlotte/Onapua/Opua Bay.

The additional farms that we have been asked to consider in this report (and the preceding one) are all in Tory Channel. Strong tidal currents ensure that Tory Channel (and the immediately adjacent part of Queen Charlotte) is vigorously mixed and flushed relatively rapidly. The individual 'pelagic-zone footprints' of each farm quickly merge. Previous work (Broekhuizen and Hadfield 2015) suggests that, had we simulated the farms individually, and then combined their individual footprints, the results would be very similar to those inferred from the simulations that we have made (where two or more new farms were added into a single simulation). This near-additivity indicates that the model predictions (with respect to fish-farming at the scales that we have considered) are not sensitive to any of the non-linear interactions present within the model's mathematical structure.

5 Conclusions

The key findings from this work are:

- For ammonium, the largest farm-effects arise in the immediate farm vicinities. For nitrate and seston, the largest effects arise in Grove Arm and side bays of Tory Channel (especially Onapua Bay). The explanation is straight-forward. Fish farms are net sources of ammonium (directly excreted by the fish), and of particulate organic nitrogen (faeces and waste feed) – which degrades into ammonium. It takes some time for the phytoplankton to fully incorporate the farm-derived ammonium into new biomass. During that time, the water (containing the additional ammonium and seed phytoplankton population) has been transported away from the source farm and subject to dispersive mixing. A similar argument holds with respect to conversion of ammonium into nitrate by bacterial activity. The combination of dispersive mixing and gradual uptake by phytoplankton and bacteria implies that ammonium concentration increases must decline with increasing distance from the farm. Conversely, population increases by phytoplankton etc., take time to develop, so phytoplankton and seston concentration increases tend to be greatest at some distance (travel time) away from the farms. Even close to the fish-farms, ammonium concentrations will remain well below levels considered toxic to aquatic life.
- The farms are predicted to have little effect upon phytoplankton, zooplankton and detritus during the winter-months. During those months, algal growth is limited by light rather than nutrients. Thus, the additional nitrogen can only be slowly incorporated into additional biomass. Much of it is exported from the system (to Cook Strait or to the atmosphere through denitrification) before it can be utilized.
- Regardless of which farms are added, the largest summertime changes in phytoplankton abundance tend to arise in Onapua Bay and Grove Arm. The changes in Onapua Bay tend to exceed those in Grove Arm.
- The changes (relative to baseline_{f2016}) induced by the AM_AF_WD+Tipi2+Oyster3+Motu5 are approximately twice as large as those induced by the AM_AF_WD+Tipi2+Oyster3 scenario.
- The smallest (by total annual feed load) scenario (AM_AF_WD+Tipi2+Oyster3) yields summertime chlorophyll and detritus concentration increases of circa 2-4% within Grove Arm and Onapua Bay. The larger scenario (AM_AF_WD+Tipi2+Oyster3+Motu5) induces changes of around 4-8% in Grove Arm (and a little more in Onapua Bay).
- Threshold chlorophyll concentrations of 3.5 mg m^{-3} and 5 mg m^{-3} are both relevant in the context of the existing NZKS farms in Queen Charlotte/Tory Channel. The addition of new fish-farms, instantaneous chlorophyll concentrations will, perhaps, exceed 5 mg m^{-3} more often than they have over the past four years' of monitoring, but we believe that such events will remain rare and short-lived. Indeed, we believe they will usually remain below 3.5 mg m^{-3}.

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Appendix A Change maps for near-bed water quality properties

AM_AF_WD versus AM_AF_WD+Tipi2+Oyster3

Baseline$_{f2016}$ concentration	Relative concentration	Concentration change

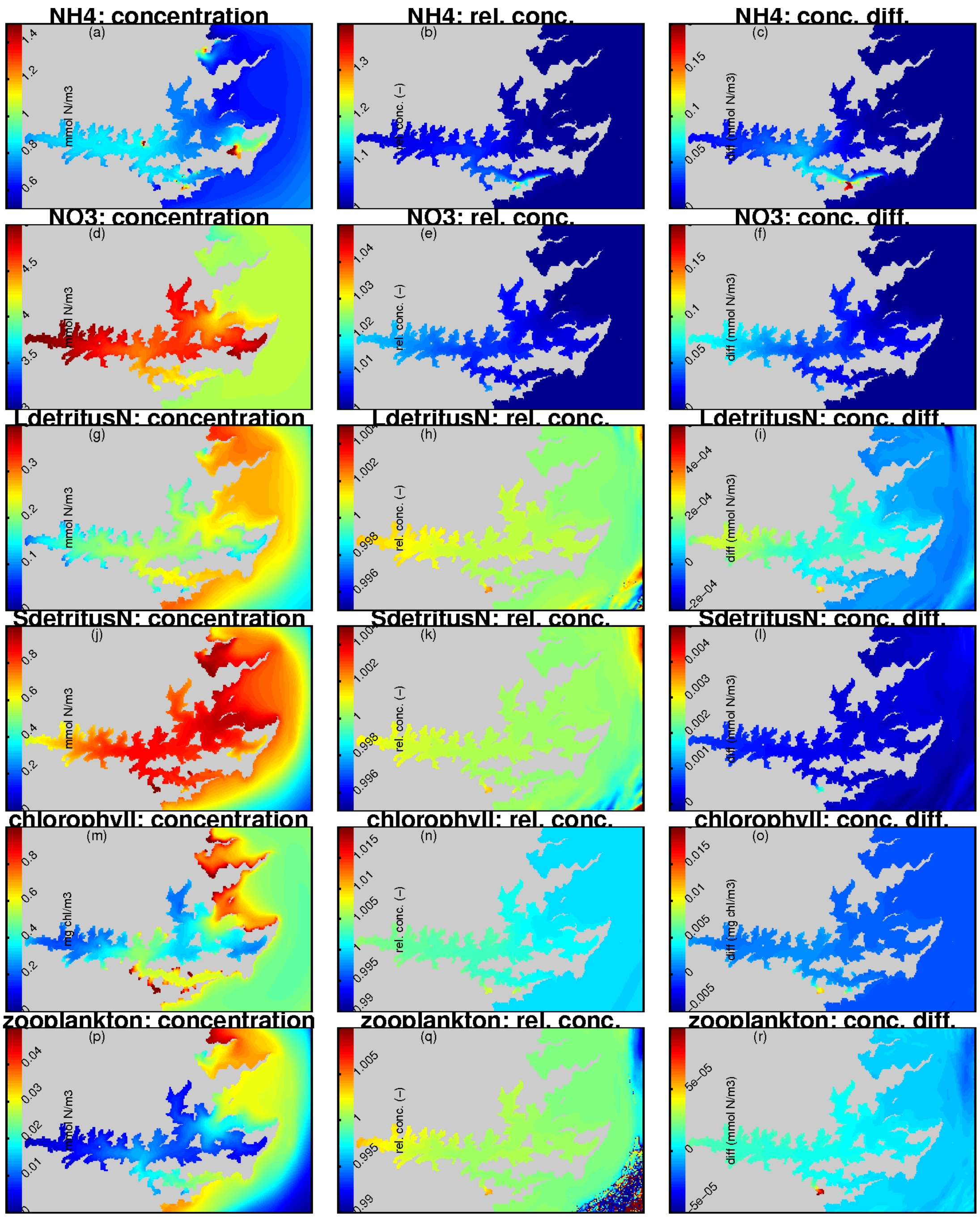

Figure A-1: False colour maps of time-averaged, winter-time, near-bed water-quality characteristics for the AM_AF_WD and AM_AF_WD+Tipi2+Oyster3 scenarios. Left-hand images: time-average concentration in the AM_AF_WD scenario. Central images: relative concentration (AM_AF_WD+Tipi2+Oyster3 relative to AM_AF_WD). Right-hand images: concentration change (AM_AF_WD+Tipi2+Oyster3 minus AM_AF_WD). Each row shows results for a different state-variable (as indicated in the title of the left-hand-most image of each row).

Baseline$_{f2016}$ concentration	Relative concentration	Concentration change

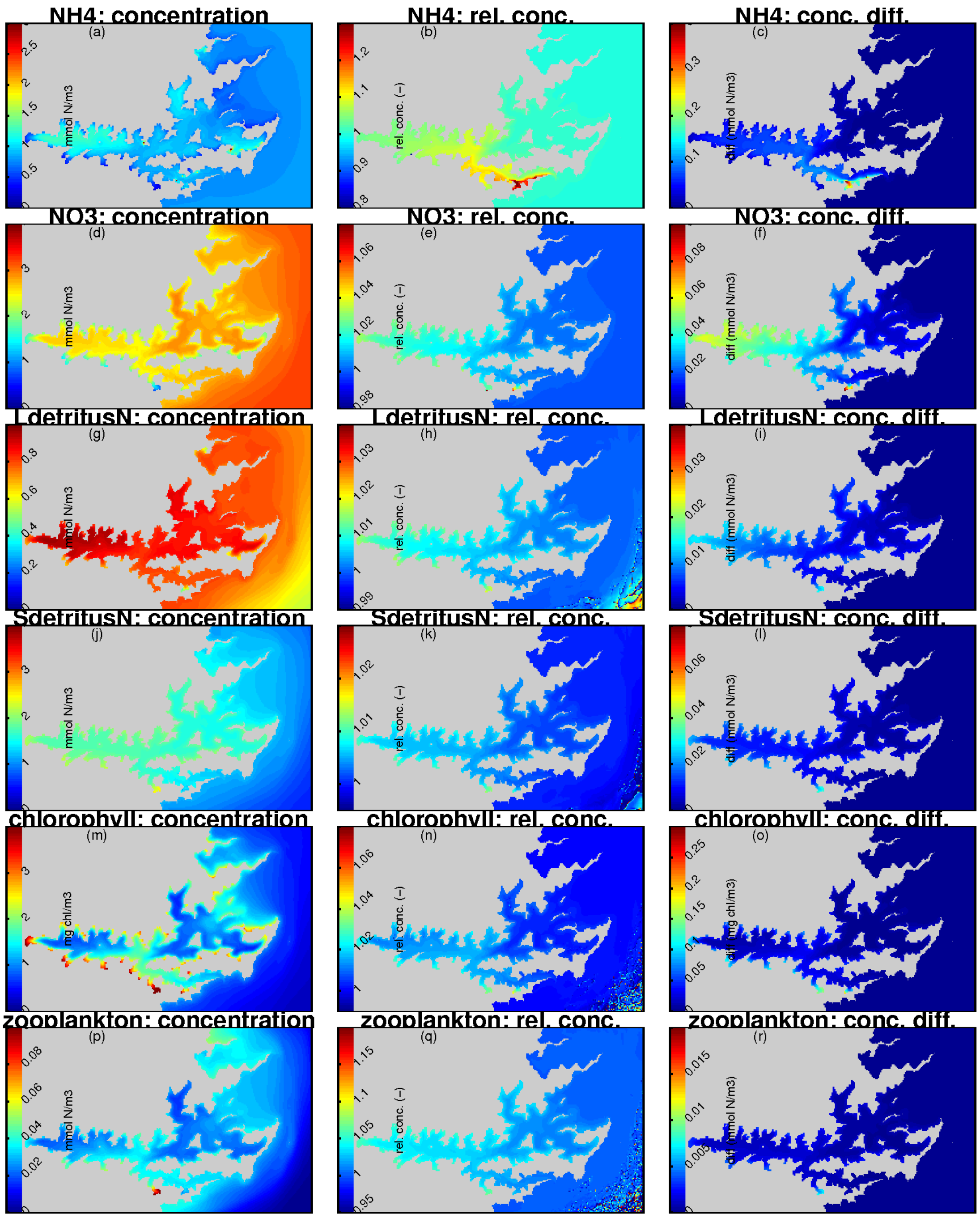

Figure A-2: False colour maps of time-averaged, summer-time, near-bed water-quality characteristics for the AM_AF_WD and AM_AF_WD+Tipi2+Oyster3 scenarios. Left-hand images: time-average concentration in the AM_AF_WD scenario. Central images: relative concentration (AM_AF_WD+Tipi2+Oyster3 relative to AM_AF_WD). Right-hand images: concentration change (AM_AF_WD+Tipi2+Oyster3 minus AM_AF_WD). Each row shows results for a different state-variable (as indicated in the title of the left-hand-most image of each row).

AM_AF_WD versus AM_AF_WD+Tipi2+Oyster3+Motu5

Baseline$_{f2016}$ concentration	**Relative concentration**	**Concentration change**

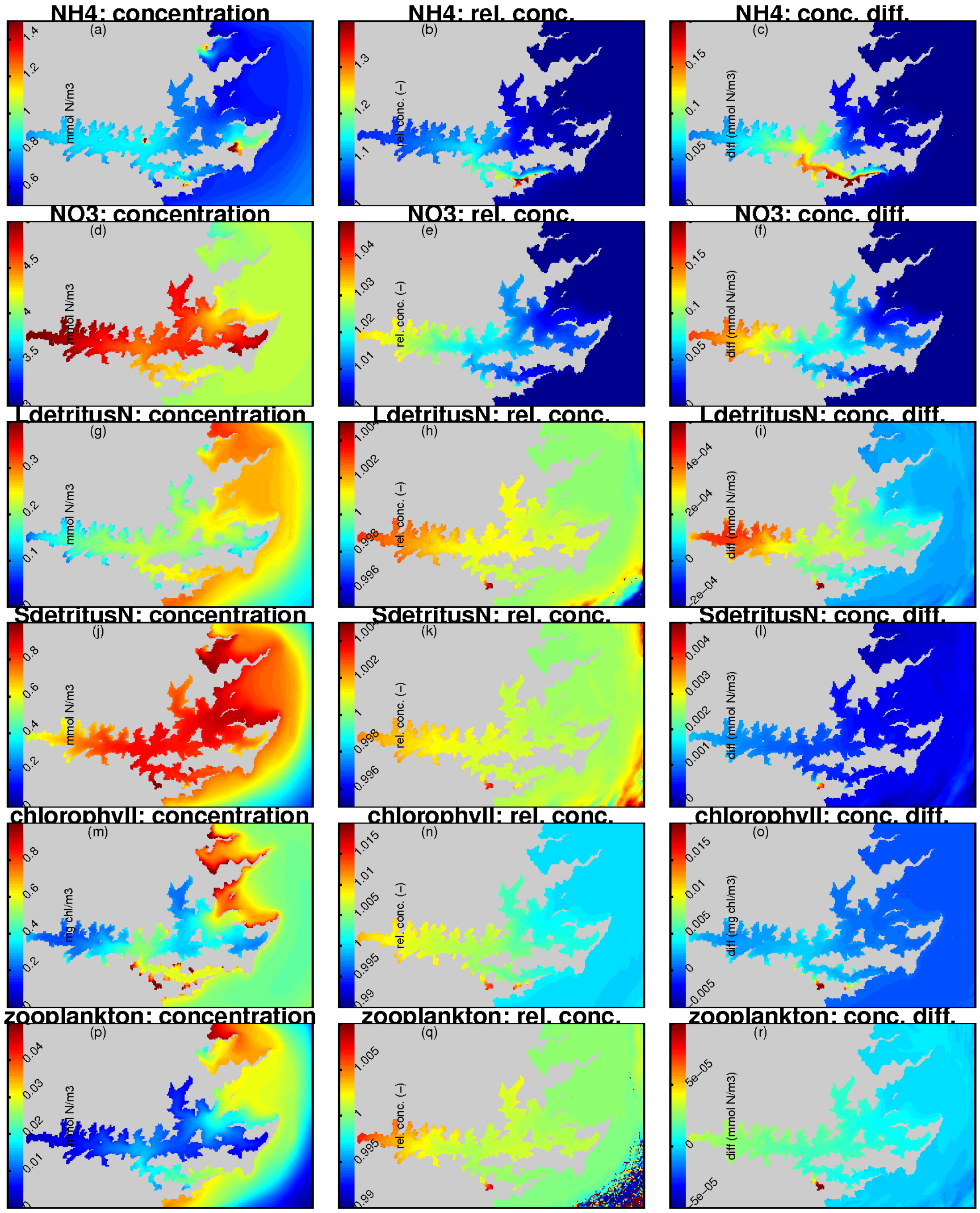

Figure A-3: False colour maps of time-averaged, winter-time, near-bed water-quality characteristics for the AM_AF_WD and AM_AF_WD+Tipi2+Oyster3+Motu5 scenarios. Left-hand images: time-average concentration in the AM_AF_WD scenario. Central images: relative concentration (AM_AF_WD+Tipi2+Oyster3+Motu5 relative to AM_AF_WD). Right-hand images: concentration change (AM_AF_WD+Tipi2+Oyster3+Motu5 minus AM_AF_WD). Each row shows results for a different state-variable (as indicated in the title of the left-hand-most image of each row).

Baseline$_{f2016}$ concentration	Relative concentration	Concentration change

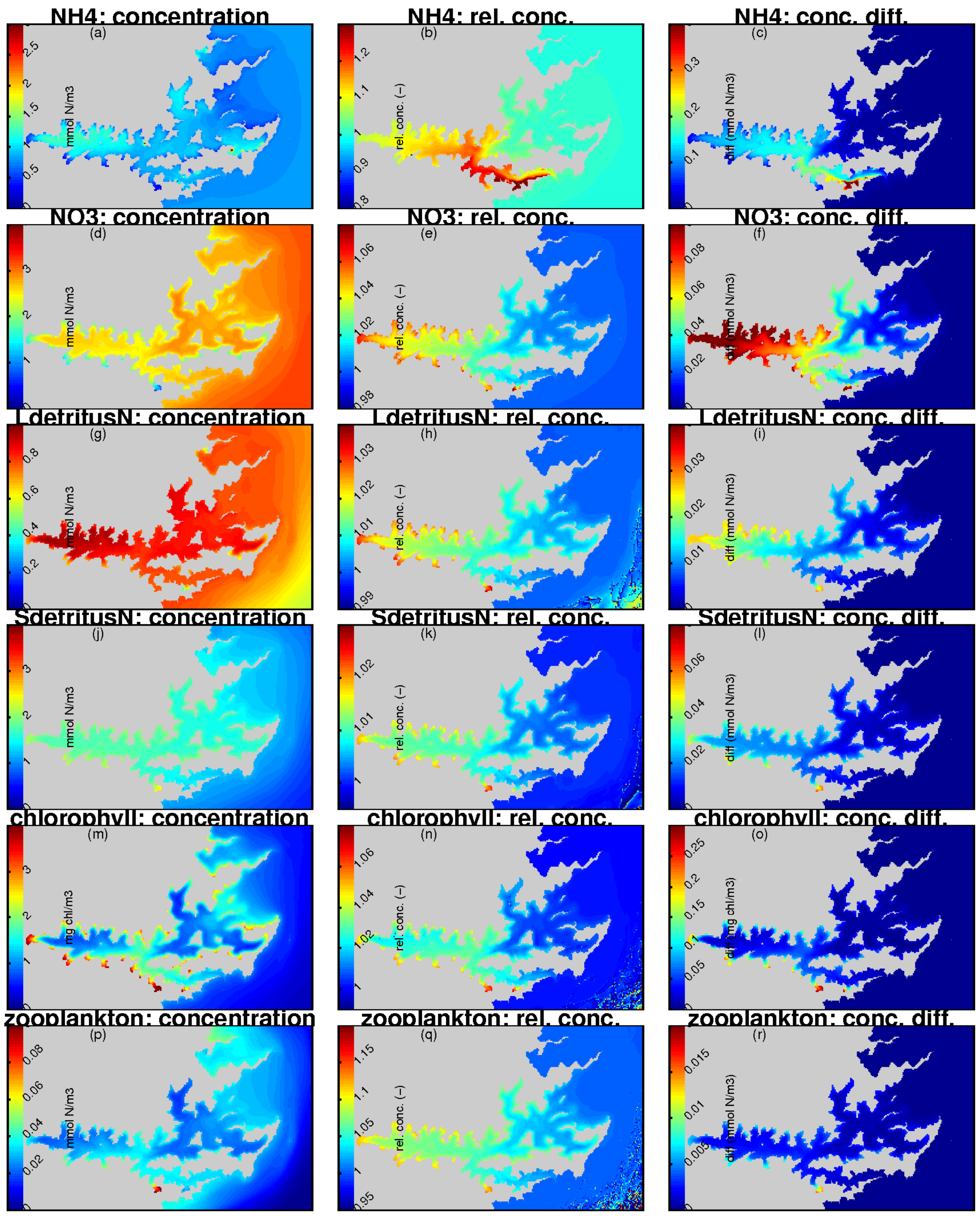

Figure A-4: False colour maps of time-averaged, summer-time, near-bed water-quality characteristics for the AM_AF_WD and AM_AF_WD+Tipi2+Oyster3+Motu5 scenarios. Left-hand images: time-average concentration in the AM_AF_WD scenario. Central images: relative concentration (AM_AF_WD+Tipi2+Oyster3+Motu5 relative to AM_AF_WD). Right-hand images: concentration change (AM_AF_WD+Tipi2+Oyster3+Motu5 minus AM_AF_WD). Each row shows results for a different state-variable (as indicated in the title of the left-hand-most image of each row).

AM_AF_WD versus AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5

Baseline$_{f2016}$ concentration	Relative concentration	Concentration change

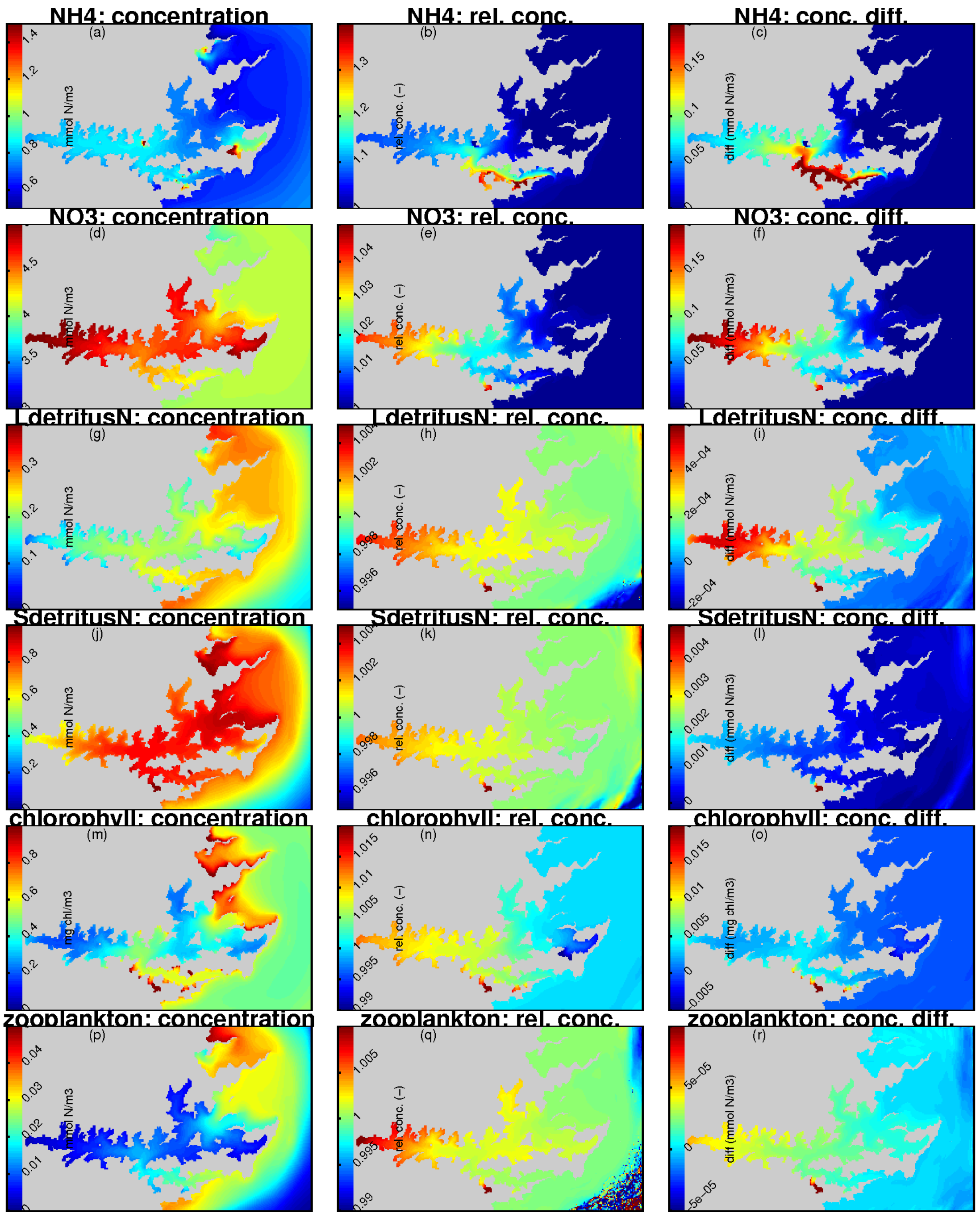

Figure A-5: False colour maps of time-averaged, winter-time, near-bed water-quality characteristics for the AM_AF_WD and AM_AF_WD+Tipi2+Oyster3+Motu5+Weka5 scenarios. Left-hand images: time-average concentration in the AM_AF_WD scenario. Central images: relative concentration (AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 relative to AM_AF_WD). Right-hand images: concentration change (AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 minus AM_AF_WD). Each row shows results for a different state-variable (as indicated in the title of the left-hand-most image of each row).

Baseline$_{f2016}$ concentration	Relative concentration	Concentration change

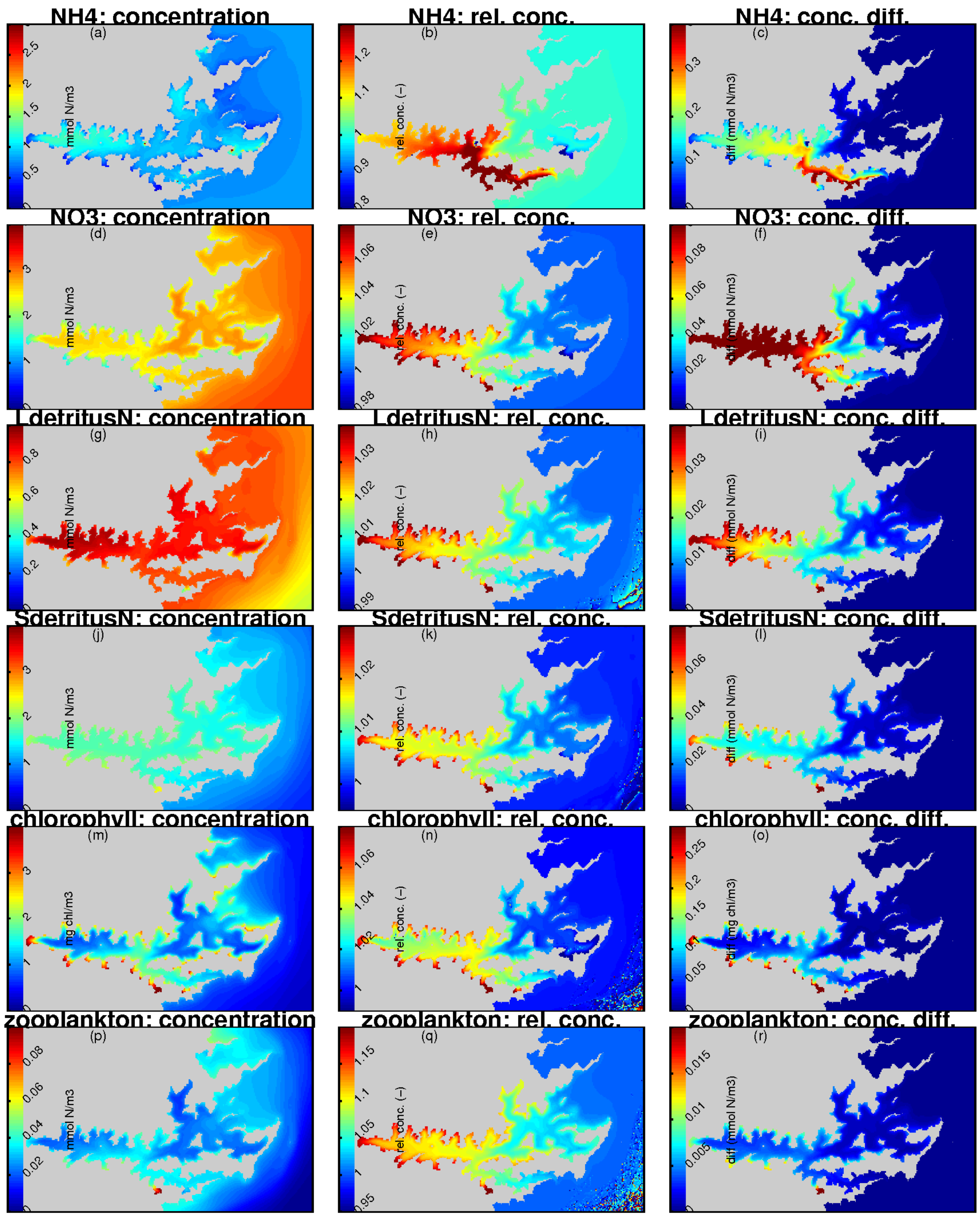

Figure A-6: False colour maps of time-averaged, summer-time, near-bed water-quality characteristics for the AM_AF_WD and AM_AF_WD+Tipi2+Oyster3 scenarios. Left-hand images: time-average concentration in the AM_AF_WD scenario. Central images: relative concentration (AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 relative to AM_AF_WD). Right-hand images: concentration change (AM_SF_WD+Tipi2+Oyster3+Motu5+Weka5 minus AM_AF_WD). Each row shows results for a different state-variable (as indicated in the title of the left-hand-most image of each row).