NIWA
Taihoro Nukurangi

Modelled water column effects on potential salmon farm relocation sites in Pelorus Sound

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Contents

Executive Summary ... 7

1 Introduction ... 16

2 Methods ... 21

2.1 Model modifications that have been implemented since our prior report ... 21

2.2 Farming scenarios & production schedules ... 22

2.3 Analysis and presentation of simulation results ... 25

3 Results ... 27

3.1 Changes examined at the scale of Pelorus Sound ... 27

3.2 Changes examined at bay-scale and finer ... 32

4 Discussion ... 60

4.1 Caveats and model limitations ... 60

4.2 Influence of the seaward boundary condition ... 64

4.3 Magnitudes and locations of change ... 64

4.4 Water-quality thresholds ... 66

4.5 Assessment relative to water-quality standards ... 68

4.6 Degrees of enrichment – a between scenario ranking ... 69

5 Acknowledgements ... 72

6 References ... 73

Appendix A Time-averaged results for near bed layer ... 75

Appendix B Time-series of state-variables at specific locations: comparison of Scenario 13 and the baseline$_{f2016}$ scenario ... 97

Tables

Table 1-1: Farm feed inputs for each scenario. 19

Table 3-1: Time-and-volume averaged differences (alternative scenario - baseline$_{f2016}$ scenario) of total nitrogen concentration. 30

Figures

Figure 1-1:	Location-maps for the various fish-farms considered in this report.	8
Figure 1-2:	Map of Pelorus Sound showing the locations of the seven Marlborough District Council water-quality monitoring sites.	14
Figure 2-1:	Maps illustrating which farms were present in each scenario.	24
Figure 3-1:	Time-series of the difference in volume averaged total nitrogen concentration (alternative scenario minus baseline$_{f2016}$ scenario).	28
Figure 3-2:	Time-series of the difference in volume averaged total nitrogen concentration (alternative scenario minus baseline$_{f2016}$ scenario).	29
Figure 3-3:	Scatter plot illustrating the relationship between the average total nitrogen concentration and total feed loads.	32
Figure 3-4:	Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 2 vs scenario 1).	37
Figure 3-5:	Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 2 vs scenario 1).	38
Figure 3-6:	Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 4 vs scenario 1).	39
Figure 3-7:	Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 4 vs scenario 1).	40
Figure 3-8:	Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 5 vs scenario 1).	41
Figure 3-9:	Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 5 vs scenario 1).	42
Figure 3-10:	Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 6 vs scenario 1).	43
Figure 3-11:	Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 6 vs scenario 1).	44
Figure 3-12:	Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 7 vs scenario 1).	45
Figure 3-13:	Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 7 vs scenario 1).	46
Figure 3-14:	Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 8 vs scenario 1).	47
Figure 3-15:	Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 8 vs scenario 1).	48
Figure 3-16:	Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 9 vs scenario 1).	49
Figure 3-17:	Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 9 vs scenario 1).	50
Figure 3-18:	Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 10 vs scenario 1).	51
Figure 3-19:	Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 10 vs scenario 1).	52
Figure 3-20:	Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 11 vs scenario 1).	53
Figure 3-21:	Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 11 vs scenario 1).	54

Figure 3-22: Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 12 vs scenario 1). 55
Figure 3-23: Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 12 vs scenario 1). 56
Figure 3-24: Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 13 vs scenario 1). 57
Figure 3-25: Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 13 vs scenario 1). 58

Figure A-1: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 2 vs scenario 1). 75
Figure A-2: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 2 vs scenario 1). 76
Figure A-3: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 4 vs scenario 1). 77
Figure A-4: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 4 vs scenario 1). 78
Figure A-5: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 5 vs scenario 1). 79
Figure A-6: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 5 vs scenario 1). 80
Figure A-7: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 6 vs scenario 1). 81
Figure A-8: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 6 vs scenario 1). 82
Figure A-9: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 7 vs scenario 1). 83
Figure A-10: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 7 vs scenario 1). 84
Figure A-11: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 8 vs scenario 1). 85
Figure A-12: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 8 vs scenario 1). 86
Figure A-13: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 9 vs scenario 1). 87
Figure A-14: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 9 vs scenario 1). 88
Figure A-15: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 10 vs scenario 1). 89
Figure A-16: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 10 vs scenario 1). 90
Figure A-17: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 11 vs scenario 1). 91
Figure A-18: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 11 vs scenario 1). 92
Figure A-19: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 12 vs scenario 1). 93

Figure A-20:	Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 12 vs scenario 1).	94
Figure A-21:	Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 13 vs scenario 1).	95
Figure A-22:	Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 13 vs scenario 1).	96
Figure B-1:	Simulated near-surface concentrations at the Marlborough District Council site PLS-1.	97
Figure B-2:	Simulated near-surface concentrations at the Marlborough District Council site PLS-2.	97
Figure B-3:	Simulated near-surface concentrations at the Marlborough District Council site PLS-3.	98
Figure B-4:	Simulated near-surface concentrations at the Marlborough District Council sites PLS-4.	98
Figure B-5:	Simulated near-surface concentrations at the Marlborough District Council site PLS-5	99
Figure B-6:	Simulated near-surface concentrations at the Marlborough District Council site PLS-6	99
Figure B-7:	Simulated near-surface concentrations at the Marlborough District Council site PLS-7	100

Executive Summary

The Ministry for Primary Industries (MPI) is seeking to determine whether Pelorus Sound[1] has the capacity to support more sustainable salmon production through relocating[2] some existing farms to alternative sites that are believed to be better suited to salmon farming. These sites may be better flushed, in deeper water, or less prone to high water temperatures and are expected to have greater capacity to sustain fish-farming under present and future environmental conditions.

MPI commissioned NIWA to assess the manner in which the Sound's water-quality (trophic status) might change in response to changed locations and numbers/size of fish farms. We were not asked to examine any effects that might arise on the seabed in the vicinity of the farms.

The farms which may be relocated are: the two in Crail Bay, the one in Forsyth Bay and the one in Waihinau Bay. The potential new sites to which these may be relocated are in: (a) inner Waitata Reach (Horseshoe Bay and Richmond Bay South); (b) central Waitata Reach (Waitata mid-channel SW and Waitata mid-channel NE); and (c) the outer-most reaches of Pelorus Sound (Blowhole Point South and Blowhole Point North).

We discuss results from 12[3] different farm combinations (Figure 1-1, Table 1-1). Henceforth, we refer to each combination as a 'scenario'. Scenario 1 includes only those farms that are currently permitted to operate (albeit that two of these have only recently gained consents and have only had fish in the water for a matter of months). We refer to this scenario as the 'baseline scenario'. We refer to the remaining scenarios as 'alternative scenarios' or 'future scenarios'. The assessment was made relative to a baseline scenario that includes all currently (2016) approved farms (mussel and fish). There are (Crail Bay 1, Crail Bay 2, Beatrix Bay, Waitata, Richmond, Waihinau & Forsyth). We will refer to this baseline as baseline_{f2016}. The baseline_{f2016} differs from the baseline (baseline_{f2012}) adopted in an earlier report to Marlborough District Council (Broekhuizen, Hadfield & Plew, 2015). 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 Waitata & Richmond salmon farms was not present in the earlier baseline_{f2012} scenario.

There are seven distinct fish farms in the baseline_{f2016} scenario. The majority of the alternative scenarios also have seven farms but three (scenarios 2, 11, 12) have only six farms. Summed across all constituent farms within a scenario, all of the alternative scenarios permit a greater total annual feed input than the baseline_{f2016} scenario (Table 1-1). Amongst the alternative scenarios, the smallest (by feed inputs) has the feed inputs increasing by approximately 25% over the baseline_{f2016} (implying approx. 10 tonne d^{-1} additional feed). In the largest scenarios (by feed input), the permitted annual feed inputs increase by more than 300% relative to the baseline_{f2016} (implying approx. 65 tonne d^{-1} additional feed).

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[1] In this report, we consider Pelorus Sound to include all the water on the landward side of the diagonal line between Paparoa and Culdaff Points (Figure 1-1). This includes water within the inner-most parts of Pelorus Sound (Mahau and Kenepuru Sounds) and the water within Forsyth Bay. Anakoha and Guards Bay are excluded. The volume of Pelorus Sound as defined here is approximately 1.07×10^{10} m^3, or 10.7 km^3.

[2] The term 'relocate' is used as a convenient short-hand. The annual feed-load limits at the potential new sites that we have been asked to consider are often larger than those of any of the sites which the relocated farms 'replace'.

[3] Initially, we were asked to examine 12 different farm-combinations (scenarios) but, at a later date, we were instructed to ignore the third of the 12 combinations. Later still, we were asked to examine yet another scenario. To minimise risk of confusion in discussion amongst parties, we collectively agreed to retain the original numbering scheme when referring to scenarios. Results from scenarios 1, 2 and 4 - 13 are described in this report. Simulations corresponding to scenario 3 were never made.

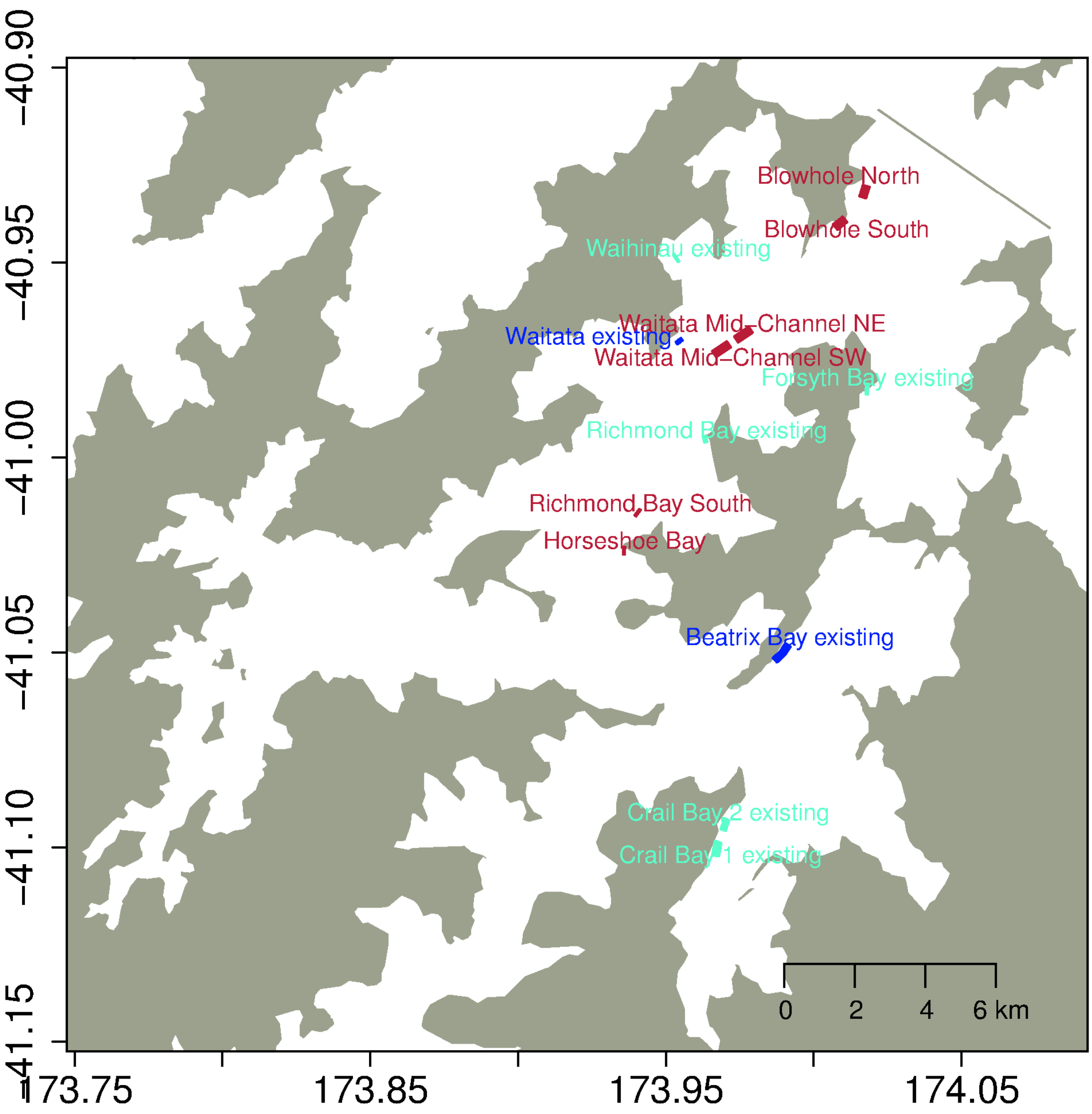

Figure 1-1: Location-maps for the various fish-farms considered in this report. Farms with current consents are shown in medium- or light- blue. Those in light blue are candidates for possible relocation. Red locations are candidates to receive the relocated farms. Note that none of the scenarios that we have examined included all of these farms. Scenario 13 includes a farm at the Waitata mid-channel NE site and none at the mid-channel SE site; however the spatial extent of the mid-channel NE farm is a little greater than indicated in this map. Figure 2-1 presents the farm-location maps corresponding to each individual scenario. In this report, we consider Pelorus Sound to include all the water on the landward side of the diagonal line between Paparoa and Culdaff Points.

The model we used for our simulations is based upon the widely used, open-source ROMS framework[4]. In earlier work, NIWA has used this framework to develop a specific implementation for the Pelorus Sound system (Broekhuizen, Hadfield et al. 2015). That implementation has been reviewed by Marlborough District Council, Cawthron Institute and MPI's Aquatic Environment Working Group.

[4] We have modified the open source code to enable mussel- and fish-farm influences upon water-quality to be represented.

The model aims to represent the influences that shellfish farms and fin-fish farms have upon the water-quality (trophic status) at the scale of large bays and the Sound as a whole (rather than at the scale of individual farms). It has 200 m resolution in the horizontal and twenty layers in the vertical. It accounts for the influences of wind, tides and freshwater inputs on flow. The model's state-variables[5] (used to describe the cycling of nitrogen-nutrient through the planktonic food-web) are: total ammoniacal nitrogen[6], 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 food web. The model has not been used to examine whether farms will increase the probability of hypoxia.

Mussel farms and fish-farms are represented within the model. Mussels are assumed to consume phytoplankton, zooplankton, and detritus. They release some of that material back into the water-column as faeces/pseudo-faeces (which rapidly sink to the seabed and mineralize). They also release ammonium directly into the water-column. Fish-farms are sources of rapidly sinking detritus (fish faeces and uneaten feed) and ammonium (directly excreted from the fish, and stemming from the decay of faeces and uneaten feed). Inevitably, farm-induced ammonium concentration increments are greatest in the immediate vicinity of the source farm. Over time, this ammonium may be incorporated into growing algae. During the intervening period, the farm-derived ammoniacal nitrogen may be transported away from the source. Thus, any particulate-biomass increases induced by the farm-derived nitrogen will often be greatest some-distance away from the source-farm.

For each of the 12 scenarios, we ran a single simulation. Each simulation spanned a total of 500 simulated days and used an integration time step of 12 seconds. The principal differences between the scenarios related to the specific locations and production schedules[7] for the farms but we also introduced minor changes to the Cook Strait hydrodynamic conditions before making the revised scenario 1 simulation and its accompanying scenario 13 simulation.

Summary of results

Detailed results are presented in Section 3. We show them in three forms: (a) time-series and time-average of total nitrogen averaged across the entire Sound (including Forsyth Bay, but excluding the water further out in Cook Strait); (b) maps[8] of time-averaged near-surface (and near-bed) state-variable concentrations; and (c) time-series of state-variable concentrations at specific locations within Pelorus Sound (namely, the locations where Marlborough District Council monitors water-quality).

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[5] In this context, a 'state-variable' refers to one of the components that are tracked by the coupled hydro-dynamic and biogeochemical model. The hydrodynamic state-variables are: 3-dimensional temperature, salinity, velocity and sea-surface height. The biogeochemical state-variables are: concentrations of ammonium, nitrate, organic detritus (several classes), phytoplankton (as nitrogen), phytoplankton (as chlorophyll) and zooplankton. The magnitude of each state-variable evolves through time under the influence of prescribed mathematical functions. Each function depend upon one or more of: (a) constant coefficients; (b) time-varying user-prescribed 'forcing data' (e.g., solar radiation, river-flows, fish feed inputs and stocking details and state-variable values at the external boundaries of the model etc.); and (c) instantaneous values of the state variables.

[6] Ammoniacal nitrogen is comprised of NH_4^+ (ammonium) and NH_3 (ammonia). Within the pH-range that is typical of seawater, NH_4^+ is the dominant form. For brevity, we have often used the notation "ammonium", "NH_4^+" or "NH_4" despite the fact that we are referring to total ammoniacal nitrogen.

[7] time-schedules of feed inputs and fish-numbers-by-size-class.

[8] We present separate maps for the winter-time and summer-time periods, because fish-farm derived nutrients are expected to have a greater potential to induce trophic change during the summer-months when ambient nutrient concentrations are low and primary production is nutrient limited.

The results are summarised as follows:

1. Pelorus Sound has a marked estuarine circulation. Fresher (lower density) near-surface-water tends to flow outward to Cook Strait. Saltier (denser) near-bed water tends to flow inward from Cook Strait, mixing towards the surface as it does so. As a result of this estuarine circulation, ammonium excreted from the fish (of the fish-farms) tends to flow out toward Cook Strait, but ammonium stemming from the decaying fish faeces and uneaten feed (both of which sink rapidly to the seabed) tends to flow toward the inner parts of Pelorus Sound.

2. All of the alternative-scenarios yield higher Pelorus Sound average concentrations of total nitrogen[9] (TN) than is present in the baseline_{f2016} scenario.

3. For most of the simulation period, Scenario 7 yields the smallest TN increments (followed by Scenarios 5, 6 & 9) whilst Scenario 13 (preceded by Scenarios 8, 2, 10 and 11) yields the largest. In Scenario 7, the time-and-space averaged TN increment amounts to approximately 0.04 mmol N m^{-3}. In Scenarios 8 & 13, it amounts to approximately 0.16 mmol N m^{-3}. This latter figure equates to approximately 2–3% of the Pelorus Sound time-and-space averaged TN concentration in the baseline_{f2016} scenario. Simulated TN concentrations in all scenarios are close to (but above) the minimum TN concentrations that have been recorded within Pelorus Sound in the Marlborough District Council monthly monitoring data.

4. During the winter, fish-farm derived nitrogen tends to accrue as solute (ammonium and nitrate). During the summer (when higher light levels and water temperatures favour more rapid algal growth), the farm-derived ammonium is quickly consumed by algae.

5. There is a near-linear relationship between quantum of enrichment (as measured by TN) and total (over all farms) daily average feed input rate (r^2=0.81, p<0.01). The slope is approximately 0.00282 (mmol N m^{-3}) per (tonne feed day^{-1}). Thus, for each additional 10 tonne of feed added per day, the time-and-space averaged TN concentration is predicted to rise by approximately 0.028 mmol N m^{-3}. Marlborough District Council monitoring data indicate that present-day TN concentrations in Pelorus Sound usually fall in the range 7−20 mmol N m^{-3}.

6. At least some of the scatter in the relationship between average TN and average feed input rate appears to reflect the differing locations of farms between scenarios. As one might anticipate, scenarios in which farms are located closer[10] to the seaward (Cook Strait) end of Pelorus Sound induce less enrichment within Pelorus Sound than would be anticipated on the basis of their feed loading alone. Scenario 9 has the fourth largest total feed input (only marginally less than the second and third highest), but

[9] In the context of this simulation model, the simulated concentration of 'Total nitrogen' can be derived from the raw state-variables (sum of nitrogen within ammoniacal forms, nitrate, phytoplankton, zooplankton and detritus). In the context of a laboratory determination, total nitrogen would also include any dissolved organic nitrogen (DON) – however, the model includes no DON inputs and any DON that would be generated by natural processes within the Sounds (e.g., decay of organic matter) is implicitly assumed to mineralize to inorganic nitrogen (ammonium, or nitrogen gas) instantaneously.

[10] We are using 'closer' in a qualitative sense rather than a strict quantitative one. In this context, geographic 'as the water-flows' distance is one aspect of distance, but travel-time to/from Cook Strait is a related (and, perhaps more important one). Referring to the map in Figure 1-1 , we regard the farms in Crail Bay and Beatrix Bay to be further from Cook Strait than any others. More importantly in the context of note (6) of our summary, we regard the Richmond Bay South farm to be further from Cook Strait than the Blowhole Point farms.

induces the third smallest quantum of nitrogen enrichment. By way of contrast, though feed inputs in scenario 4 are about 30% lower than those of scenario 9, scenario 4 induces marginally greater enrichment within Pelorus Sound. Both scenarios place one relocated one farm in central Waitata Reach. Scenario 9 relocates other farms close to Cook Strait (around Blowhole Point) whilst scenario 4 places a second farm much further from Cook Strait (Richmond Bay South).

7. Nonetheless, at a larger spatial scale, there is no 'free-lunch'. Placing the relocated farms close to the mouth of Cook Strait tends to reduce enrichment within Pelorus Sound, but only because much of the farm-derived nitrogen is quickly exported out into Cook Strait. Instead of enriching Pelorus Sound, the farm-derived nitrogen of these scenarios tends to enrich adjacent areas outside Pelorus (notably regions around Admiralty Bay and Port Gore). The degree of enrichment arising in these areas can be as great as is seen within Pelorus Sound in some of the scenarios. Enrichment of neighbouring areas tends to be greater (relative to what is seen within Pelorus) during winter than during summer.

8. In the alternative scenarios, ammonium concentrations tend to be lower in the immediate vicinity of the (now absent) 'old' farm sites and higher in the (replacement) 'new' farm sites. Whilst ammonium concentrations can be increased by circa 30% in the immediate environs of the alternative (new) farm locations, they are predicted to remain well below the chronic toxicity levels for marine life.

9. Changing the location of farms has little impact upon the concentrations of nitrate and particulates in the immediate vicinities of the farms (original- or new locations). Rather, changes in those properties arise further afield. The regions in which far-field changes are expressed are similar across all alternative scenarios. Within Pelorus, the far-field changes are most prominent in the central and inner parts (Tamaki Strait and, more especially, Mahau Sound and Kenepuru Sound). In some simulations, noticeable changes also arise in the coastal environs around the mouth of Pelorus Sound (e.g., Admiralty Bay and Port Gore).

10. Scenario 13 induces the largest far-field changes (increases) in nitrate, phytoplankton, detritus and zooplankton. In this scenario, zooplankton increases by up to 6% (in Mahau Sound) of the simulated baseline$_{f2016}$. For the remaining state-variables the changes amount to no more than 2%.

The base-line

Unfortunately, during the review process, it was noted that we had been provided with incorrect production schedules for the existing Richmond Bay farm (Scenarios 1–12) and for the existing Waitata Reach farm (Scenario 1 only). The Richmond schedule implied an annual feed load of approximately 3000 tonne (cf. the maximum consented load of 4000 tonne). The Waitata Scenario 1 schedule did not introduce a second cohort of fish (and feed) in the autumn of the first simulation year. Consequently, total feed inputs of the 500 day simulation period amounted to approximately 6600 tonne rather than approximately 8000 tonne in other scenarios. The feed 'deficits' implied by these errors amount to about 8% of the total feed input in the (falsely low) baseline$_{f2016}$ scenario feed input and are much less than this in all of the alternative scenarios. The feed inputs from the existing Waitata Reach farm in our baseline$_{f2016}$ scenario were erroneously low, but were correct in subsequent scenarios. Thus, we believe that the farm-induced concentration changes derived for scenarios 2–12 (relative to Scenario 1) will be slight over-estimates in comparison with those that would have been estimated had Scenario 1 used the correct feed inputs. Both errors were remedied before Scenario 13 was simulated. Furthermore, when running Scenario 13, we also reran Scenario 1 using corresponding amended farm inputs for the farms of scenario 1). For Scenario 13 (only), all comparisons are made against the results from the corrected Scenario 1.

The baseline$_{f2016}$ scenario adopted in this report includes all presently approved farms – but some of those farms are not yet in the water or have only very recently started operating. Marlborough District Council have sampled water quality at seven stations within Pelorus Sound on a monthly basis since July 2012, but two of the approved fish-farms (Waitata Reach, Richmond Bay) that were included in our baseline scenario have only begun to operate this year. Whilst it is also true that some of the other approved farms have only operated intermittently in recent years, it might be argued that comparisons against Scenario 1 (the baseline for this report) are inappropriate if the intent is to determine by how much water-quality may change relative to recent, real-world conditions within Pelorus. In an earlier modelling study (Broekhuizen, Hadfield et al. 2015), it was determined that the addition of these newly approved farms (and a fourth at Port Ligar that was mistakenly included) would induce phytoplankton enrichment of up to about 15% relative to a (different) baseline (one that more faithfully represented fish-farm inputs during the recent past). Thus, we suggest that the 'worst-case' scenario of this report (Scenario 13) is unlikely to induce phytoplankton increases of more than about 20% (and probably less than this) relative to levels measured in the recent past.

Implications of results

We were not provided with guidance as to how to assess the 'environmental significance' of any predicted changes in water-quality. To the best of our knowledge, the consent conditions of only two of the existing salmon farms within Pelorus Sound include water-quality standards that must be met. These are the recently approved Waitata Reach and Richmond Bay; their consent conditions are set out in an appendix of the Board of Inquiry decision regarding those (and other) NZKS farm applications (Whiting, Beaumont et al. 2012). The conditions include stipulations: (a) that the frequency with which chlorophyll concentrations exceed 5 mg chl m^{-3} should not increase; and (b) that the fish-farms should not *cause a statistically significant shift, beyond that which is likely to occur naturally, from a oligotrophic/mesotrophic state towards a eutrophic state*. A suite of monitoring-and-response protocols has been designed, and approved by a review panel, with a view to ensuring that the consent conditions are met.

One threshold states that chlorophyll concentrations in excess of 3.5 mg m^{-3} on three or more successive occasions shall induce an investigation in order to determine probable cause. If the fish-farms are deemed to be the likely cause, remedial actions may be required.

Marlborough District Council have monitored water quality at seven sites in Pelorus Sound on a monthly basis since July 2012 (Figure 1-2). Until June 2014 two water samples (one near-surface, one near bed) were drawn at each site using a Van Dorn bottle sampling device. Thereafter, the near-surface water-bottle sample was replaced with a hose-sampler that collects water from throughout the upper 15 m of the water-column. At the two inner-most sites (Mahau Sound and Kenepuru Sound, respectively, stations PLS-1 and PLS-2)), this hose sampler extends almost to the sea-bed. Thus, near-bed sampling was stopped at these two sites. In total, 586 water samples have been analysed to date. Measured chlorophyll concentrations span the range 0.2–5.1 mg Chl m^{-3} (July

2012–March 2016). The median is circa 0.9 mg m^{-3} and the 95th percentile is just below 3.0 mg m^{-3}. Concentrations > 3.5 mg chl m^{-3} have been recorded in 15 of 586 samples (about 2.5% of records).

Relative to field-data, the model over-predicts chlorophyll concentrations. At the locations of the inner-most Marlborough District Council monitoring sites (Kenepuru and Mahau Sounds), the simulated summer concentrations usually exceed 3.5 mg m^{-3}. At the stations closer to Cook Strait (for example, stations PLS-6 and PLS-7), baseline$_{f2016}$ scenario simulated concentrations exceed 3.5 mg m^{-3} on fewer than five occasions per station, and usually only briefly. If one naively compared the simulated concentrations with the nominated threshold, one might be tempted to conclude that even the farms of the baseline$_{f2016}$ scenario are inducing excessive phytoplankton. This would be false. Earlier simulations with this model (Broekhuizen, Hadfield et al. 2015) indicate that, summertime chlorophyll concentrations tend to be over-predicted even when no fish (or mussel) farms are present. Thus, one should not naively compare simulated concentrations (whether baseline$_{f2016}$ or alternative scenario) with prescribed thresholds, because it is known that the simulation results are over-predictions whereas the prescribed threshold contains no over-prediction. Instead, when assessing whether an alternative scenario is likely to induce breaches of the threshold, we believe that it is better to calculate the concentration increment between the alternative scenario and a relevant baseline and then add that increment onto present-day measured values. The resultant figure can then be compared with the threshold.

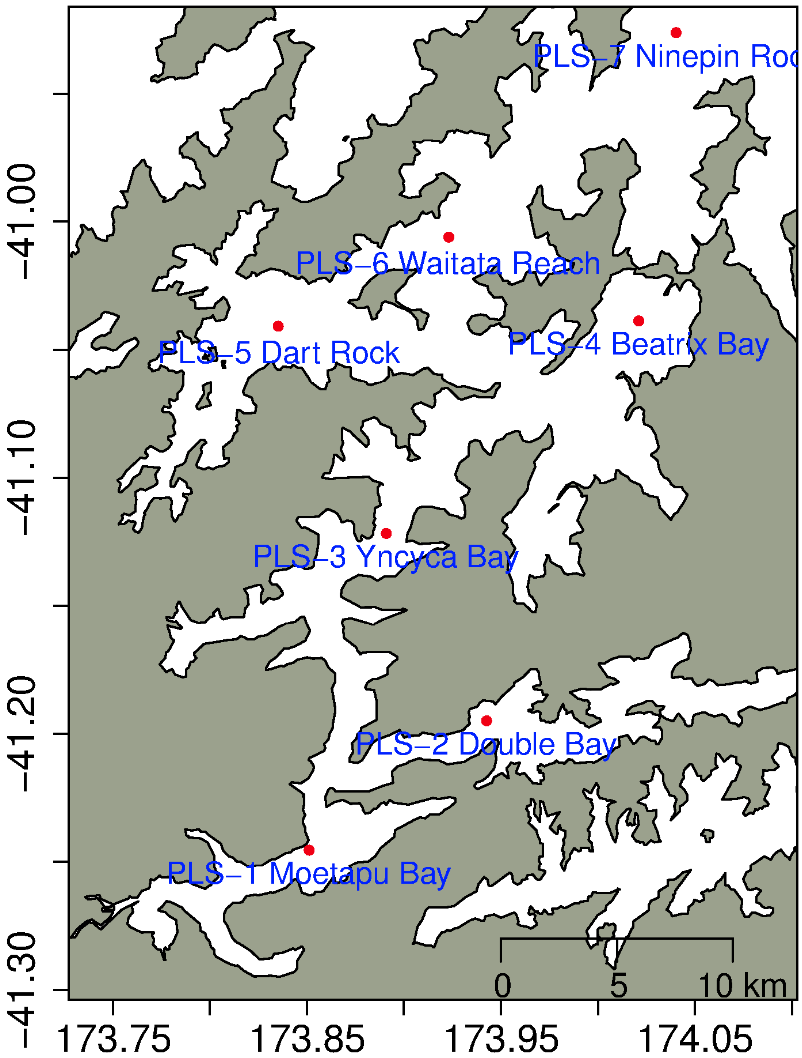

Figure 1-2: Map of Pelorus Sound showing the locations of the seven Marlborough District Council water-quality monitoring sites.

In our simulations, the maximum time-averaged chlorophyll increase (relative to baseline_{f2016}) arises in the summer and amounts to < 0.1 mg m^{-3}. Given that the median chlorophyll concentration in the MDC data is less than 1 mg Chl m^{-3} and the 3.5 mg m^{-3} threshold equates to the 95^{th} percentile of chlorophyll concentrations measured in the MDC sampling programme, we infer that, relocation-and-expansion of the fish-farms is unlikely to induce frequent exceedances of the 3.5 mg m^{-3} threshold.

On the other hand, our modelling does indicate that all of the alternative scenarios will induce a small quantum of enrichment. Recalling the consent condition that the fish-farms should not *cause a statistically significant shift, beyond that which is likely to occur naturally, from a oligotrophic/mesotrophic state towards a eutrophic state*, and noting that a quantitative value corresponding to the phrase "*statistically significant shift, beyond that which is likely to occur naturally"* has not been specified (let alone approved by a review panel), we must admit a note of caution. Whilst we consider it unlikely, it is conceivable that a numerical value for the acceptable quantum of change could be chosen such that none of the alternative scenarios would be deemed acceptable.

1 Introduction

The Ministry for Primary Industries (MPI) is seeking to determine whether Pelorus Sound has the capacity to support more sustainable salmon production through one or both of:

(a) relocating[11] some existing farms to alternative sites (that are believed to be better suited to salmon farming – for example, because they are better flushed, deeper, or less prone to high water temperatures)

(b) introducing no more than one additional salmon farm into the Sound.

MPI commissioned NIWA to assess the manners in which the Sound's water-quality (trophic status) might change in response to changed locations and sizes of the fish farms.

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 render nuisance algal blooms or other unwanted trophic changes to become a frequent/wide-spread [12]phenomenon within the Pelorus Channel system.

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) 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 rotting 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 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.

[11] The term 'relocate' is used as a convenient short-hand. The annual feed-load levels adopted at the potential new sites are often larger than the present limits at any of the sites that may be 'relocated'.
[12] Nuisance blooms of toxic algae have occurred within Queen Charlotte/Tory Channel in the past (notably, within Onapua, Opua Bay).

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. Whilst tidal flows drive material to-and-fro within the Sound on time-scales of hours, the estuarine circulation within the main channel of Pelorus Sound implies that, on time-scales of days-to-weeks, near surface waters tend to flow out towards Cook Strait but near-bed ones tend to flow from Cook Strait towards the inland headwaters of the Sound. Wind-driven surface flows will change on scales of hours to days as weather systems pass by.

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 – 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.

Previously, NIWA has developed a water-quality (trophic status) model for Pelorus Sound (Broekhuizen, Hadfield et al. 2015). That model aims to represent the influences that shellfish farms and fin-fish farms have upon the trophic status of the Sound and has been used to quantify the effects of the farms which presently operate in Pelorus Sound. We use an updated variant of that model in the analyses presented in this report.

We were asked to examine 12 different farm combinations (Figure 1-1, Table 1-1). Henceforth, we refer to each combination as a 'scenario'. Scenario 1 includes only those farms that are currently permitted to operate. We refer to this scenario as the 'baseline scenario' (baseline_{f2016}). It is important to recognise that this baseline differs from that used in prior work (ie Broekhuizen, Hadfield et al. 2015), because this new baseline_{f2016} includes all permitted farms (whether or not they currently contain fish) rather than only those operating around the 2012 period (henceforth, we will use the term baseline_{f2012} to refer to the baseline simulation used in Broekhuizen, Hadfield et al. (2015)). The new baseline_{f2016} also differs from the 'all permitted farms' scenario used in previous work because that earlier work mistakenly included a farm at Port Ligar that had been rejected by the Environment Court.

The existing farms which may be relocated are: (a) the two in Crail Bay; (b) the one in Forsyth Bay; and (c) the one in Waihinau Bay. The potential new sites are located in: (a) inner Waitata Reach (Horseshoe Bay and Richmond Bay South); (b) central Waitata Reach (Waitata mid-channel SW and Waitata mid-channel NE); and (c) the outer-most reaches of Pelorus Sound (Blowhole Point South and Blowhole Point North). There are seven distinct fish farms in the baseline$_{f2016}$ scenario. The majority of the alternative scenarios also have seven farms (although the locations of some of these farms differ) but three of the alternative scenarios (2, 11, & 12) have only six farms. All of the alternative (i.e., non-baseline$_{f2016}$) scenarios permit a greater total annual feed input than the baseline$_{f2016}$ scenario (Table 1-1). Amongst the alternative scenarios, the smallest (by feed inputs) has the feed inputs increasing by approximately 25% over the baseline scenario. In the 'largest' (by feed input) scenario, the permitted annual feed inputs are more than three times greater than those of the baseline$_{f2016}$ scenario.

Table 1-1: Farm feed inputs for each scenario. Scenario 1 includes only the farms that are currently approved to operate. It is our so-called ‘baseline_{f2016}’. Note the absence of a Scenario 3: while this was included in the original project definition, it was subsequently dropped because some of the sites included in that scenario proved unacceptable for reasons unrelated to potential water-quality effects (which is the subject of this investigation). The total feed inputs (tonne bag weight) are for the period 1 May 2017 to 31 October 2018. The Beatrix Bay inputs come from daily values yielded by a salmon production model (NIWA, unpublished). The inputs for the remaining farms come from projected monthly production schedules constructed specifically for the purpose by New Zealand King Salmon Ltd. Two feed inputs rates are listed for the Waitata reach (existing farm) in Scenario 1, the baseline_{f2016} scenario. Results from the other scenarios are assessed relative to Scenario 1. Initially, we were provided with an erroneous farm production schedule for this farm in Scenario 1. For Scenarios 2–12, all comparisons have been made against a Scenario 1 simulation that used the erroneous schedule. When we made the Scenario 13 simulation, we also reran Scenario 1 using a corrected production schedule. Results for Scenario 13 are assessed relative to this corrected scenario 1. The bracketed figures in the Scenario 1 column are the corrected figure used in the simulation against which Scenario 13 is compared. The simulation period for the model was 24 May 2012-6 October 2013. Feed inputs to the model were derived from these NZKS data by interpolation (after subtracting four years from the nominal dates in the NZKS data).

	Scenario											
Farm	1	2	4	5	6	7	8	9	10	11	12	13
Crail Bay Farm 1 [existing site]	822.8		805.30	780.26	735.54	799.60						
Crail Bay Farm 2 [existing site]	822.8		805.30	780.26	735.54	799.60						
Forsyth Bay [existing site]	4352.2											
Richmond Bay [existing site]	3538.00 (5865.6)	3898.95	3820.59	3820.59	3820.59	3820.59	3820.59	3820.59	3820.59	4991.47	3820.59	5850.02
Waihinau Bay [existing site]	3983.8											
Waitata Reach [existing site]	6671.5 (8432.4)	8355.53	7909.61	7909.61	7909.61	7909.61	7909.61	7909.61	7909.61	7248.659	7909.61	8164.00
Beatrix Bay [existing site]	1590.3	1590.30	1590.30	1590.30	1590.30	1590.30	1590.30	1590.30	1590.30	1590.30	1590.30	1590.30
MPI125 (Waitata reach NE) [candidate site]		9715.66	8183.64			8397.67	10140.01	10033.38	10086.1	8789.76		15758.69
MPI106 (Richmond Bay south) [candidate site]		9238.12	8179.06	8162.09	8162.09		9509.26		8089.61	10147.19	8265.95	8508.56
MPI124 (Horseshoe Bay) [candidate site]					3683.17							3882.86

						Scenario						
Farm	**1**	**2**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
MPI122 (Blowhole South) [candidate site]				6895.13			7218.15	7166.71	7192.81		7338.65	8019.02
MPI118 (Waitata Reach SW) [candidate site]						7946.82	7839.68	7842.06		8570.24		
MPI34 (Blowhole North) [candidate site]								8331.14	8375.42		8174.35	7542.86
Total number of farms	7	6	7	7	7	7	7	7	7	6		6
Implied total feed input (tonne) over the period 1 May 2017 – 31 October 2018 [excluding Beatrix inputs]	20191.2 (24079.7)	35636.9	29703.5	28347.9	25046.5	29673.9	46437.3	45103.5	45474.1	39747.3	35509.1	57726.01
Implied total feed input (tonne) over the final 12 months of the feed projection period (i.e., 1 November 2017-31 October 2018)	12275.5 (16002.4)	24189.5	20599.5	19720.1	17563.4	20571.4	31080.4	30263.0	30505.3	26750.6	24188.6	38615.12

2 Methods

Our methods are similar to those adopted in prior work (Broekhuizen, Reeve et al. 2014; Hadfield, Broekhuizen et al. 2014; Broekhuizen and Hadfield 2015; Broekhuizen, Hadfield et al. 2015). The reader may consult those earlier works for a detailed description of the biophysical model and its performance relative to field data, etc. Within the remainder of this section, we focus only upon: (a) describing the (minor) changes to the biophysical model; (b) describing the derivation of farm stocking & feeding schedules; and (c) re-iterating our previous descriptions of the manner in which simulation results were analysed and presented.

2.1 Model modifications that have been implemented since our prior report

The model which we have used remains very similar to that reported within Broekhuizen, Hadfield et al. (2015) but, during the intervening months, several changes have been implemented to improve its performance (reduce runtime and/or improve fit to calibration data). The changes are described in more detail below.

Whilst the changes have slightly improved the model's hydrodynamic performance, and reduced the model's tendency to over-predict summertime phytoplankton abundance, they have not remedied its tendency to yield a summertime peak in phytoplankton abundance in areas (such as Beatrix Bay) where field data indicate the annual peak usually occurs in late winter.

Modified hydrodynamic boundary conditions

In the model described by Broekhuizen, Hadfield et al. (2015) the tidal variations in sea level and depth-averaged velocity at the boundary were taken from the NIWA EEZ tidal model. In the present work they are calculated from a high-resolution tidal model of Cook Strait, which is itself nested in the NIWA EEZ tidal model. The change has the effect of reducing the amplitude of the modelled tides in Pelorus Sound by approximately 5%, bringing the model into slightly better agreement with measurements overall.

Implicit faeces and pseudo-faeces

The faeces and pseudo-faeces from mussels (and faeces from fish) sink much more rapidly than the 'natural' detritus (dead plankton material etc.). In our previous variant of the Pelorus model, we introduced an additional state-variable that was dedicated to representing the spatial and temporal dynamics of this material within the water-column. Unfortunately, this approach demanded that we adopt a computationally expensive numerical integration scheme. As a result, individual simulations became extremely time-consuming. Thus, an alternative approach has been implemented.

In reality, faecal and pseudo-faecal material sinks very rapidly (3 - 10 cm s^{-1}), such that almost none of it travels more than about 100 m from the farm before settling onto the seabed. Given that: (i) our model is intended to run with horizontal resolutions of 100 m or more (200 m in the work described here) and, (ii) the focus is upon large-bay-scale and far-field effects rather than near-farm effects, there is little to be gained by bearing the cost of explicitly representing the passage of the (pseudo-)faecal material through the water-column. In the revised version of our current model the material deposits on the bottom beneath the farm without explicitly passing through the intervening water. Material deposits onto the seabed as soon as it is produced (i.e., there is no time-lag between production and deposition). It is possible to gain acceptable results using this revised ('implicit pelagic detritus') approach without having to resort the computationally expensive numerical integration scheme.

As before, the model assumes that a fixed fraction of the nitrogen within the material which hits the seabed instantly mineralizes and returns to the bottom-most layer of the water-column. The remaining nitrogen is permanently lost (denitrified).

Modified description of light attenuation within the water-column

The ROMS modelling system offers several biogeochemical models to describe nutrient cycling through the planktonic food-web. We have adopted the Fennel variant. The standard variant of the Fennel biogeochemical model assumes that water attenuates all wavelengths of photosynthetically active radiation equally efficiently. In reality, pure water attenuates light from the 'red' end of the spectrum very much more rapidly than it attenuates light from the 'green' end of the spectrum. The field data that we use to parameterise light attenuation come the model from measurements made at depths greater than 5 m below the water-surface. By the time light reaches 5 m depth, the 'redder' components of the spectrum will have been absorbed. Consequently, the inferred PAR attenuation coefficients are indicative of the manner in which 'greener' (rather than 'whole') light are attenuated. To accommodate this fact, we have adopted the PAR-attenuation model proposed by Taylor, Watson et al. (1991). Specifically, we have modified the ROMS/Fennel code such that photosynthetically-active radiation incident at the sea-surface is split into two equal components (by energy content) ('red' and 'green'). The background attenuation coefficient for 'green' light is set to 0.15 m^{-1} (which is consistent with our field data). The background attenuation coefficient for 'red' light is chosen to be a further 0.35 m^{-1} greater than that for 'green' light (i.e., 0.5 m^{-1}; 0.35 m^{-1} being approximately the difference between the attenuation coefficients for 'reddish' and 'greenish' light in pure water).

Seasonally varying day-length

Whilst our previous simulations incorporated seasonally varying daily average solar-radiation inputs, they did not incorporate seasonally varying day-lengths. Thus, whilst the total daily radiation input varied appropriately, the instantaneous input rates tended to be too high during the artificially short summer days and too low during the artificially long winter ones. Since light intensity has a non-linear influence upon phytoplankton photosynthetic rates, we considered it possible that this may have introduced a small seasonal bias into the earlier simulations. For the simulations presented in this report, we have allowed the day-length to vary in the appropriate seasonal manner.

In conjunction with the changed light attenuation formulation (see preceding sub-section), the outcome is a small reduction in the phytoplankton standing stocks (more so in the winter months than in summer ones).

2.2 Farming scenarios & production schedules

Production schedules (monthly of fish numbers by cohort, fish size by cohort and corresponding cohort-specific total feed input mass) were generated for us by New Zealand King Salmon Ltd for their present farms and for the candidate alternative farms.

NZKS report the following key assumptions were made when generating the production schedules: (a) all new cohorts of fish would put into the water during the months April-June (incl.), (b) all harvests would occur during the months April-December, (c) farms operate mixed year-class systems.

Four points are worth noting. Firstly, the farm production schedules for the existing (presently approved) farms differ from those used in our prior work. In the prior work, the production schedules were derived from historical farm records. For this new work, all schedules were generated anew on the basis of anticipated future production practices and potential availability of alternative water-space. Secondly, in this new work, the temporal characteristics of the production schedule for any given farm sometimes differed between at least some of scenarios in which the farm was present (albeit that the overall annual feed load for the farm remained very similar). These differences arise because it is anticipated that the different farms will not be operated entirely independently of one another. Thirdly, and for a similar reason, the feed loads associated with a given farm may differ between scenarios (in which that farm is present). Finally, we note that, summed across all farms within a scenario, the daily total feed inputs tend to be greater in the early part of the simulation than in the later part.

For the one remaining fin-fish farm (Beatrix Bay), we reused a schedule which we generated for our previous work. That schedule was generated using a model for hapuku growing within a hypothetical Beatrix Bay farm (NIWA unpublished data).

The locations of the farms involved in each scenario are illustrated in Figure 2-1 (below). The farm specific feed input totals stemming from the various production schedules are listed in Table 1-1 (within section 1).

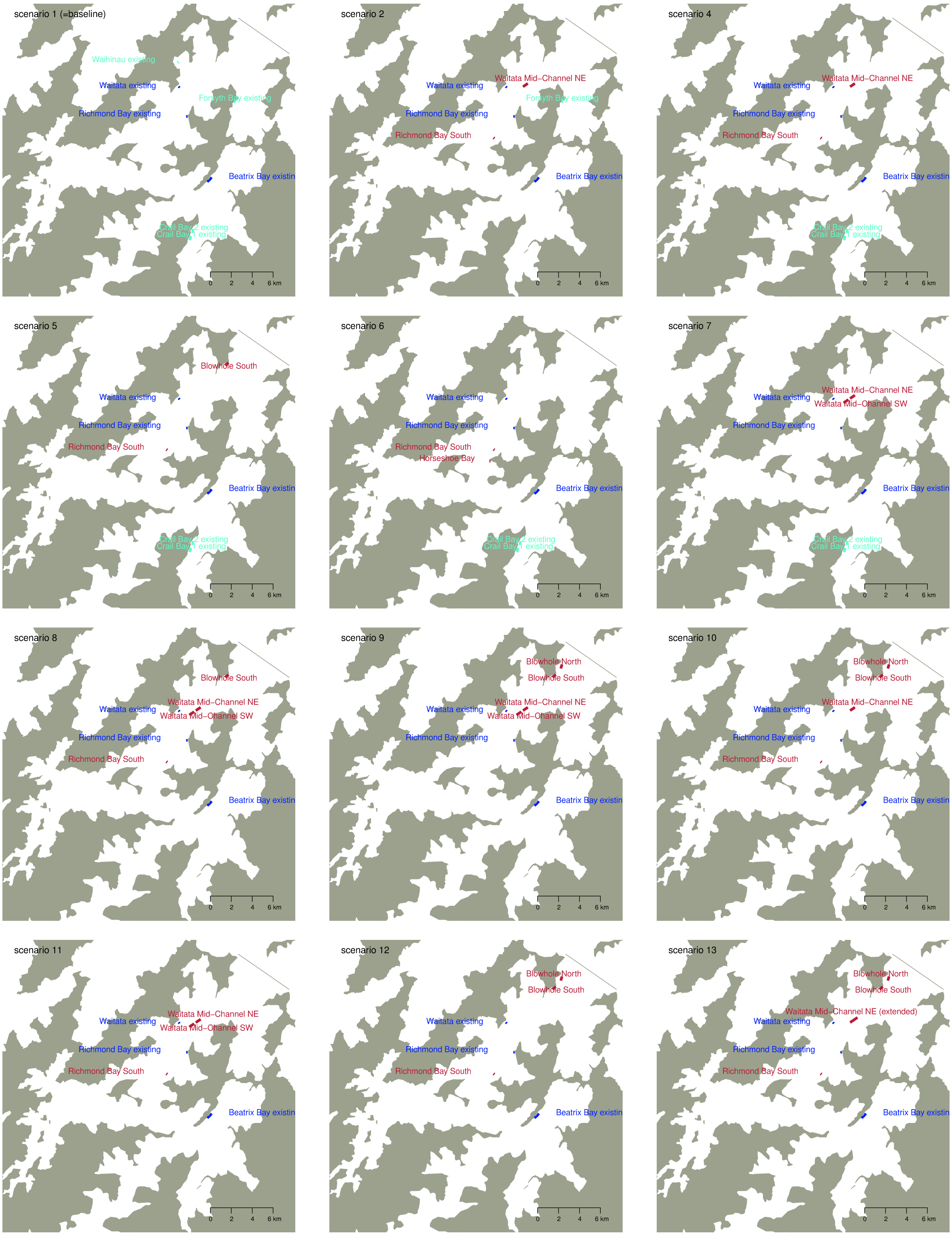

Figure 2-1: Maps illustrating which farms were present in each scenario. There is no map corresponding to scenario 3 because this scenario was discarded mid-way through the project. Farms named in royal blue are existing farms that are not under consideration for relocation. Those in pale blue are existing farms that are under consideration for relocation. Those in red are potential sites to which farms may be relocated.

2.3 Analysis and presentation of simulation results

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. We made our biophysical simulations on a 200 m resolution horizontal grid. At 200 m resolution, the detailed structures of individual fish farms and mussel farms are not resolved – and nor have their effects upon local flow patterns. 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 associated with 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.

2.3.1 Space-averaged analysis

We begin our presentation of the results by considering effects at the whole of Pelorus Sound spatial-scale. For the purposes of this report, we define Pelorus Sound to be the water contained on the landward side of the line running between Paparoa and Culdaff Points in Figure 1-1. We have placed the Cook Strait boundary of Pelorus Sound a little further out toward Cook Strait than in Broekhuizen, Hadfield et al. (2015). This ensures that more of the plumes emanating from the farms (especially the most seaward ones) are included in the whole-of-Pelorus budget. Note, however, that despite moving the boundary seaward a little, some of the scenarios yield relatively marked plumes which do extend to the seaward of this boundary.

We calculate the volume-average concentrations of total nitrogen (sum of nitrogen within nitrate, ammonium, suspended organic detritus[13], phytoplankton and zooplankton) and present these as: (a) time-series; and (b) time-averages (over the final 365 days of the simulation period).

2.3.2 Spatially-explicit analysis

We illustrate the predicted influences which the various alternative scenarios have upon water quality (relative to the *baseline*$_{f2016}$ *scenario*), using a series of false-colour figures. Each figure contains six rows and each row will contain three panels (maps). Each panel is a false colour map of the model domain. Pixel colour at any location in the map is indicative of the numerical value of the property[14] in question at the pixel-location (yellow/red being 'high', and deep blue being 'low'). The colour-scheme is designed to yield colours that allow differences to be distinguished readily in whichever scenario-pair yields the largest range of differences. In scenario-pairs that yield smaller differences, this may imply that these smaller differences cannot be readily distinguished on the chosen colour-scale. Extremes of colour (deep blue for concentration decline, rust-red for concentration increase) should <u>not</u> be interpreted as necessarily implying that the magnitude of change is large in any environmentally meaningful sense. Similarly, the colours should <u>not</u> 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 amongst properties. For a given property and time-averaging period, the colour-scales are identical in all inter-scenario comparisons, but the

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[13] Excluding the waste-food and fish-faeces – which sink to the seabed very quickly

[14] In this context, *property* is used as a convenient short-hand to refer to one or other of: (a) time-averaged concentration, (b) time-averaged relative concentration, or (c) time-averaged concentration difference for a particular state-variable. See ensuing main text for more details.

colour-scale magnitudes often differ between properties and between the two time-averaging periods (seasons) for a given property. Our decision to adopt shared colour-scales across scenario comparisons (within one time-averaging period) facilitates ready visual assessment of the (perhaps) differing magnitudes of effects associated with differing scenarios within the given averaging period. On the other hand, because the ranges spanned by the colour-scales differ between the winter and summer averaging periods for some variables (notably, chlorophyll), one should take care to consult the numerical values that correspond to each colour when comparing winter- and summer results for a given property.

Each row corresponds to a different model state-variable (i.e., ammonium, nitrate, etc.). Within a row, the left-hand[15] most panel will show a time-averaged concentration for the state-variable under the *baseline*$_{\text{f2016}}$ *scenario*. The central columns panel will illustrate the time-averages of relative concentration (RC_{p}) for an alternative scenario. For example, the central column may show results from scenario 2 relative to the *baseline*$_{\text{f2016}}$ (scenario 1). The right-hand column illustrates the time-averages of the concentration differences between the alternative scenario and the baseline$_{\text{f2016}}$ scenario.

The time-averages of relative concentration (RC_{p}) and concentration difference are calculated as follows:

Equation 2-1: Definition of time-averaged relative concentration

$$RC_p = 1 + \frac{1}{N}\sum_{n=1}^{N}\frac{P_{\mathrm{n}}^{\mathrm{f}} - P_{\mathrm{n}}^{\mathrm{e}}}{P_{\mathrm{n}}^{\mathrm{e}}}$$

Equation 2-2: Definition of time-averaged concentration difference:

$$\Delta C_p = \frac{1}{N}\sum_{n=1}^{N} P_{\mathrm{n}}^{\mathrm{f}} - P_{\mathrm{n}}^{\mathrm{e}}$$

Here, *N* is the number of time-levels involved in the time-average and P_n^e and P_n^f represent the simulated 12-hour average concentration P at time-level n in the baseline and alternative scenarios respectively. If, on time-averaging, the alternative scenario tends to yield higher (lower) concentrations than the baseline, then the relative concentration will take a value greater (lower) than 1 and the concentration difference will be positive (negative).

[15] The *baseline* scenario is the same for all comparisons. Thus, for a given time-averaging period (winter, or summer) and hydrodynamic layer (e.g., near-surface), corresponding left-hand images are identical in all of the figures that we show.

3 Results

3.1 Changes examined at the scale of Pelorus Sound

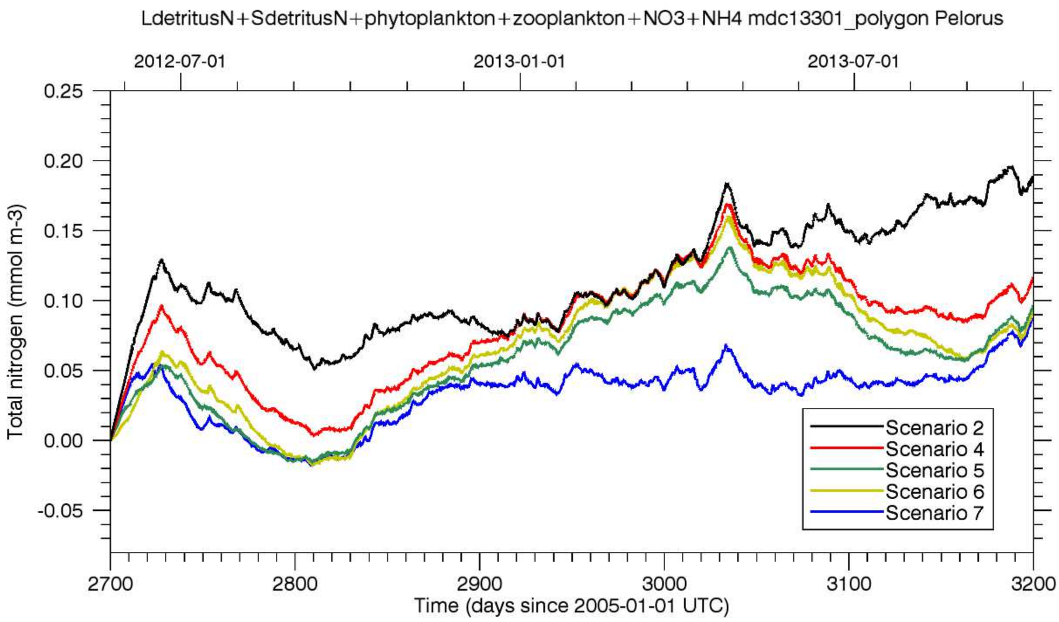
We start by aggregating the model results to the whole-of-Pelorus Sound spatial scale. This provides a convenient manner by which to introduce the key, qualitative differences that arise between the various scenarios.

Figure 3-1 and Figure 3-2 illustrate the time-series of the differences (alternative scenario minus baseline_{f2016} scenario) in volume-average total nitrogen concentrations in each alternative scenario.

For clarity, Figure 3-1 has two panels, for (a) Scenarios 2 to 7 relative to the original scenario 1and (b) Scenarios 8 to 12 relative to the original scenario 1. For most of the period, Scenario 7 yields the smallest differences (followed by 5, 6 and 9) while Scenario 8 yields the largest (followed by 2, 10 and 11). Figure 3-2 shows Scenario 13, relative to the corrected Scenario 1. The differences in this case are often slightly larger than for Scenario 8, with the largest daily difference being 0.29 mmol N m^{-3}.

Table 3-1 presents the corresponding time-averaged differences. These range from 0.04 mmol N m^{-3} (Scenario 7) to 0.16 mmol N m^{-3} (Scenarios 8 and 13). The time-averaged and volume averaged concentration of total nitrogen in the baseline_{f2016} scenario is 7.18 mmol N m^{-3} (with the corrected Scenario 1 a little higher at 7.25 mmol N m^{-3}). These values are at the lower end of the range that has been measured during monthly sampling by Marlborough District Council since July 2012 (the majority of values have fallen inside the range 7–30 mmol N m^{-3}). The differences in Table 3-1 amount to approximately 3% of the simulated total nitrogen concentration in the baseline_{f2016} simulations.

a



b

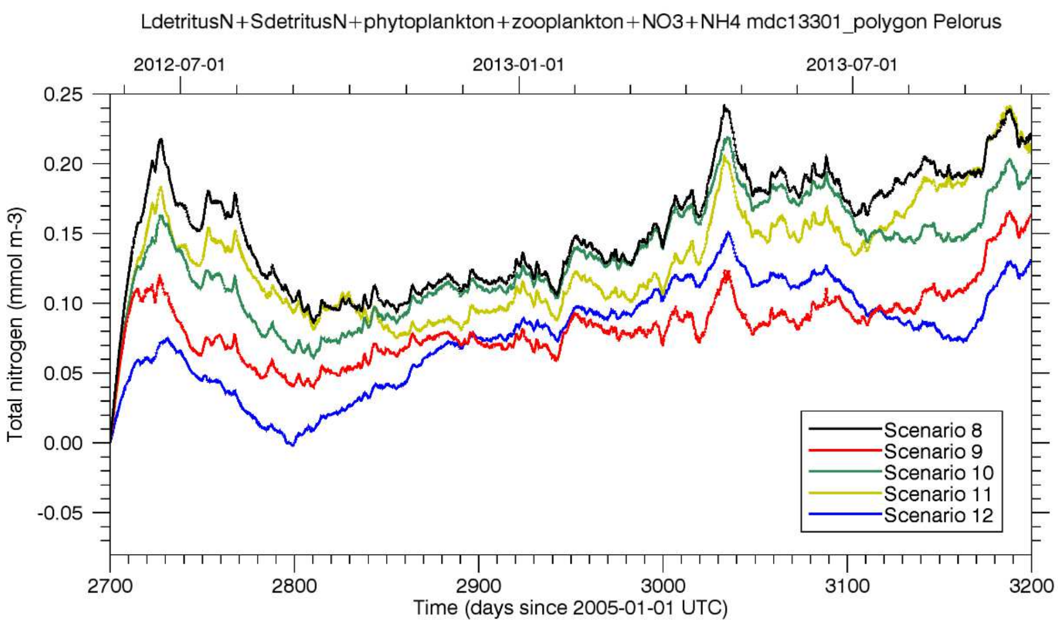


Figure 3-1: Time-series of the difference in volume averaged total nitrogen concentration (alternative scenario minus baseline$_{f2016}$ scenario). Total nitrogen is calculated as the sum of nitrate nitrogen, ammonium nitrogen, detrital nitrogen, phytoplankton nitrogen and zooplankton nitrogen. Over the last 365 days of the simulation, the time-and-space averaged concentration of total nitrogen in the baseline$_{f2016}$ scenario is 7.19 mmol N m^{-3}. Marlborough District Council monitoring data (monthly since July 2012) indicate that real-world total nitrogen concentrations typically range between approximately 7 and 30 mmol N m^{-3} in the central and outer Sound. Time is expressed in days-from January 1, 2005 (lower horizontal axis) and calendar data (upper horizontal axis). Panel a shows Scenarios 2, 4, 5, 6 and 7 minus Scenario 1 (uncorrected); panel b shows Scenarios 8, 9, 10, 11 and 12 minus Scenario 1 (uncorrected).

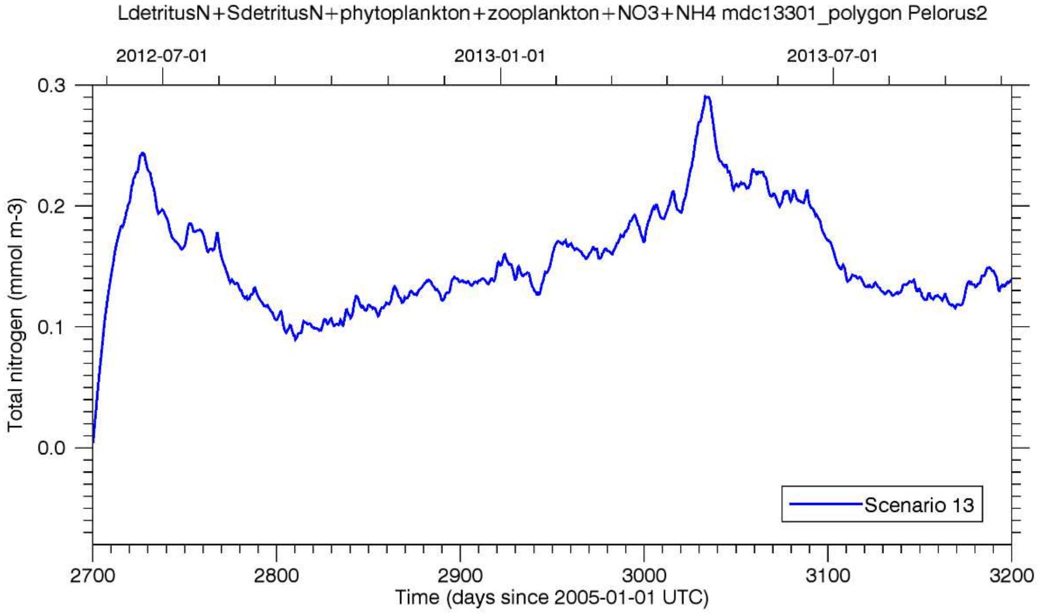


Figure 3-2: Time-series of the difference in volume averaged total nitrogen concentration (alternative scenario minus baseline$_{f2016}$ scenario). As Figure 3-1 but showing Scenario 13 minus Scenario 1 (corrected).

Table 3-1: Time-and-volume averaged differences (alternative scenario - baseline$_{f2016}$ scenario) of total nitrogen concentration. Time-averaging is over the final 365 days of the simulations. Volume averaging is over the volume illustrated in Figure 3-1(c). Over the last 365 days of the simulation, the time-and-space averaged concentration of total nitrogen in the baseline$_{f2016}$ scenario is 7.18 mmol N m^{-3}. Marlborough District Council monitoring data (monthly since July 2012) indicate that real-world total nitrogen concentrations typically range between approximately 7 mmol N m^{-3} and 30 mmol N m^{-3} in the central and outer Sound.

Scenario	Mean daily feed rate (tonne feed /day)	Mean total nitrogen (mmol N m^{-3})	Mean concentration difference from scenario 01 (mmol N m^{-3})	Ranked quantum of enrichment relative to the uncorrected scenario 01 (smaller ranks imply lesser nitrogen increments)
Scenario 01	43.4	7.176		0
Scenario 02	72.7	7.300	0.124	8
Scenario 04	63.3	7.270	0.094	7
Scenario 05	60.3	7.251	0.075	2
Scenario 06	54.7	7.259	0.083	4
Scenario 07	63.2	7.218	0.042	1
Scenario 08	91.2	7.334	0.158	11
Scenario 09	89.3	7.267	0.091	5
Scenario 10	89.8	7.319	0.143	10
Scenario 11	79.1	7.310	0.134	9
Scenario 12	72.8	7.268	0.092	6
Scenario 01 (corrected)	58.7	7.254		3
Scenario 13	111.3	7.415	0.161	12

Figure 3-3 illustrates the relationship between total scenario-specific feed load (over the final 365 days of each simulation) and the corresponding time-and-volume averaged total nitrogen concentration increments. There is a clear positive (near linear) correlation between the total feed load and the resultant concentration increment. The fact that the relationship is close to linear and the correlation is strong suggests that, across the scenarios that we have considered, feed-loading plays a greater role in determining Sounds-wide total nitrogen increment than farm location does. Nonetheless, farm location does have some influence: the proposed additional site near Richmond Bay is deeper within Pelorus Sound (further from Cook Strait) than all potential alternative sites other than Horseshoe Bay. The proposed Richmond Bay farm is present in all of the alternative scenarios <u>except</u> scenarios 7 and 9. Those two stand out as being particularly 'efficient', in the sense that the increment in total nitrogen lies further below the value predicted from the feed-increment/TN-enrichment regression line (Figure 3-3) than is the case for other scenarios.

It is worth noting that the daily feed input rates shown in Figure 3-3 are all greater than those implied by the final row of Table 1-1. The discrepancy amounts to between 6% and 14% in the majority of the scenarios but they amount to 28% and 32% in the original and revised versions of the baseline$_{f2016}$ scenario. In part, the discrepancies can be attributed to the fact that the final 365 days of the simulation (i.e., nominally 7 Oct 2012 - 6 Oct 2013) do not perfectly align with the final 365 days of the monthly data summarized in Table 1-1 (1 Nov 2012-31 Oct 2013). So far as we have been able to ascertain, the remaining discrepancies arise from 'cumulative rounding and approximation errors' that are almost unavoidable when converting the quantities provided to us into values that are used by the model[16]. Within all of the simulations, total feed inputs prove to have been somewhat greater than intended. The implication is that nitrogen inputs are over-estimated in all of our simulations. Consequently, we anticipate that the resultant absolute concentrations of ammonium, nitrate, phytoplankton etc., will also be over-estimated. We do, however, note that the two largest over-estimates of feed inputs arose in the original and revised variants of scenario 1 (the baseline$_{f2016}$ scenario). The implications of this are that, whilst the absolute concentrations of ammonium etc., are likely to be slightly over-estimated in each scenario, the magnitudes of the absolute concentration differences (alternative scenario minus baseline scenario) and the relative concentration changes (alternative scenario / baseline scenario) are both likely to be under-estimated (because the concentrations in the baseline may have been over-estimated by a larger quantum than those in the alternative scenario were).

[16] We were provided with farm-specific values for the numbers and average weight of each cohort of fish at the beginning and end of each month, and also with the total feed provided to the fish over the course of the month. The model requires time-series of fish numbers, fish weight and daily feed (kg feed/kg fish /d) for each water-column of the spatial domain. Approximations and rounding errors arise when calculating: (a) daily specific feed rate to feed into the model, (b) densities of fish within each water-column to feed into the model. Further approximations and rounding errors arise at run-time: (a) when calculating instantaneous fish concentrations (fish m^{-3}) within each control-volume (concentrations will change as sea-level changes and as some members of the cohort die), and (b) when calculating total instantaneous feed inputs (kg/control-volume/d) from the cohort-specific fish concentration, the cohort-specific mean weight and the weigh-specific daily feeding rate.

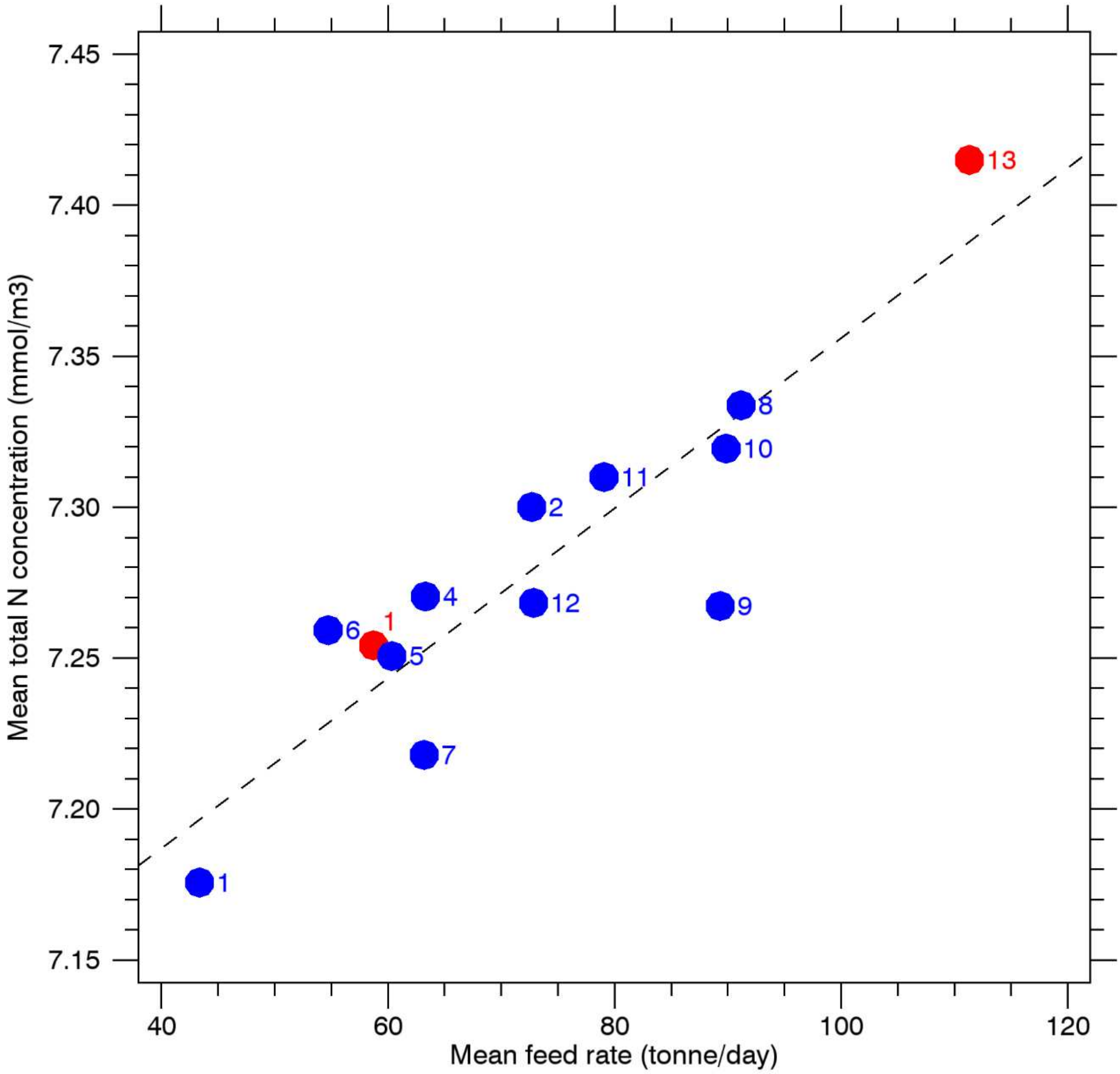


Figure 3-3: Scatter plot illustrating the relationship between the average total nitrogen concentration and total feed loads. The concentration and feed loads were averaged over the final 365 days of the simulation (nominally 7 Oct. 2012 - 6 Oct. 2013). The blue symbols indicate the original 11 scenarios (1–12, excluding 3) and the red symbols indicate Scenario 13 and the corrected Scenario 1.The dashed line is the least-squares linear fit. The slope of the line is 0.00282 (mmol m^{-3}) per (tonne day^{-1}). This regression has an adjusted r^2=0.81 and the slope is significantly different from zero ($p < 0.01$).

3.2 Changes examined at bay-scale and finer

The time-and-volume average total nitrogen results provide an indication of the magnitude of the changes that might arise at a whole-of-Sound scale as a result of a switch to an alternative farming scenario, but they provide less indication of what might be observed in any specific sub-region (bay-scale and finer) or in particular components of the food-web (e.g., phytoplankton). We use maps of time-averaged properties to illustrate those.

The simulation results for the near-surface time-averaged properties of the surface-most layer of each water-column are presented in Figure 3-4 to Figure 3-25. The results for the bottom-most layer of the water column are presented within corresponding figures in Appendix A.

Scenario 13 is the one which tends to induce the largest far-field changes. Accordingly, and as a means of introducing some general concepts, we choose to describe[17] some of the results from that scenario in detail. Whilst we concentrate upon Scenario 13, the qualitative nature of the statements is equally applicable to other scenarios, though with smaller magnitudes.

Maps illustrating the time-averaged of results from Scenario 13 relative to scenario 1 ($Baseline_{f2016}$) are presented in Figure 3-24 (winter time-average, near-surface waters), Figure 3-25 (summer time-average, near surface waters), Figure A-11 (winter time-average, near-bed waters) and Figure A-22 (summer time-average, near-bed waters). Time-series of near-surface results from scenarios 1 and 13 (respectively, blue and red lines) at the Marlborough District Council monitoring sites are presented in Appendix B.

Patterns of change in Pelorus Sound

Fish-farms are a source of reactive nitrogen (as ammonium that the fish excrete directly and as faeces and uneaten food that decay into ammonium). Over time, this ammoniacal nitrogen is either: (a) consumed by phytoplankton (from which it may pass into zooplankton or detritus); or (b) converted to nitrate by nitrifying bacteria. Some of the resultant nitrate may subsequently be converted to inert nitrogen gas by denitrifying bacteria. Naturally, therefore, ammoniacal-nitrogen shows the greatest change in the immediate vicinity of the farms. In the $baseline_{f2016}$ scenario ammoniacal nitrogen concentrations are usually <3 mmol N m^{-3}, even close to the existing fish-farms (see Figure 3-14a, Figure 3-15a, Figure A-11a, Figure A-12a; see also the time-series of simulated ammonical nitrogen at the MDC monitoring sites in Appendix B).

In Scenario 13, surface water concentrations of ammoniacal nitrogen are predicted to increase by several 10s of percent (of $baseline_{f2016}$) in the immediate farm environs of the (new) Waitata-reach/Blowhole Point farms during both winter and summer (Figure 3-24, Figure 3-14b, Figure 3-15b). Conversely, concentration declines of around 5–10% are seen at the locations of the (former) Crail Bay & Forsyth Bay farms. Further from the farms, increases that are in the range 5–15% (of $baseline_{f2016}$) are predicted to extend over much of outer Pelorus and the coastal region immediately outside Pelorus (e.g., Figure 3-24, Figure 3-14b) during the winter months. The magnitudes of relative increase in the immediate farm environs also amount to several tens of percent of the $baseline_{f2016}$ during the summer-months, but the spatial extent of the plume is much-reduced (Figure 3-25b).

In near-bed waters, the magnitudes of near-field change are similar to those in the surface, but the plumes of farm-derived ammonium tend to extend into Pelorus Sound rather than out of the Sound (Figure A-21, Figure A-11b, Figure A-22, Figure A-12b). Again, the spatial extent of the ammonium plumes is smaller during the summer months than during the winter ones.

[17] In this section, we concentrate upon describing the results. We interpret the results (e.g., relative to water-quality standards etc.,) in section 4.5 of this report.

In Scenario 13, five-day moving time-average values of near-surface ammoniacal nitrogen concentrations never exceed 10 mmol N m^{-3} and rarely exceed 5 mmol N m^{-3} (70 mg N m^{-3}) even within grid-cells that host fish-farms. These are well below the levels considered toxic to marine life (see Section 4.4). The concentration increment associated with the new farms declines rapidly as one moves away from the farms, falling to less than 0.3 mmol N m^{-3} at a distance of 200 m or so (Figure 3-24, Figure 3-14c, Figure 3-25c, Figure A-21c, Figure A-22c).

The estuarine circulation in Pelorus Sound implies that near-surface waters in the main-stem of Pelorus Sound are flowing out toward Cook Strait. The circulation is driven by freshwater inputs to the system, but the outflowing freshwater entrains some saltier, denser water from deeper in the water-column. This induces a near-bed inflowing current of dense (cool & salty) water from Cook Strait. Fish excrete ammonium, and in the surface waters, the plume of farm-derived ammonium tends to flow toward Cook Strait. Despite this, the farm induced increases in far-field concentrations of surface water nitrate, phytoplankton, zooplankton and detritus tend to be greatest in inner/central Pelorus Sound (for example, Tawhitinui Reach/Fitzroy Bay, and Kenepuru Sound). The explanation for this is that ammonium stemming from the decay of fish faeces and uneaten feed (both of which sink rapidly) will tend to be transported into the inner parts of the Sound in the sub-surface circulation of dense, salty water that flows in from Cook Strait. The hydrodynamic model reproduces the real-world estuarine flow. Consequently, a plume of inward-flowing fish-farm derived nutrient is evident in deeper waters (see the illustrations of near-bed simulation results in Appendix A). Over a period of days-to-weeks, this nutrient is simultaneously: (a) transported into the inner parts of Pelorus Sound; (b) mixed towards the surface waters; and (c) incorporated into phytoplankton biomass (and, subsequently, zooplankton and detritus).

As one might expect, the farm-induced changes in concentrations of nitrate, detritus, phytoplankton and zooplankton tend to arise over an extensive area. Furthermore, the largest changes (relative or absolute) often arise at some considerable distance from the farms. During the winter, short day-lengths and lower incident light-levels restrict photosynthetic activity. Consequently, little of the farm-derived nitrogen is incorporated into phytoplankton biomass (and, from there, into zooplankton or detritus). Rather, it tends to remain in solute-form as ammonium or nitrate. During the summer, the higher light-levels permit greater photosynthetic activity and, in the far-field, the farm-derived nitrogen tends to manifest itself as particulate organic matter (phytoplankton, detritus and zooplankton) rather than as solute.

In Scenario13, the absolute and relative concentration increases tend to be smaller in the main-stem of Pelorus Sound than in the major side-arms (the Tawhitinui Reach/Fitzroy and Kenepuru Sound)[18]. In these latter locations, summertime nitrate concentration increases are predicted to amount to up to about 0.06 mmol N m^{-3} or about 6% of the concentrations at the corresponding locations in the $baseline_{f2016}$ scenario (Figure 3-14e,f, Figure 3-15e,f Figure A-11e,fFigure A-22e,f). Whilst the relative nitrate concentration increases are similar in winter and summer, the absolute concentration increases tend to be greater in the winter (up to 0.15 mmol N m^{-3} in winter versus 0.06 mmol N m^{-3} in summer). Interestingly, despite the removal of the Crail Bay farms, nitrate concentrations are predicted to rise a little in the Beatrix/Crail Bay system: this occurs in the model because nutrient stemming from the larger, replacement farms in the main stem of Pelorus Sound penetrates into these bays and more than offsets the loss of a local nutrient source.

[18] To varying, but generally, lesser extents, this is also true of the other alternative scenarios.

The model suggests that the relative and absolute concentration changes exhibited by particulate organic detritus and by phytoplankton are substantially smaller than those exhibited by nitrate (let alone ammoniacal nitrogen). During the winter, their concentrations are predicted to rise less than 0.5% relative to baseline$_{f2016}$ in Scenario 13 (Figure 3-14h,k,n, Figure A-11h,k,n). During summer, they are predicted to rise by up to 2% relative to baseline$_{f2016}$ (Figure 3-25, Figure 3-15h,k,n, Figure A-12h,k,n).

Relative to baseline$_{f2016}$, Scenario 13 induces very little change in zooplankton population (<0.2%, Figure 3-14q, Figure A-11q) during the winter. In the summer, zooplankton concentration is predicted to rise by up to 6% in the inner parts of Pelorus Sound, including Mahau Sound and Kenepuru Sound (Figure 3-25, Figure 3-15q, Figure A-12q). Warm water temperatures in summer combine with plentiful light to enable resident phytoplankton to exploit the farm-derived nutrient more effectively than they can during the winter months. The phytoplankton grow more rapidly, but this increased production is quickly consumed by the zooplankton. While the phytoplankton exhibit a greater absolute concentration increase than the zooplankton, it is the latter group that exhibits the larger relative increase.

Patterns of change outside Pelorus Sound

Some of the scenarios induce noticeable (in the false-colour plots) changes outside Pelorus Sound. In some cases, these changes arise relatively close to Pelorus Sound (along the coastline around to, and within Admiralty Bay (Figure 3-4: NH_4 and chlorophyll); or along the coastline towards and within Port Gore (Figure 3-4: chlorophyll and zooplankton)). In other cases, the changes arise further out towards central Cook Strait and show a spatial 'oscillation' between enhancement and depletion (Figure 3-4: small and large detritus). Regardless of where these external-to-Pelorus changes arise, they tend to be of larger magnitude (relative to those arising within Pelorus Sound) during the winter months, perhaps because the greater winter-time freshwater inputs drive greater surface export. Whilst the changes arising out in Cook Strait can sometimes be as large as those arising within the domain (in the same scenario pair and season), the magnitudes of the changes in relative and absolute concentrations are very small in those situations[19].

Unfortunately, because all the seaward boundaries of the model's domain are fairly close to Pelorus Sound, it is not possible to determine the extent to which the changes that arise outside Pelorus genuinely reflect the potential 'true' magnitudes of the influences of the farms (as opposed to being biased by the influence of the boundary conditions). Based upon inspection of current flows at various locations around the model's boundaries and in the vicinity of the Cook Strait mouth of Pelorus Sound, we are inclined to believe that the changes arising near-shore (i.e., those arising in the vicinities of Admiralty Bay and Port Gore) are more plausible than those arising further out in Cook Strait (see also Section 4.2).

[19] Recall that the colour-scales were chosen in order to enable changes to be visible rather than in order to indicate the magnitude of the changes relative to some external scale of acceptable change.

In Section 3.1 we noted that, at the whole-of-Pelorus scale (cf whole of model domain-scale), scenarios 7 and 9 induced smaller nitrogen enrichment per unit feed input than most other scenarios. Inspection of the maps for these scenarios (Figure 3-12, Figure 3-13, Figure 3-16, Figure 3-17) reveals that these two scenarios generate strong plumes of [20]near-surface ammonium that extend outside of the region over which we have calculated Pelorus Sound average increments. Thus, whilst scenarios 7 and 9 might be deemed 'efficient' with respect to Pelorus, their efficiency would tend to converge with those exhibited by other scenarios if the spatial extent of the averaging volume were to be increased.

[20] Weaker plumes of near-bed ammonium also extend outside our Pelorus region (see figures within Appendix A).

3.2.1 Scenario 2 versus Scenario 1

Concentration	Relative Concentration	Concentration difference

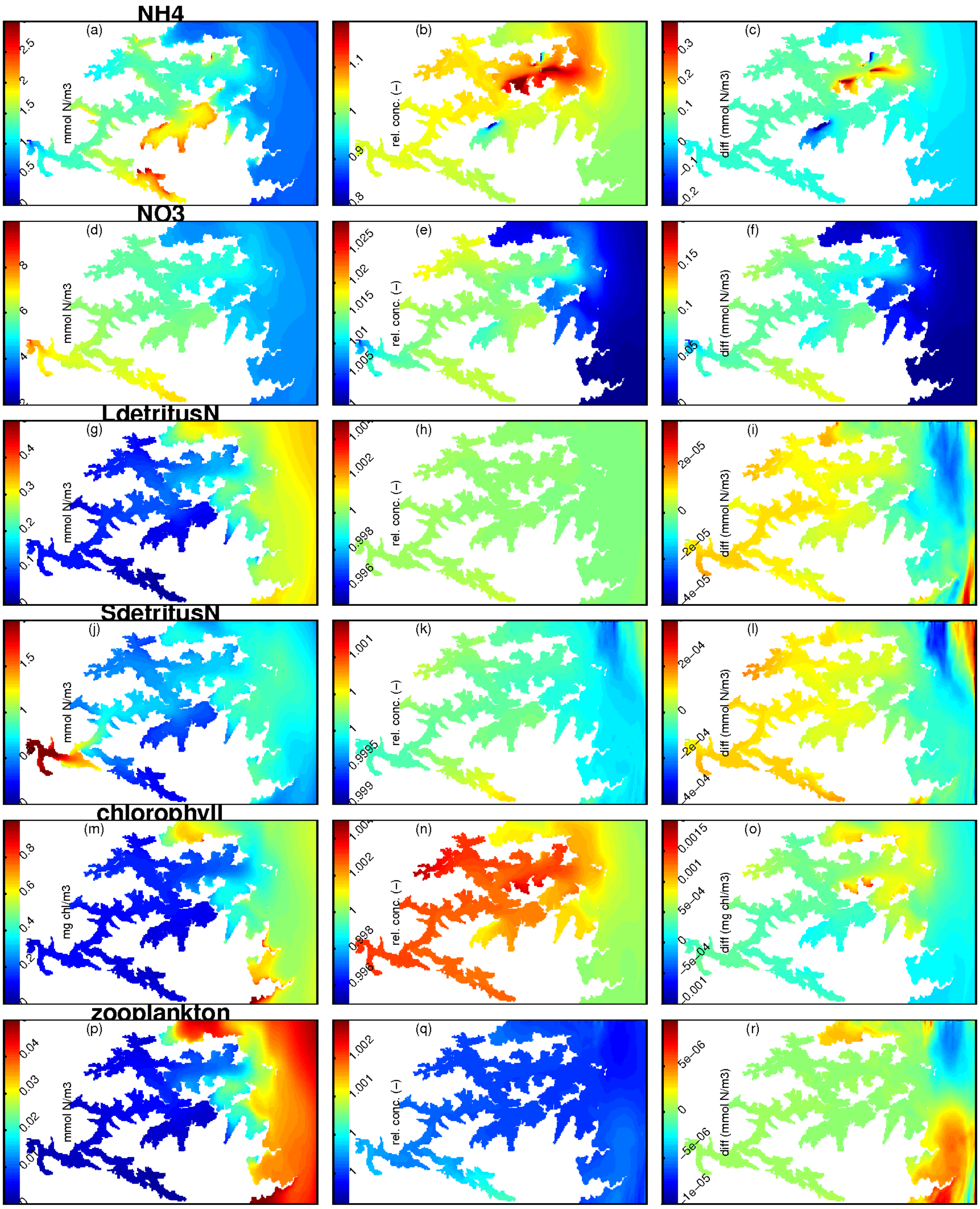


Figure 3-4: Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 2 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

Concentration	Relative Concentration	Concentration difference

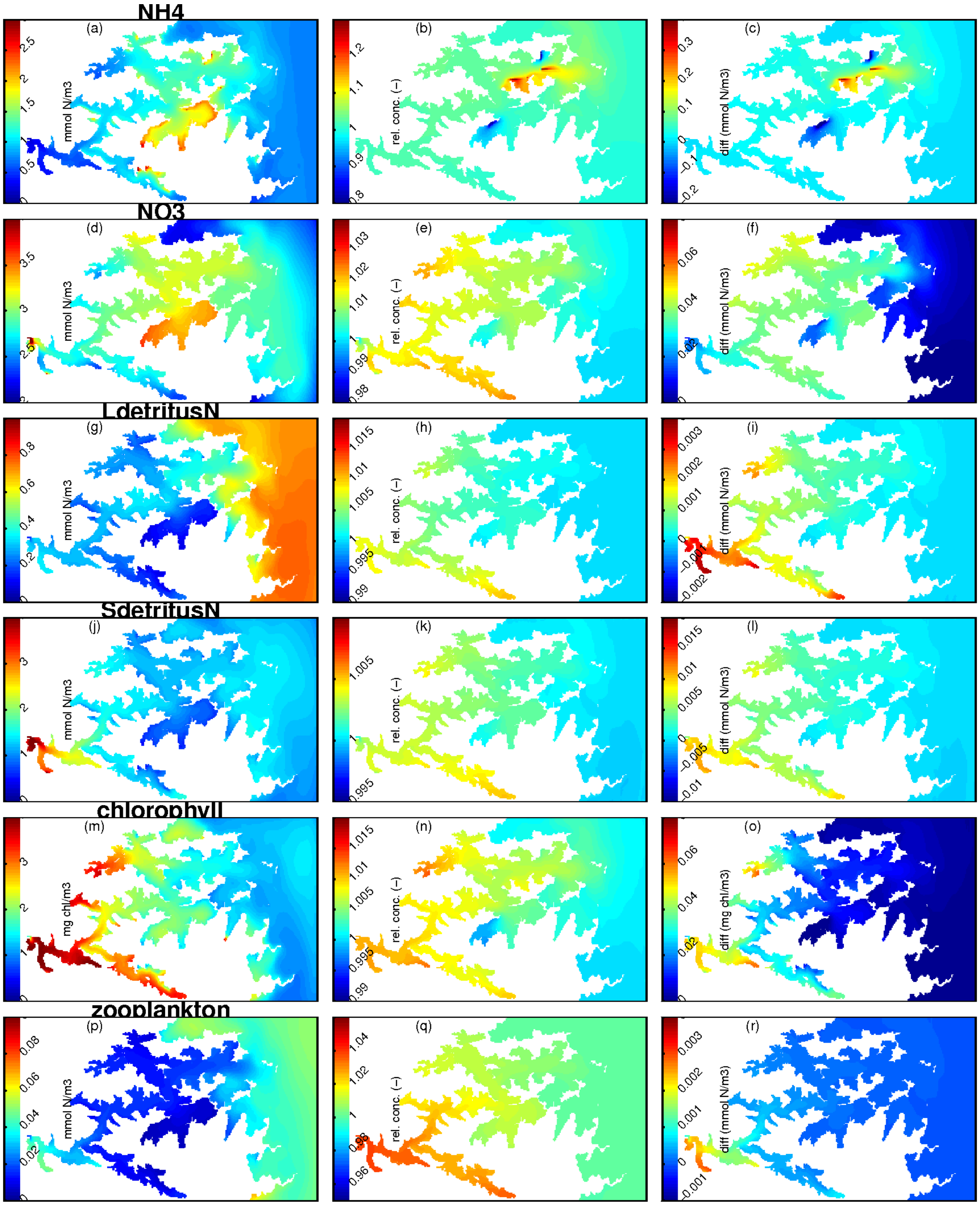


Figure 3-5: Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 2 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

3.2.2 Scenario 4 versus Scenario 1

Concentration	Relative Concentration	Concentration difference

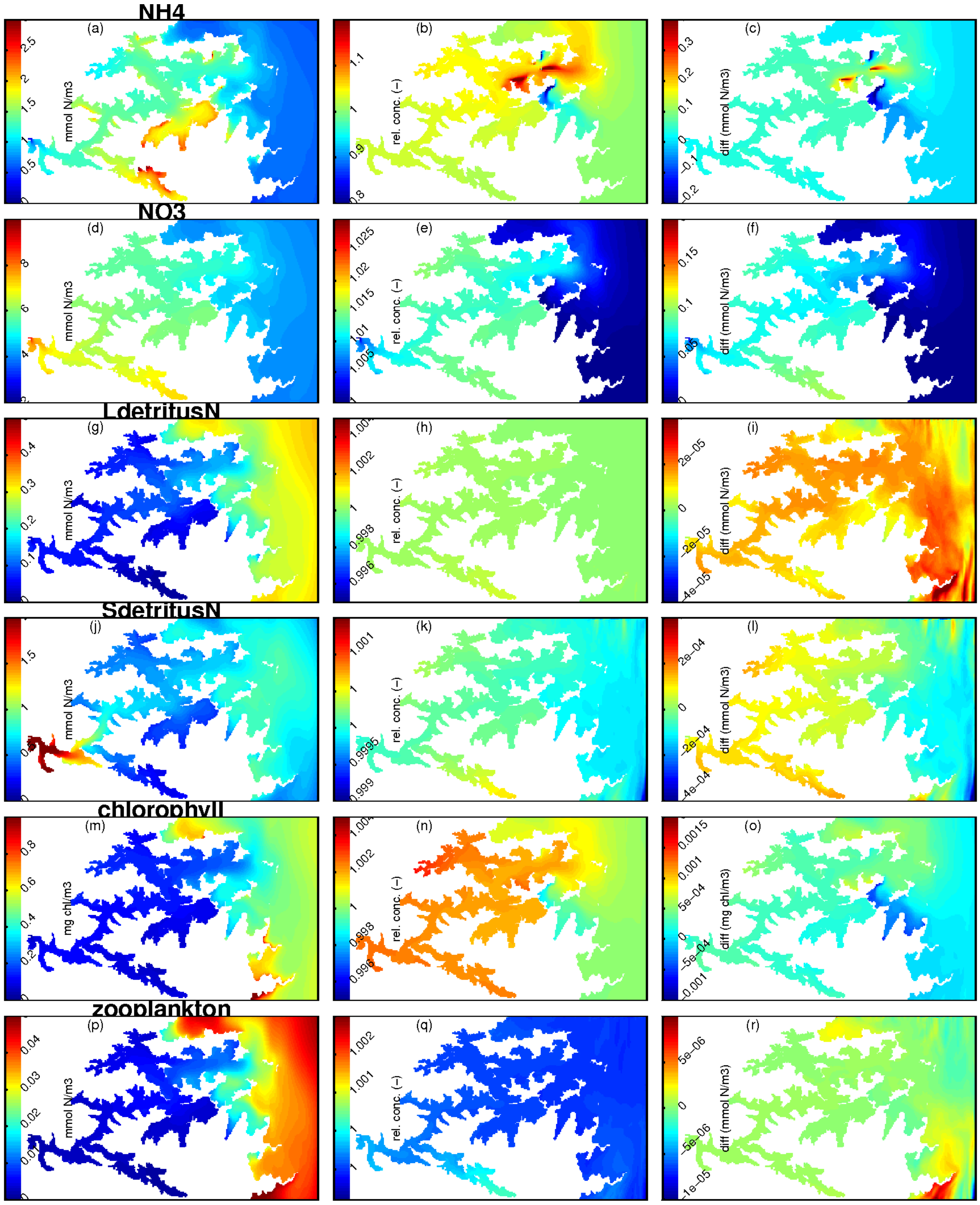


Figure 3-6: Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 4 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

Concentration	Relative Concentration	Concentration difference

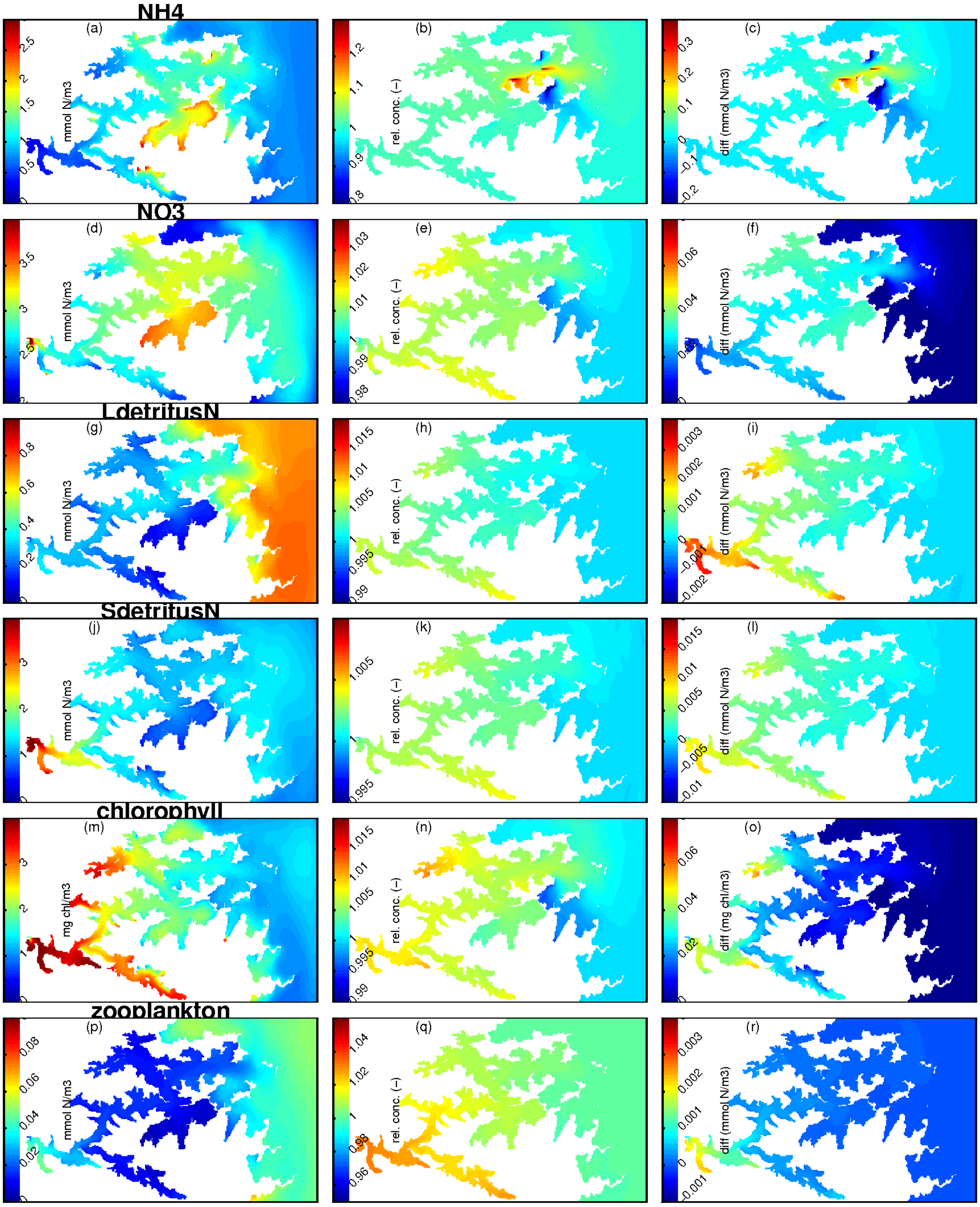


Figure 3-7: Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 4 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

3.2.3 Scenario 5 versus Scenario 1

Concentration	Relative Concentration	Concentration difference

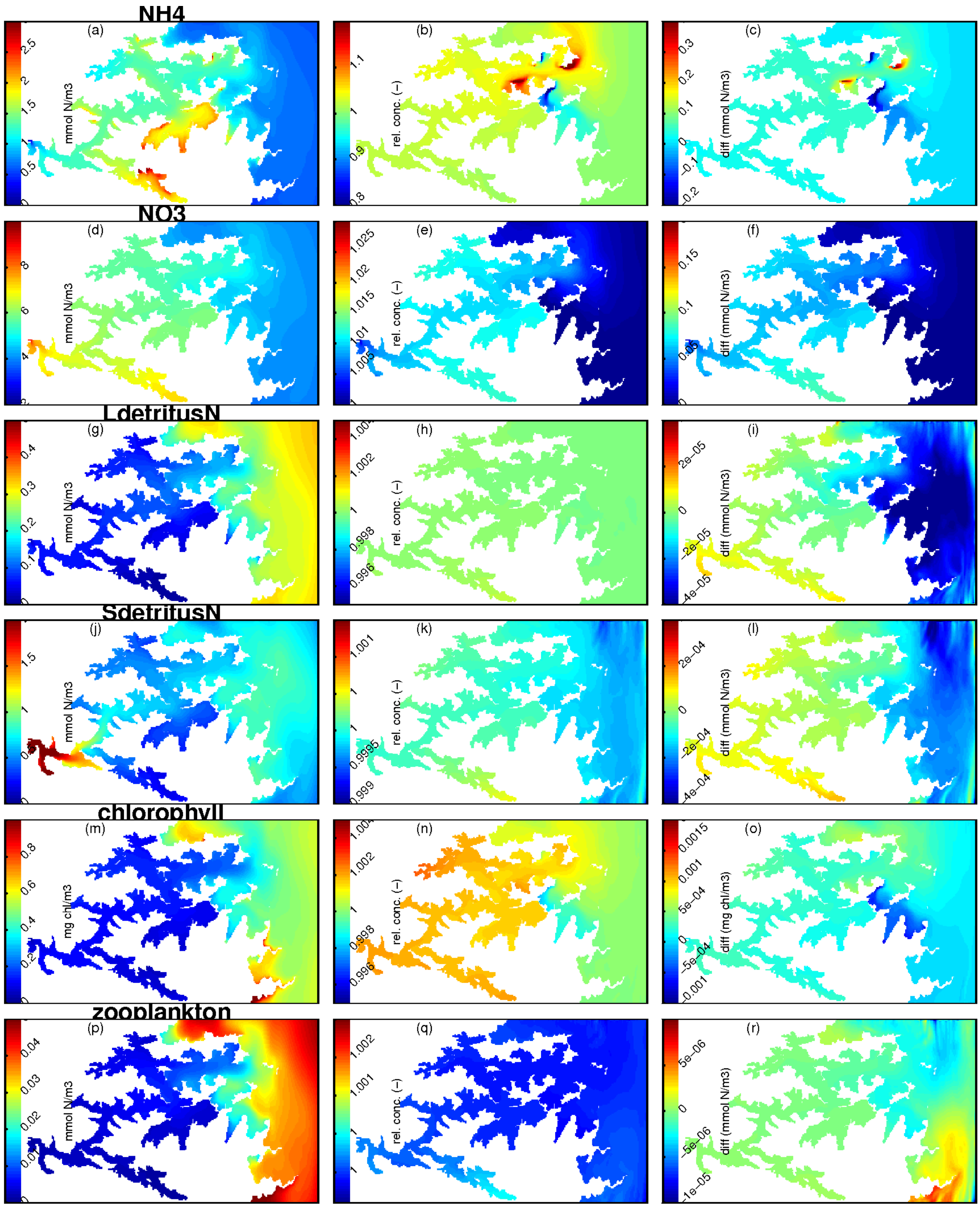


Figure 3-8: Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 5 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

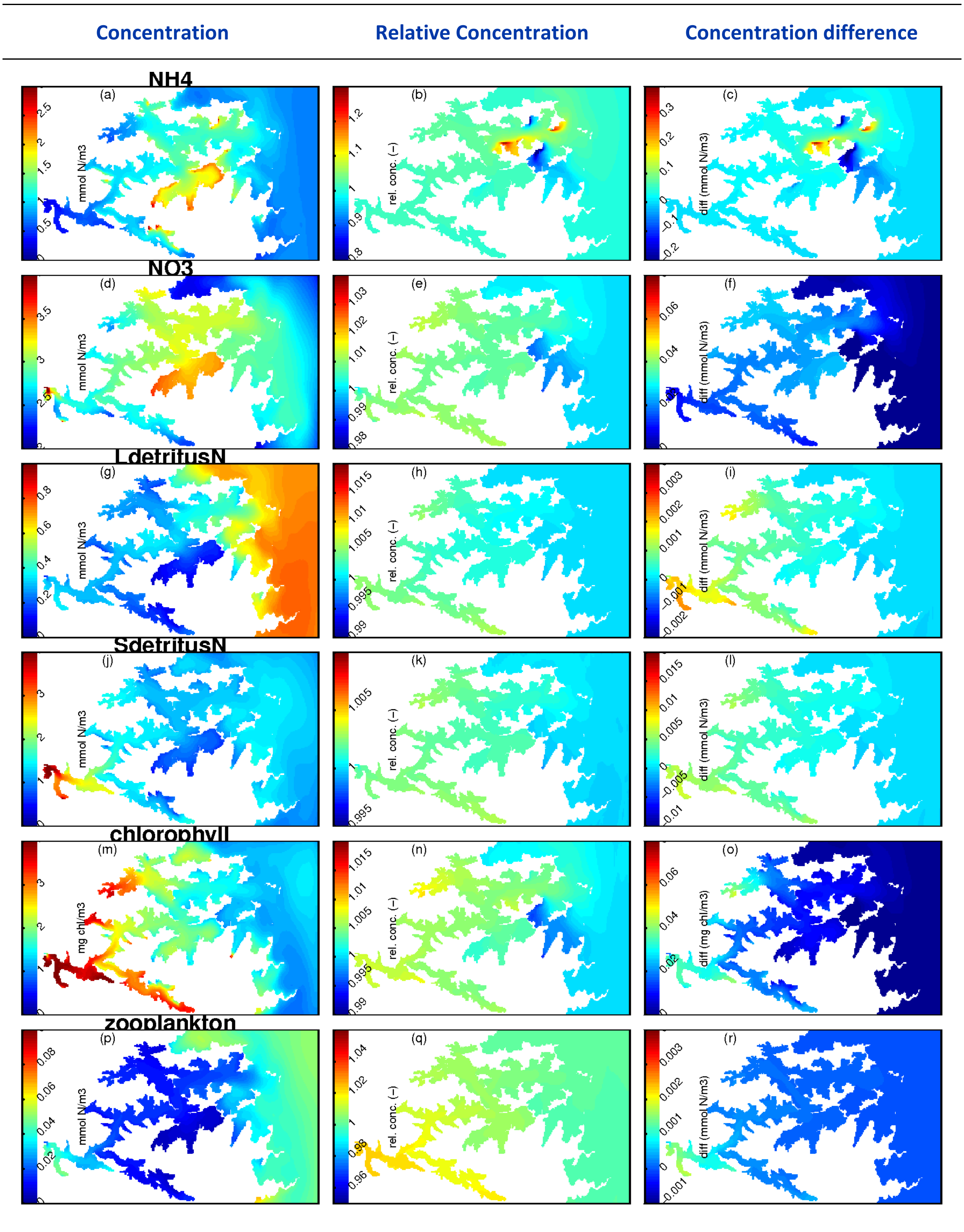


Figure 3-9: Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 5 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

3.2.4 Scenario 6 versus Scenario 1

Concentration	Relative Concentration	Concentration difference

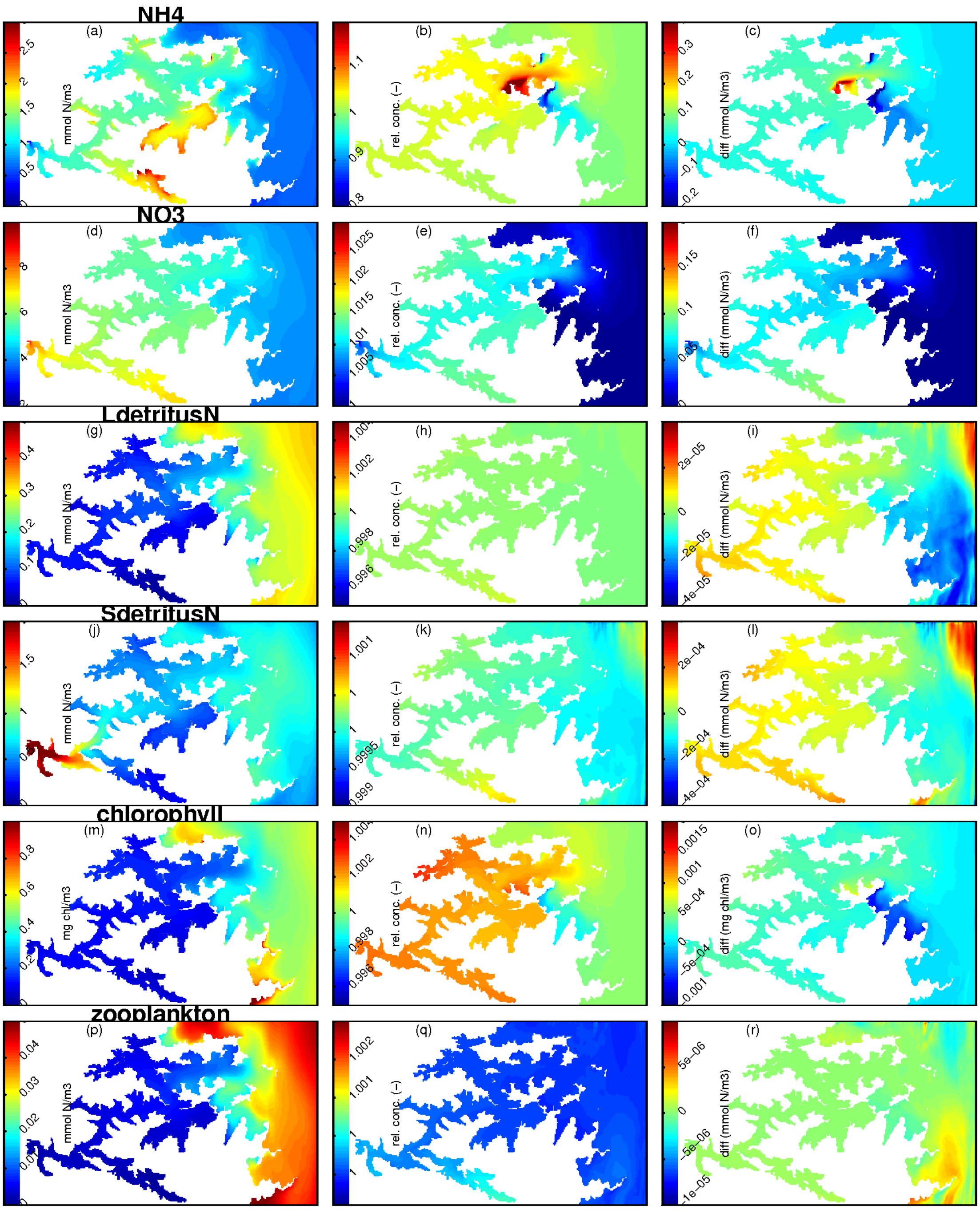


Figure 3-10: Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 6 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

Concentration	Relative Concentration	Concentration difference

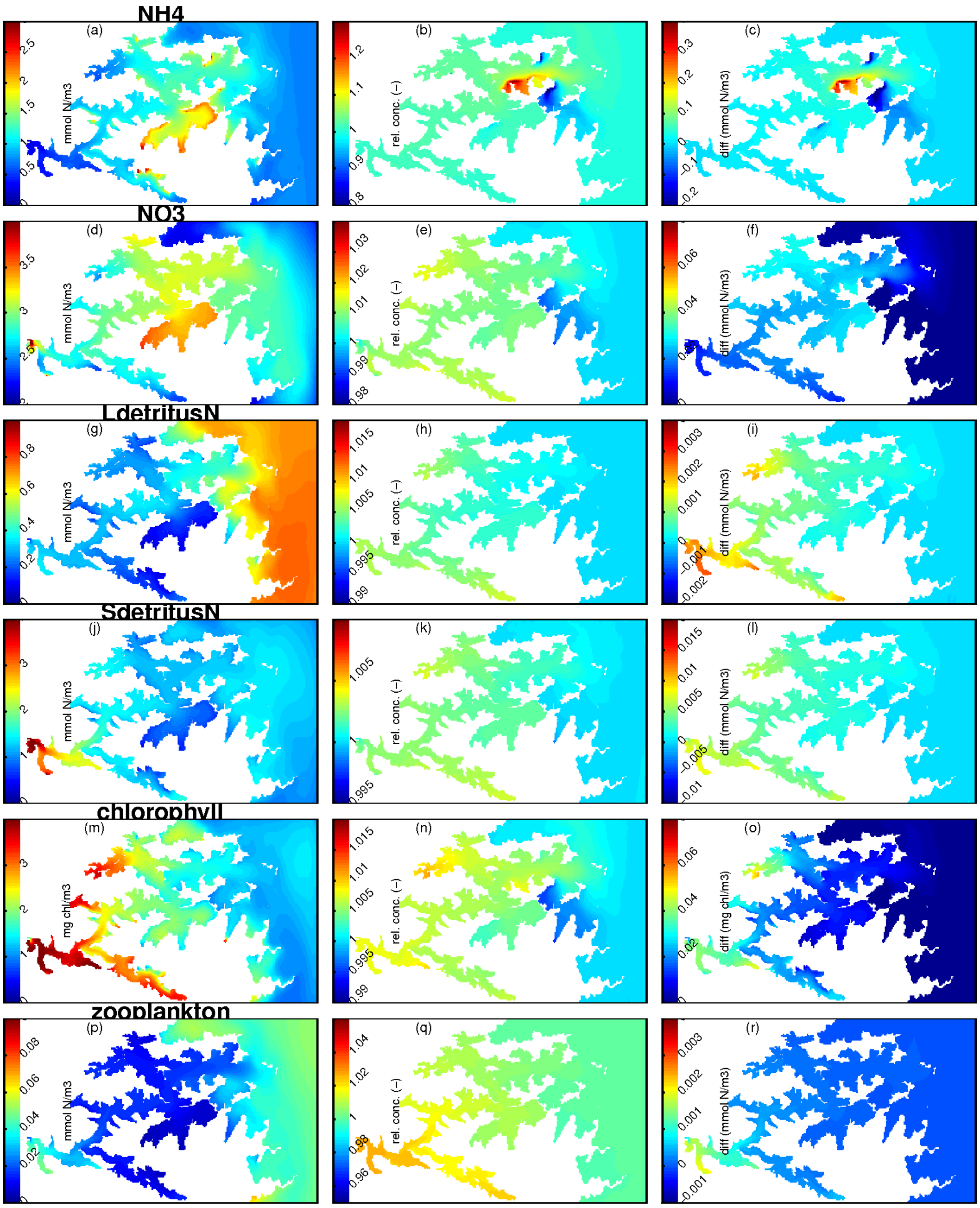


Figure 3-11: Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 6 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

3.2.5 Scenario 7 versus Scenario 1

Concentration	Relative Concentration	Concentration difference

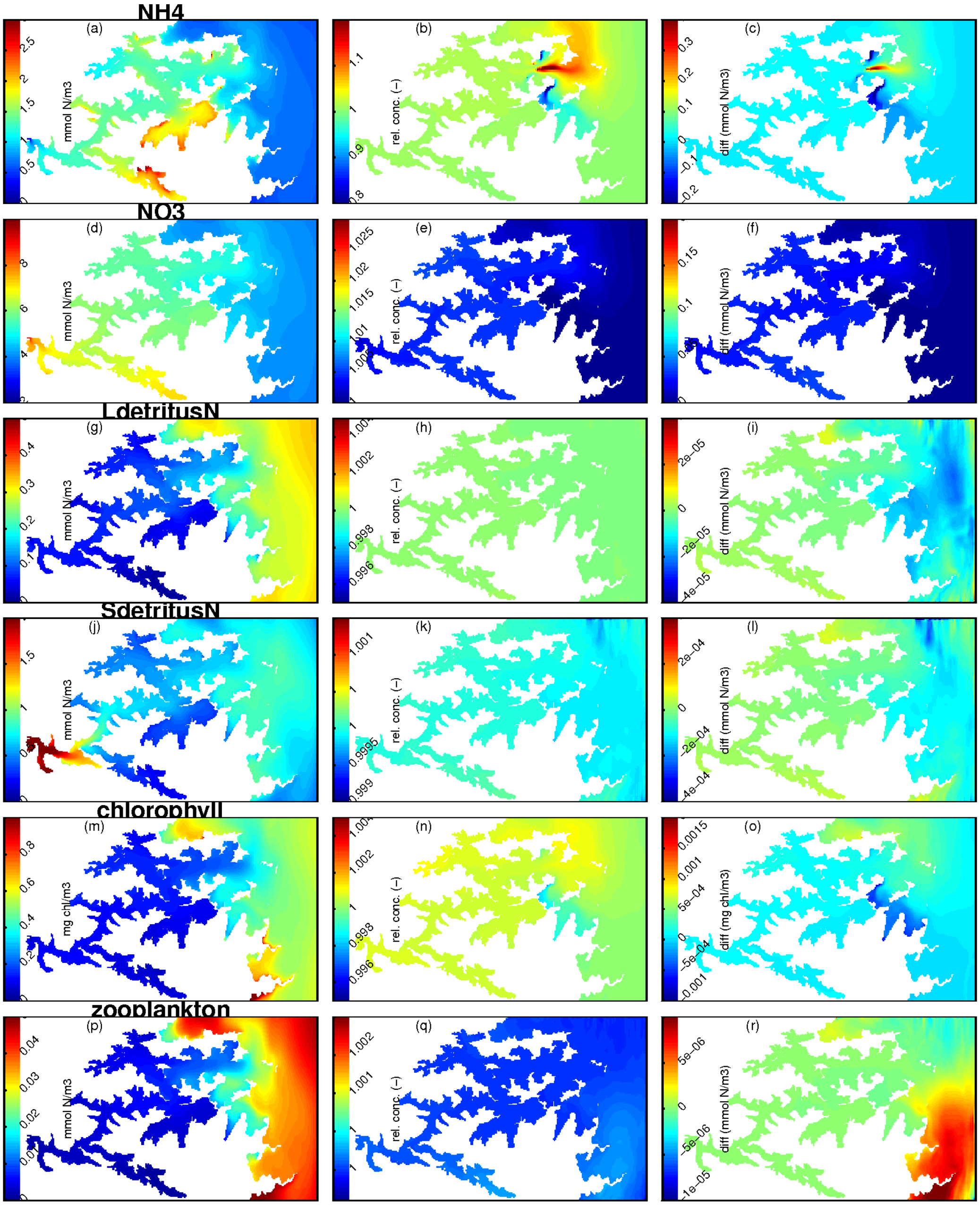


Figure 3-12: Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 7 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

Concentration	Relative Concentration	Concentration difference

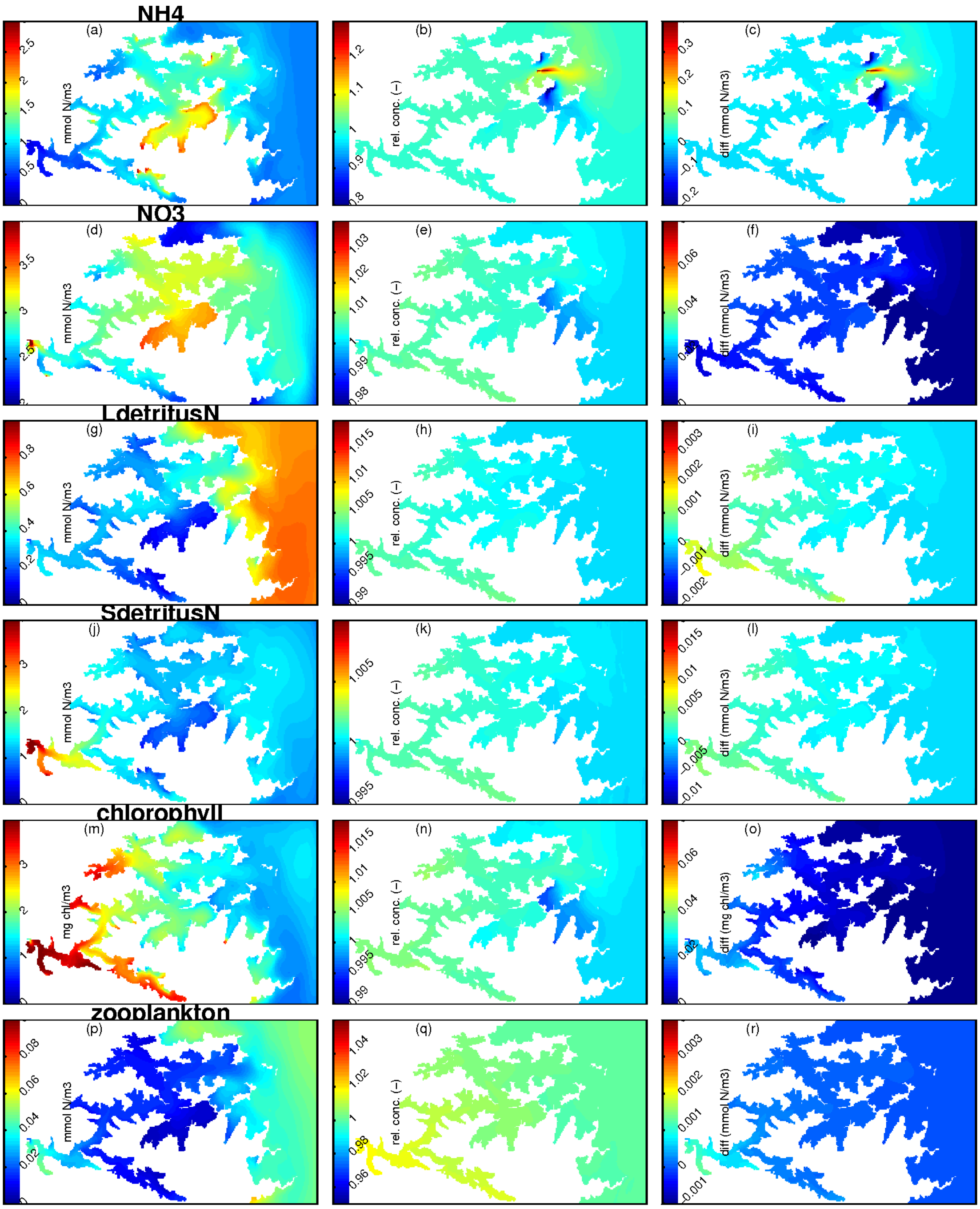


Figure 3-13: Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 7 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

3.2.6 Scenario 8 versus Scenario 1

Concentration	Relative Concentration	Concentration difference

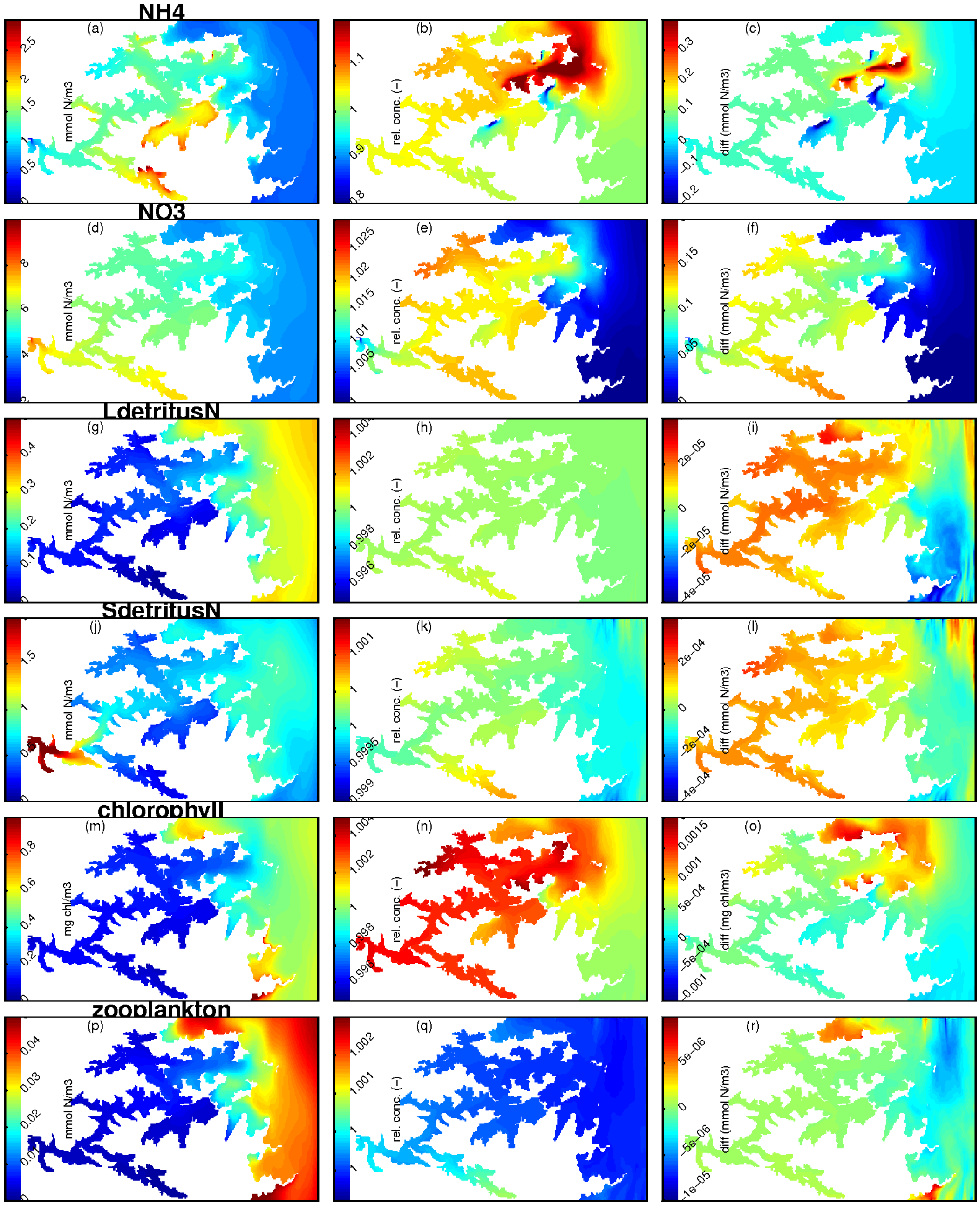


Figure 3-14: Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 8 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

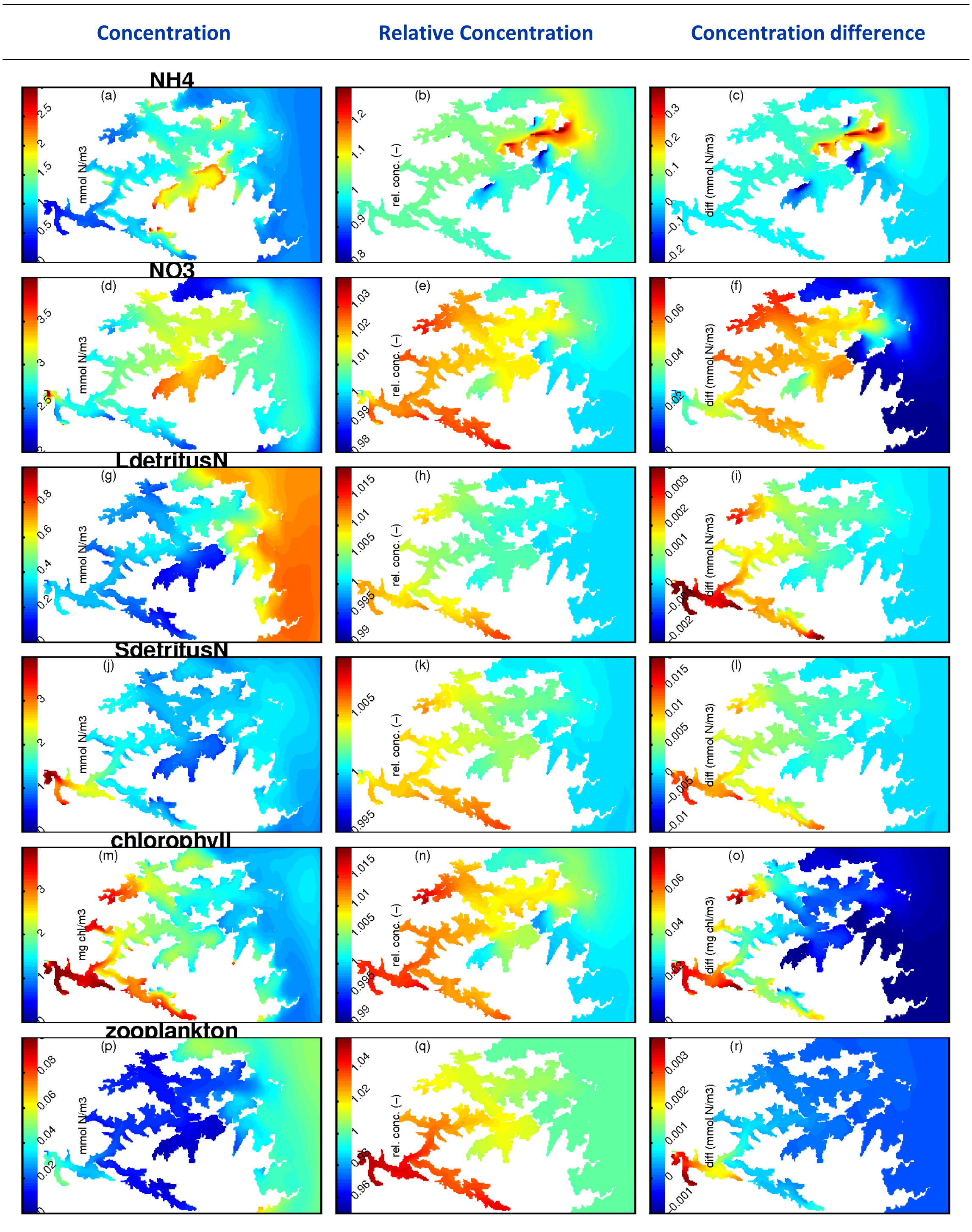


Figure 3-15: Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 8 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline_{f2016}). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline_{f2016} one.

3.2.7 Scenario 9 versus Scenario 1

Concentration | **Relative Concentration** | **Concentration difference**

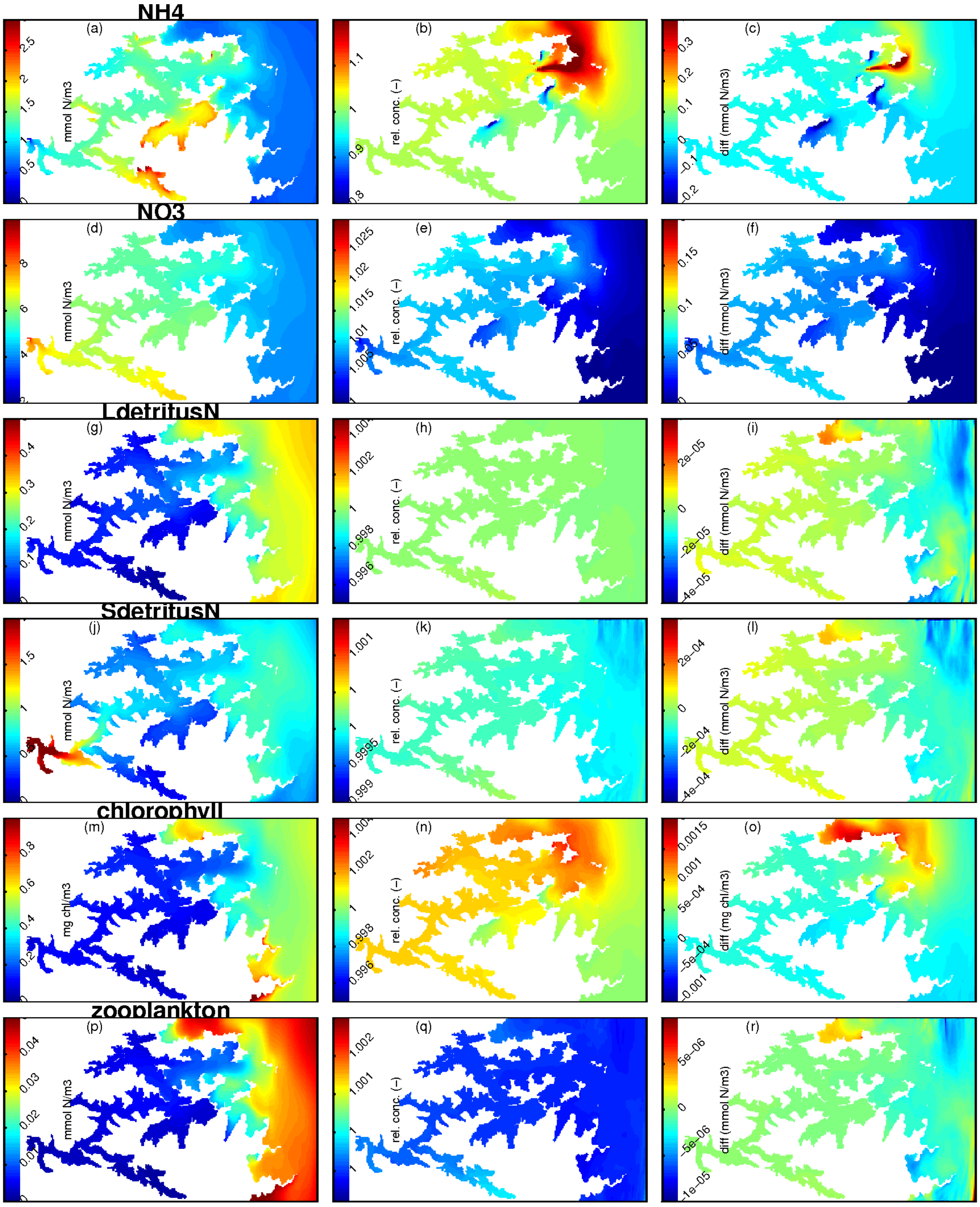


Figure 3-16: Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 9 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

Concentration	Relative Concentration	Concentration difference

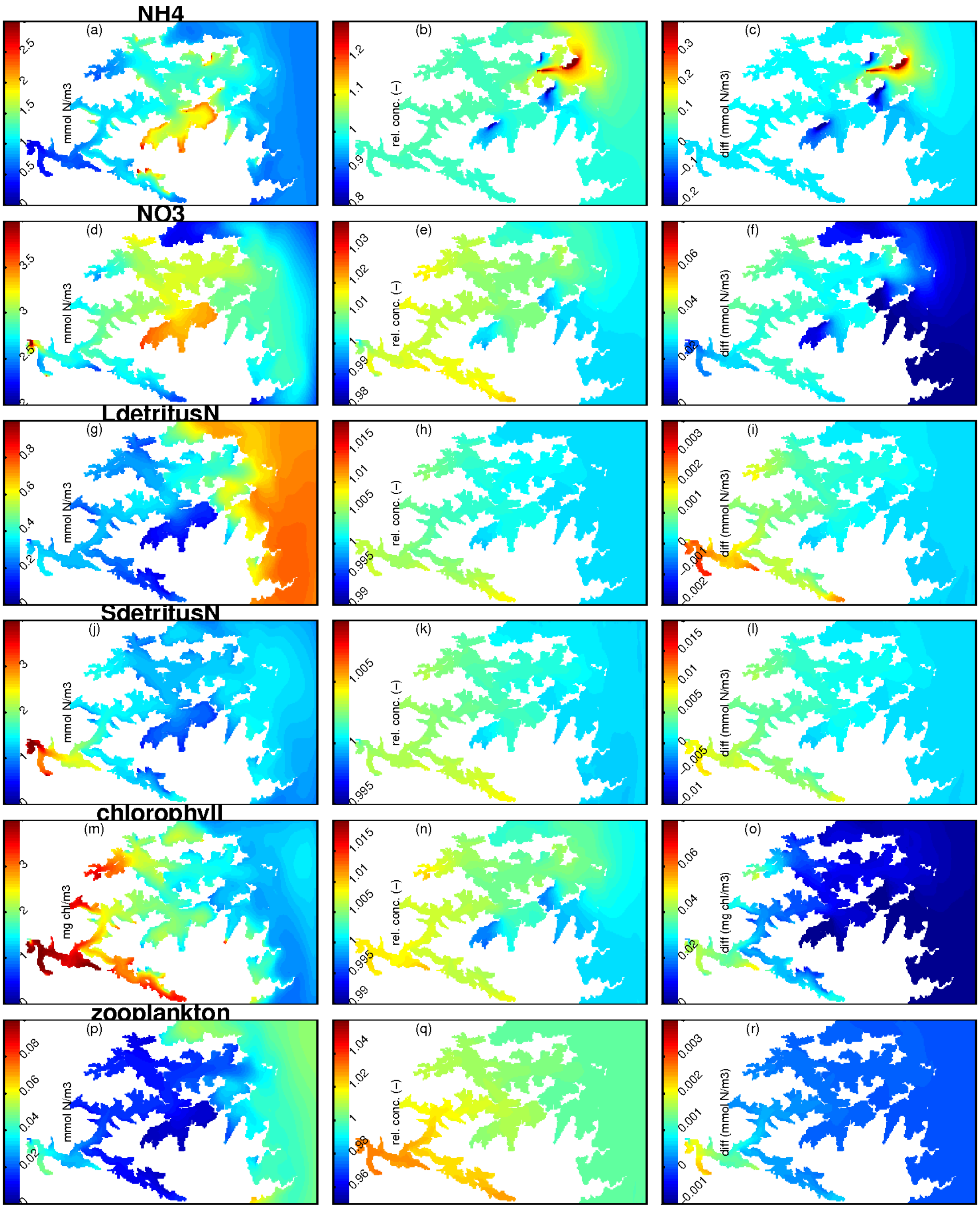


Figure 3-17: Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 9 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

3.2.8 Scenario 10 versus Scenario 1

Concentration	Relative Concentration	Concentration difference

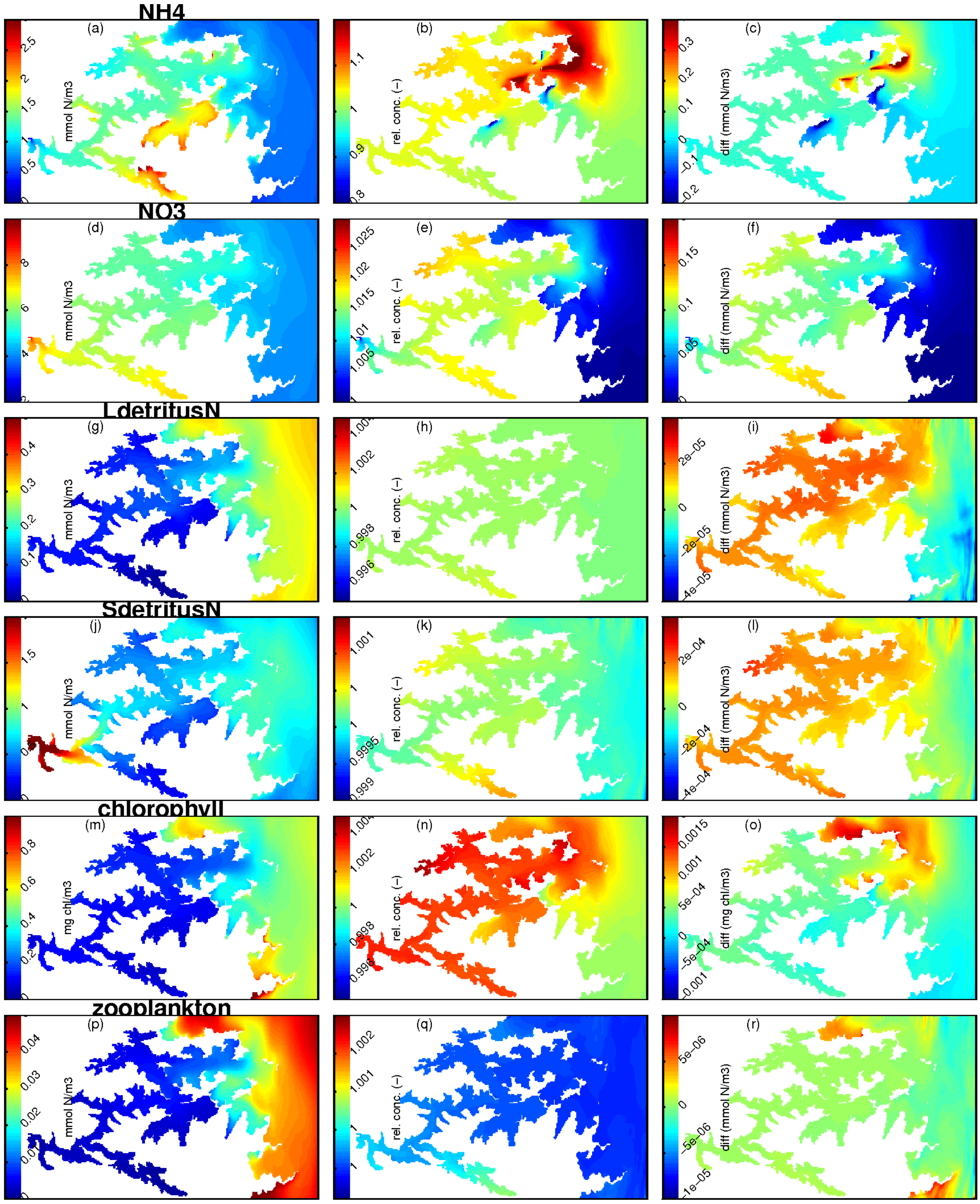


Figure 3-18: Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 10 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

Concentration	Relative Concentration	Concentration difference

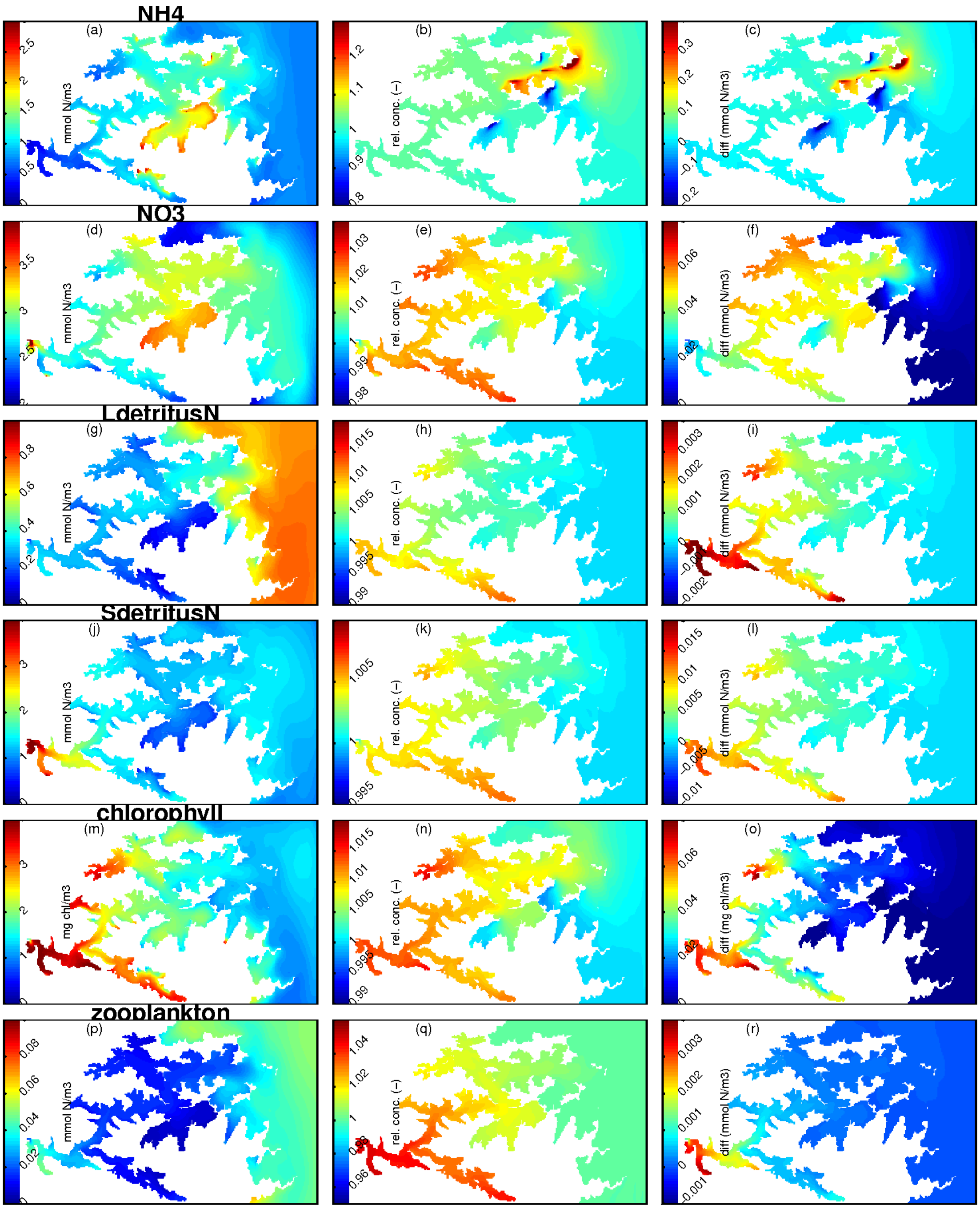


Figure 3-19: Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 10 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

3.2.9 Scenario 11 versus Scenario 1

Concentration	Relative Concentration	Concentration difference

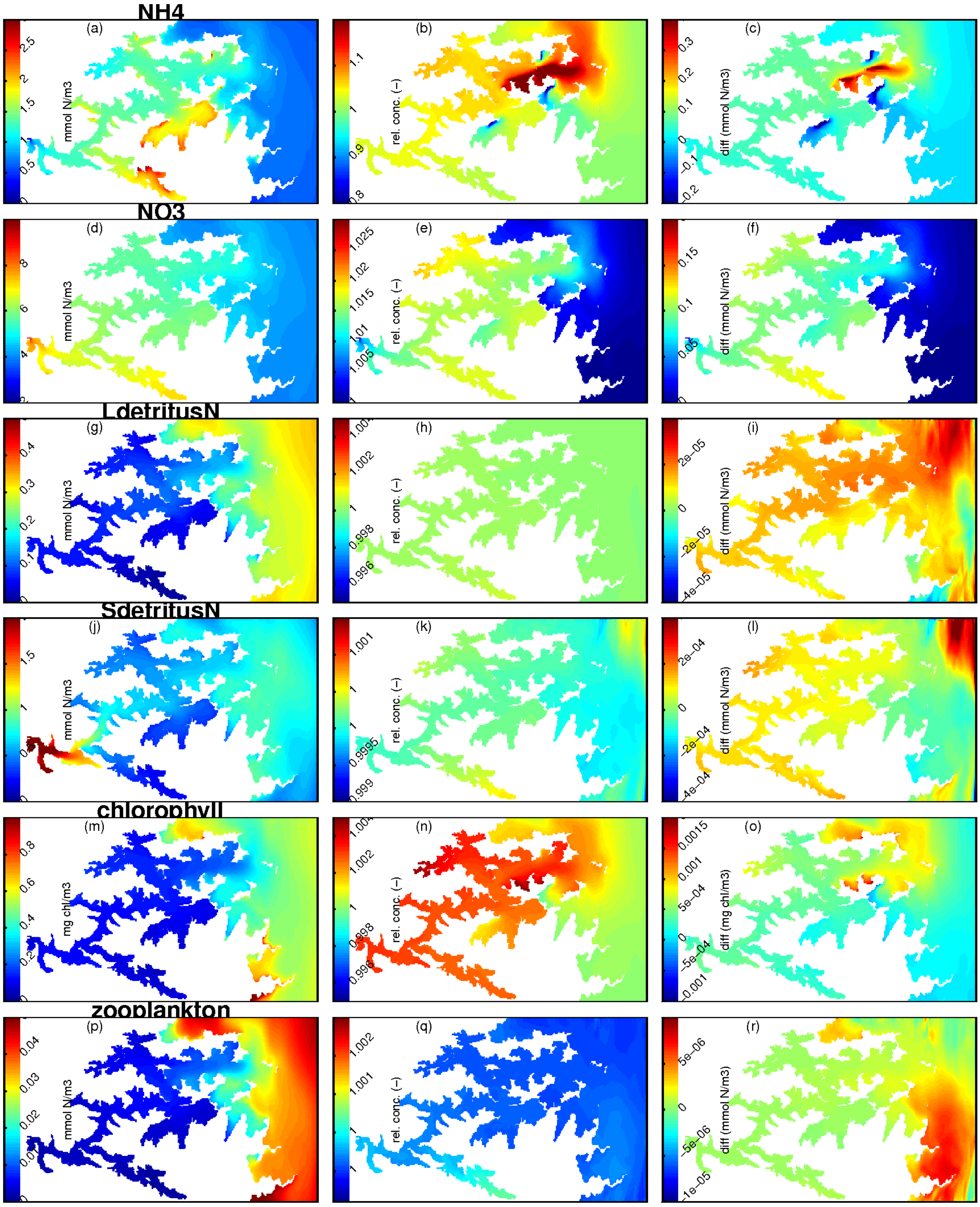


Figure 3-20: Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 11 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

Concentration	Relative Concentration	Concentration difference

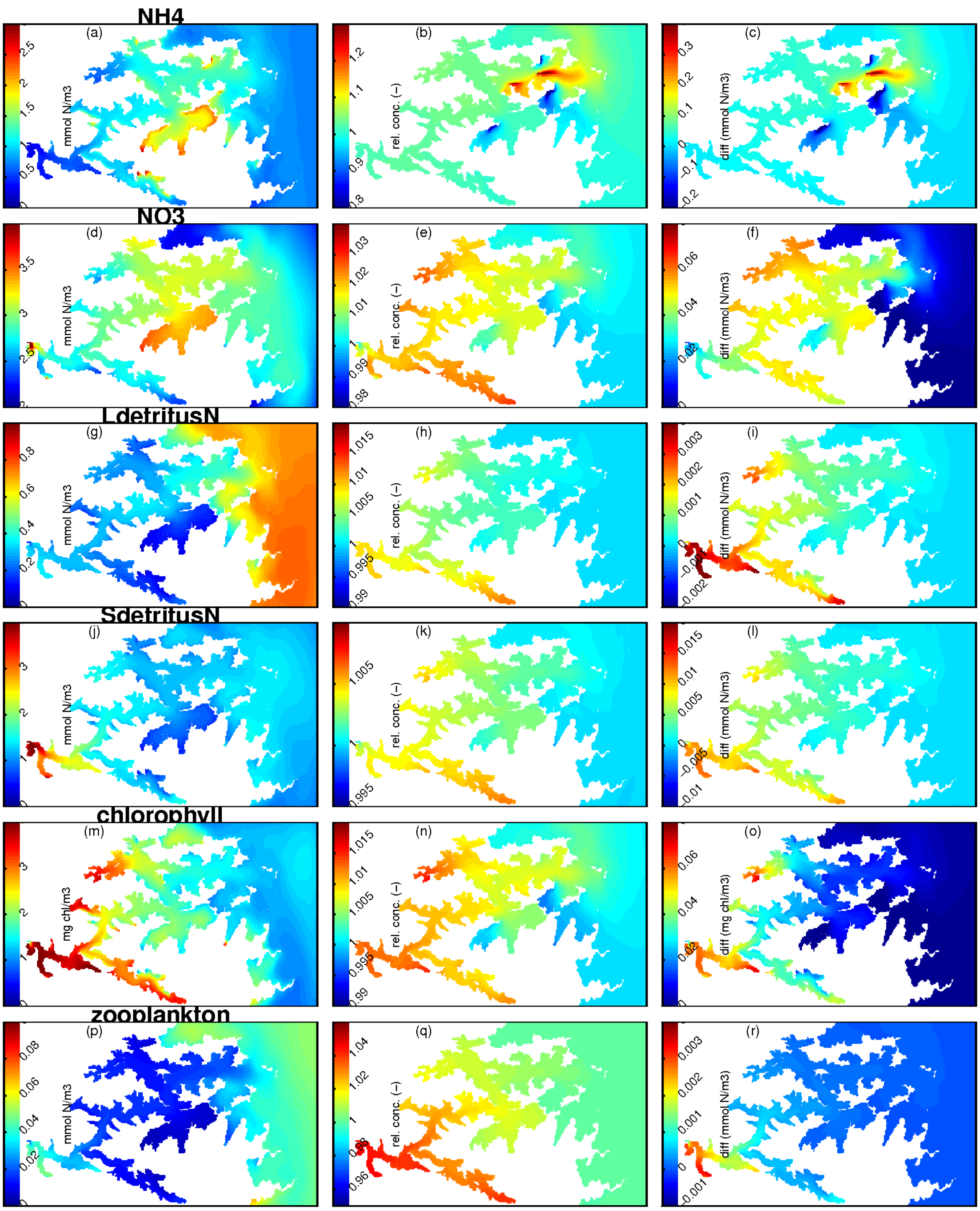


Figure 3-21: Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 11 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the $baseline_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the $baseline_{f2016}$ one.

3.2.10 Scenario 12 versus scenario 1

Concentration	Relative Concentration	Concentration difference

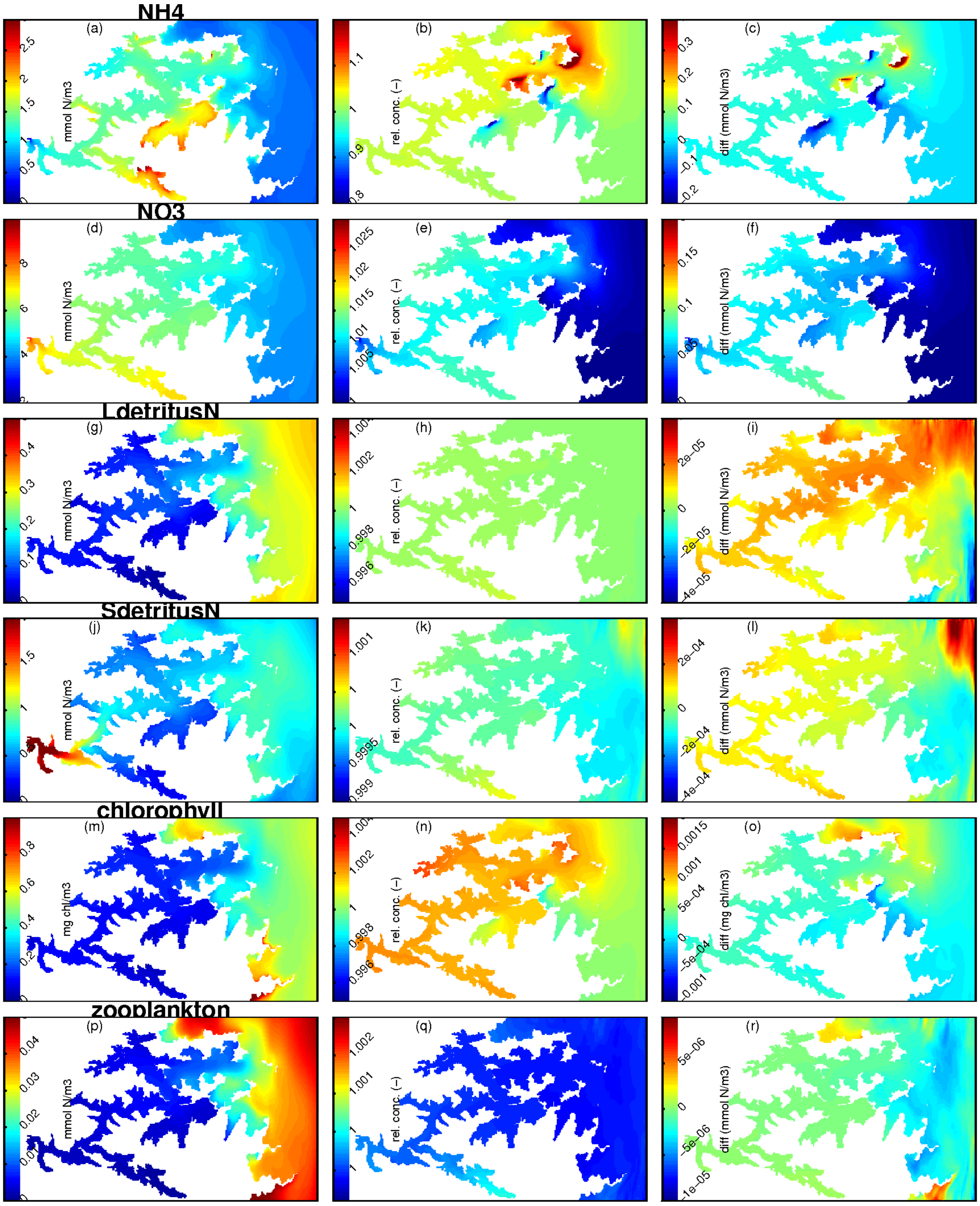


Figure 3-22: Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 12 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

Concentration	Relative Concentration	Concentration difference

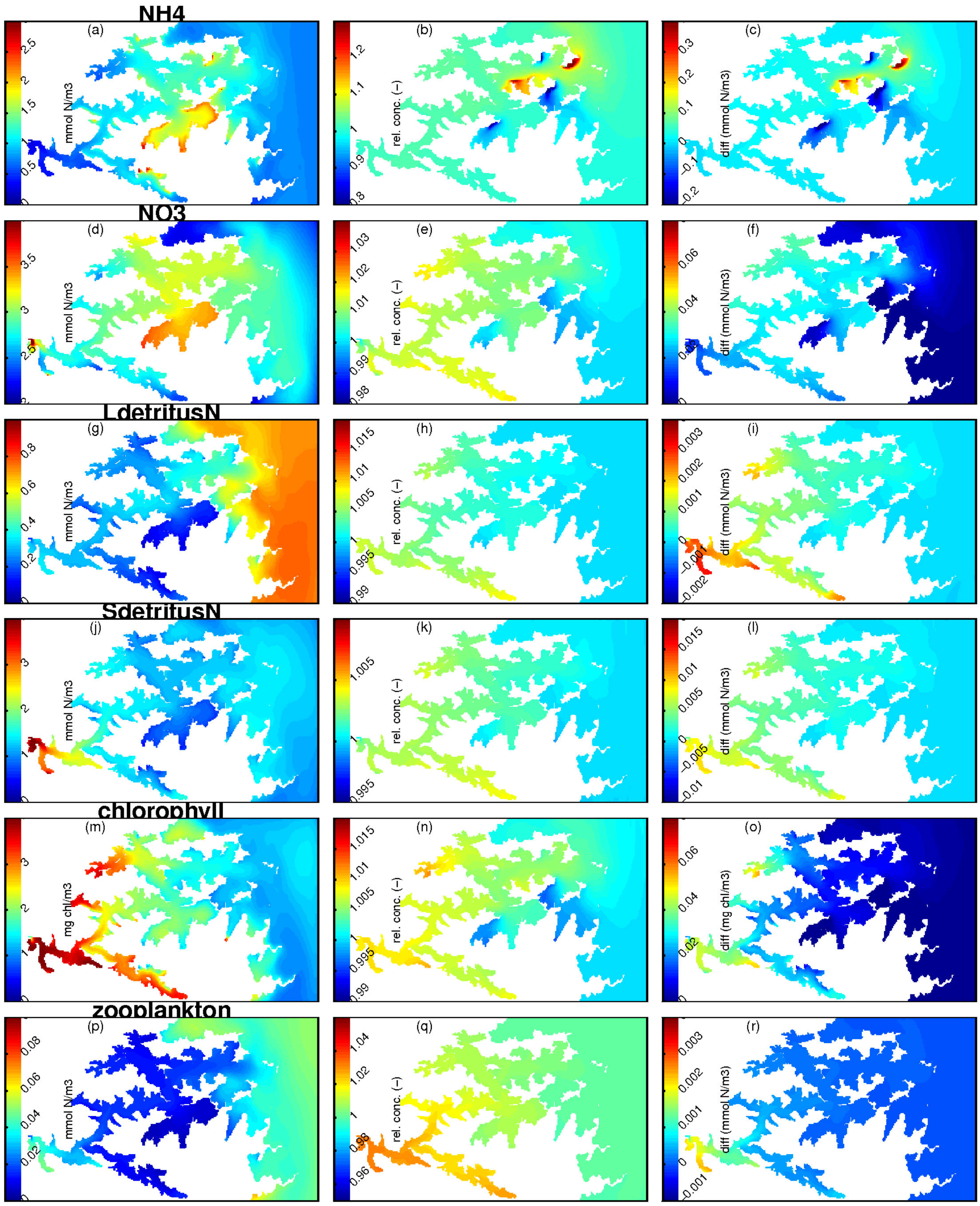


Figure 3-23: Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 12 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

3.2.11 Scenario 13 versus Scenario 1

Concentration	Relative Concentration	Concentration difference

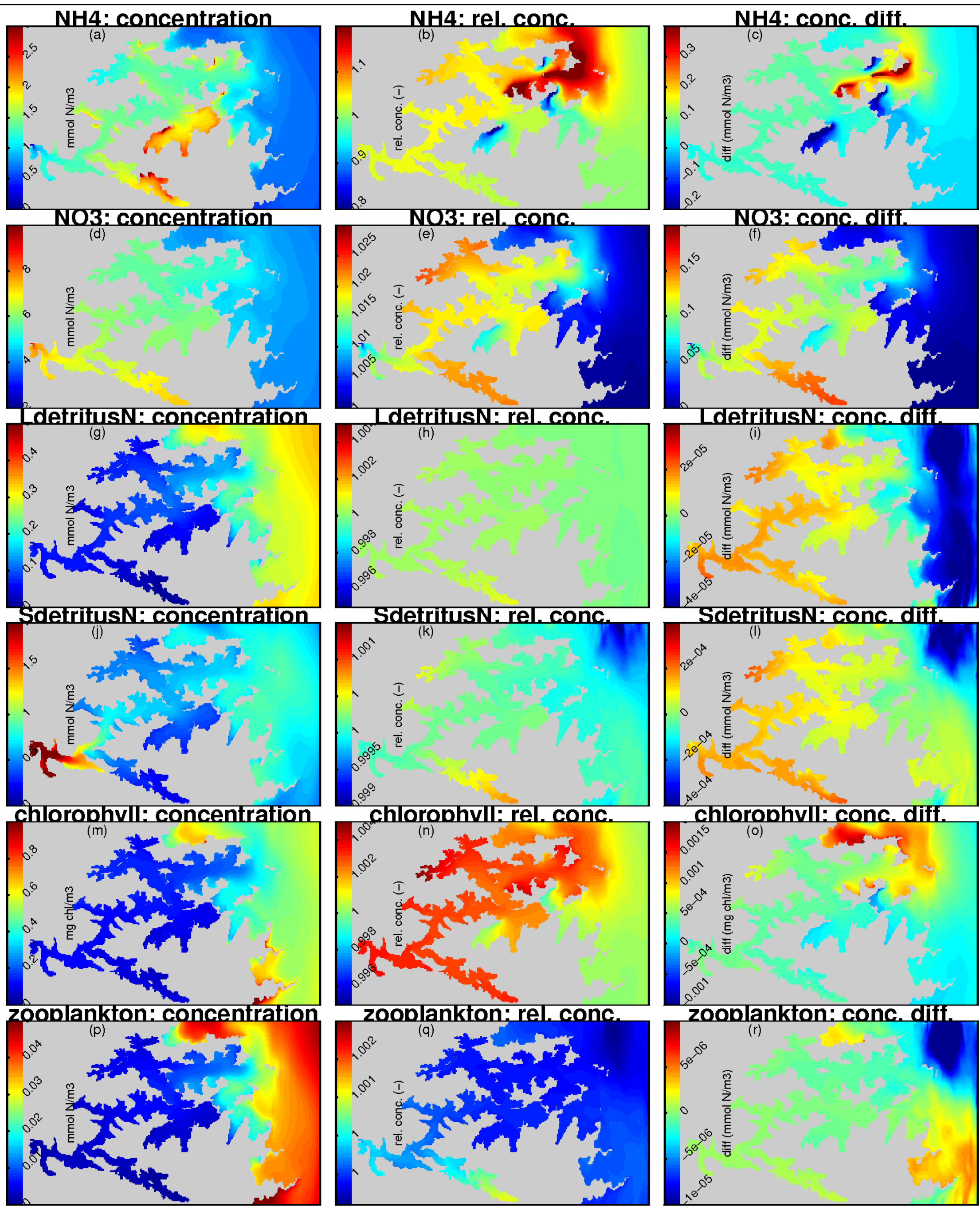


Figure 3-24: Time averages for winter-time near-surface: concentrations, relative concentrations and concentration differences (scenario 13 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

Concentration	Relative Concentration	Concentration difference

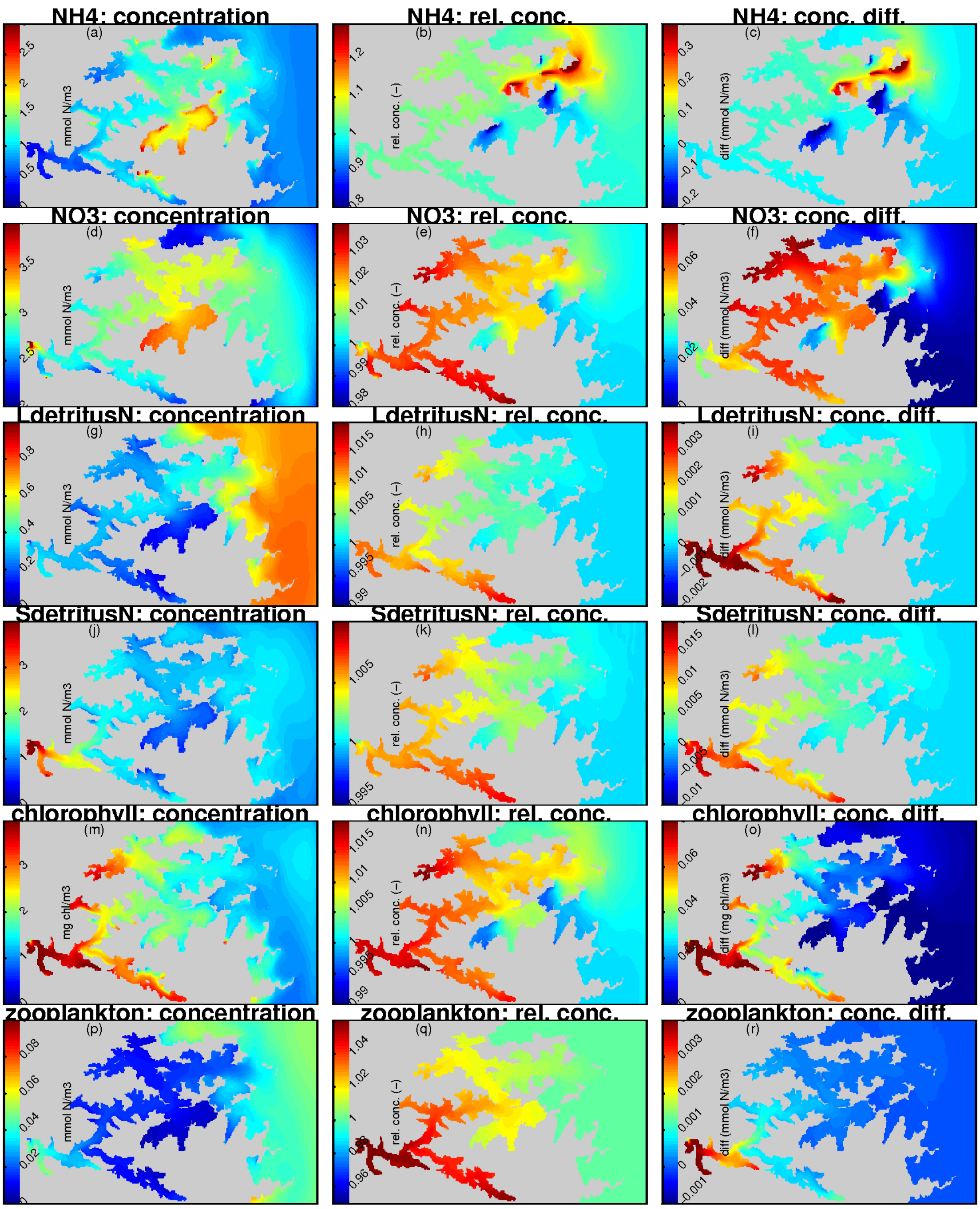


Figure 3-25: Time averages for summer-time near-surface: concentrations, relative concentrations and concentration differences (scenario 13 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. In the central images, relative concentrations in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$). In the right-hand images, positive concentration differences indicate that the alternative scenario tends to yield higher concentrations than the baseline$_{f2016}$ one.

We have examined the time-series of total nitrogen, and time-averages of individual properties. In both cases, the changes induced in the alternative scenarios are small relative to stocks in the baseline_{f2016} scenario. There is a risk that those analyses will have masked larger magnitude (but short-term, or fine-scale) changes. We have not explored this possibility exhaustively, but we have examined the temporal dynamics of individual state-variables at the locations which Marlborough District Council sample on a monthly basis. Appendix B presents examples of such time-series. It is clear that, at least at the MDC sampling locations, Scenario 8 (the one which induces the largest changes within Pelorus Sound) does not change the qualitative dynamics of any of the model's state-variables. Concentrations increase by only a few percent and there is no material change in the phase of amplitudes of the seasonal cycle. Nor are there any notable changes in the amplitudes or occurrence-pattern of shorter-term fluctuations.

4 Discussion

Much of the material presented within this section 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 in that earlier report. The adaptations are minor. Most changes can be attributed to the fact that this report concerns fish-farms in Pelorus Sound rather than in Tory Channel/Queen Charlotte Sound. 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 proposed new (relocated and enlarged) fish-farms may have upon the lower food-web components of the pelagic zones of the Pelorus Sound 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 realisable growth rates in New Zealand coastal waters.

In the simulations, the regions in the immediate farm-environs show moderately large ammoniacal-nitrogen increases – because they are the direct recipients of the farm-derived ammonium. On the other hand, even during summer, these areas exhibit only small changes in seston[21] concentration – because the estuarine transport moves the ammonium elsewhere (some, out into Cook Strait, some towards the inner parts of Pelorus Sound) before the phytoplankton have sufficient time to incorporate much of the ammonium. During the summer (i.e., when light levels and water temperatures are favourable to phytoplankton growth), this farm-derived ammonium is able to fuel additional phytoplankton growth. That growth results in increased seston concentrations at locations down-stream (with respect to prevailing average flows[22]) of the farms.

4.1 Caveats and model limitations

Biogeochemical models (like the one 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.

4.1.1 Spatial resolution and possible systematic bias

Section 2.3 notes that, whilst the model has a nominal horizontal resolution of 200 m, it is designed with the intent of being best able to reproduce system dynamics only at scales somewhat larger than this. There are several reasons for this. Below, we mention three that we believe may be most important.

[21] Suspended particulate organic matter including detrital matter and living plankton (but excluding larger, motile organisms)
[22] Primarily, estuarine circulation

Firstly, as noted in section 2.3, 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 be 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. The errors 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. Wind-errors are unlikely to have an adverse influence upon long-term transport patterns (which are dominated by estuarine circulation), but may imply that the simulated instantaneous locations of farm plumes could sometimes be wrong and that patterns of vertical-mixing and upwelling/downwelling are sometimes wrong in some parts of the Sound. 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.

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 natural (cf faecal and pseudo-faecal) detrital seston will mineralize (gradually) before hitting the seabed, but in shallow waters a 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 Pelorus).

4.1.2 Food web structure and biogeochemical processes

Our model considers the effects that fish-farms may have upon the lower food-web – but it only considers the role that feed-derived nitrogen may play. It does not consider other nutrients. The Marlborough District Council data indicate that nitrogen is invariably the most limiting element within inner and central Pelorus Sound. The data also indicate that nitrogen will usually be the limiting nutrient in the outer parts of the Sound (i.e., beyond Waitata Reach), but on occasions, silicon may also (or instead) limit the growth of those phytoplankton which form silicon-based skeletons (mainly, diatoms).

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 plants (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 means of assessing 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[23] 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 nutrients, the instantaneous (and historical) light intensities (and spectral composition), water temperature, 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 vary 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). 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.

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 Pelorus system. Those data indicate that oxygen concentrations are usually high (>90% saturation) throughout the water column and throughout the year. The lowest recorded concentrations have been around 60% saturation. Those measurements were made in low-salinity water close to the sea surface (i.e., water having a strong riverine influence). Even those 'low' concentrations are above the sub-lethal effects threshold of the vast majority of marine taxa that have been studied (Vaquer-Sunyer and Duarte 2008). Unpublished measurements of dissolved oxygen within the fish-pens of Queen Charlotte Sound/Tory Channel indicate that oxygen concentrations tend to be a little lower inside the pens than further afield. 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 induce far-field hypoxia, but the need to maintain adequate near-field dissolved oxygen may make it less likely that far-field hypoxia will be induced by the fish-farms.

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.

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

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 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 within 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 slower than in the main channel. We anticipate that the effect on current speeds over Pelorus as a whole is likely to be around 5% (D. Plew, NIWA, pers. comm.).

[*New Material*]

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 scenario would be to assume that denitrification might cease only in the immediate environs of the farms. We have not examined that scenario. 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 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'[24]) 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 – making 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 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 anywhere close the model 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 model domain.

4.3 Magnitudes and locations of change

The nominated baseline$_{f2016}$ scenario includes (only) all presently approved marine farms. As such, it is a relevant baseline$_{f2016}$, but it should be recognised that two of the presently approved fish-farms have only recently come into being (Richmond Bay existing, Waitata existing), whilst a third (Beatrix Bay) has introduced fish only very recently. In addition, from time-to-time, some of the older 'existing farms' (Crail Bay, Waihinau, Forsyth) have been fallowed. An alternative baseline (which we were not asked to consider) might comprise only those approved farms which have had fish in the water at some time in the recent past. Previous work has indicated that the addition of the recently

[24] 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.

approved farms[25] may ultimately induce changes of up to around 15% (relative to presently-in-the-water-farms) in chlorophyll abundance. That prior work mistakenly included a potential new farm in Port Ligar[26]. Thus, it probably over-estimated the potential feed-load associated with the approved-but-not-yet operating farms. Nonetheless, it seems plausible that the combination of the (genuinely) approved-but-not-yet-operating farms and at least some of the moved-and-expanded farms envisaged within the new scenarios reported in this work will induce changes (increases) amounting to 10–20% over present, real-world water-quality conditions (as measured in (for example) the Marlborough District Council monitoring of Pelorus Sound).

Removing the farms from Crail, Waihinau and Forsyth Bays tends to reduce the ammonium concentrations in these regions (ammonium is excreted by fish and is also a product of the degradation of waste feed and fish faeces). Nonetheless, it does not automatically follow that concentrations of other variables (nitrate, phytoplankton, zooplankton, and natural detritus) are also reduced in these areas. The greater overall (Sound wide) feed inputs associated with the alternative scenarios, permit (slightly) greater nitrification (conversion of ammonium to nitrate) and primary production (generation of particulate organic matter). In some cases (and particularly in the case of Waihinau), some of the increased nitrate and organic matter becomes transported into Crail, Waihinau and Forsyth Bays such that concentrations are <u>slightly</u> greater in the alternative scenario than in the baseline$_{f2016}$ one – despite the absence of the fish-farms that were present in these bays in the baseline$_{f2016}$ scenario.

For all of the alternative scenarios, the [27]far-field changes tend to manifest themselves in similar locations (i.e., throughout the inner parts of Pelorus including Tawhitinui reach, Mahau and Kenepuru Sounds and their environs). The magnitude of the far-field induced changes appears to be more strongly influenced by the overall feed-loading (summed across all farms) than by the precise location of the farms giving rise to any given overall loading level.

All of the alternative scenarios imply a greater total feed input than the baseline$_{f2016}$ scenario does. The 'smallest' (by feed input) of the alternative scenarios (scenario 6) implies a feed input which is about 25% greater than that of the baseline$_{f2016}$. The largest (by feed input; scenarios 13) imply feed inputs that are more than tripled. All of the alternative scenarios induce a degree of enrichment within Pelorus Sound relative to the baseline$_{f2016}$ but it is notable that one of the larger scenarios (by feed load; scenario 9) induces almost the same level of enrichment as the smallest (scenario 6) of the alternative scenarios (Figure 3-3). Since two of the candidate-to-be-relocated farms stem from Crail Bay (which is known to be relatively slowly flushed in comparison with the Waitata Reach area; Broekhuizen, Hadfield et al. 2015), we speculate that many (if not all) of the alternative scenarios would have yielded lesser enrichment of Pelorus than the baseline$_{f2016}$ scenario had we run our alternative scenarios with the same total feed load as in the baseline$_{f2016}$ scenario (i.e., had the relocated farms not also been expanded). By judicious selection of alternative sites <u>and</u> adopting more restrictive feed-loads (than we were asked to consider) it may prove possible to increase the quantities of salmon that can be raised within Pelorus Sound without inducing any additional nutrient enrichment (or even inducing a reduction of the total nutrient content of Pelorus Sound). This could be explored by making further simulations.

[25] Waitata reach, Richmond Bay, Beatrix Bay and, mistakenly, Port Ligar. Since the Port Ligar farm has not been approved, the feed inputs from this putative farm will never arise. The implication is that the magnitude of changes that will be induced by the remaining three farms may prove to be less than ~15%.
[26] Recall, also, that the model used in the previous work had a slightly different structure and some differing coefficients (see section 2.1).
[27] Several km removed from the fish-farms.

Placing fish-farms closer toward the seaward (Cook Strait) boundary of Pelorus Sound reduces the quantum of nutrient enrichment within the Sound – because much of the farm-derived ammonium is quickly exported out to Cook Strait rather than being imported into central/inner Pelorus and incorporated into phytoplankton (hence, zooplankton and detritus). Nonetheless, the exported ammonium remains biologically active and stimulates additional primary production outside Pelorus Strait and/or adjacent bays (such as Admiralty Bay – see, for example, Figure 3-11). Whilst the changes in these adjacent waters are small relative to natural fluctuations, one might favour a scenario which does not involve putting farms so far out towards Cook Strait if those adjacent waters are deemed to be of higher 'value' than those of Pelorus Sound.

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[28] 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].

In the event that the water-quality consent conditions for the Waitata farm serve as prototypes for those that will govern any new (replacement) farms, we note that our modelling can be viewed as having some relevance[29] to conditions (a) and (e) of the Waitata farm's consent conditions. Independent of the Waitata farm consent conditions, we note that the ANZECC guidelines are also

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

[29] 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.

relevant. For seawater, they nominate an ammoniacal nitrogen threshold concentration of 910 µg N L^{-1} at pH 8.0 (=910 mg N m^{-3}, 65 mmol N m^{-3}).

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 < 2 µm 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) 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)[30]. 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[31]) 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[32]. Systems in which chlorophyll concentrations do not exceed 5 mg chl m^{-3} during the annual bloom period are deemed to be unimpacted.

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[30] 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/.

[31] 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.

[32] 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.).

In MDC's water-quality sampling in Pelorus Sound (monthly at seven stations since July 2012 up to and including December 2015; most stations were sampled at two depths), the value of 5 mg chl m^{-3} (measured using a GF-C filter) has been exceeded in only two water samples (out of 542 such samples). Both were near-surface (rather than near bed) samples. One stemmed from site PLS-1 (Mahau Sound) and one from PLS-2 (Kenepuru). Marlborough District Council has sampled each of these sites on 41 occasions. Thus, in the Marlborough District Council data, 5 mg chl m^{-3} has been exceeded in about 5% of the near-surface sampling records from inner Pelorus and none of the stations in central or outer Pelorus[33]. Across all samples, 5 mg chl m^{-3} has been exceeded in less than 1% of samples. Within the Pelorus data, chlorophyll concentrations in excess of 3.5 mg chl m^{-3} have been recorded on 15 occasions (approx. 3% of samples). The median chlorophyll ranges between 0.6 and 0.9 mg chl m^{-3} (depending upon how one groups the individual samples by season and sampling depth). The 75th percentile ranges between 1.1 and 1.95 mg chl m^{-3}.

4.5 Assessment relative to water-quality standards

Ammonium

The ammonium concentrations arising in our simulations remain well below (about one tenth of) the ANZECC trigger value – even close to the fish-farms. Whilst we acknowledge that the model may under-estimate near-field ammonium concentrations (because it has insufficient spatial resolution to properly resolve individual farms), we consider it unlikely that the farms will induce ammonium concentrations to rise to harmful levels.

We do not believe that the ammoniacal nitrogen concentration increases induced by the relocated farms will meaningfully increase the water's ammonium toxicity – either close to the farms or further afield. Nonetheless, though the concentration increases are of small absolute magnitude beyond the immediate environs of the farm, the small-magnitude plume is predicted to extend several km from the farms' perimeters during the winter months. That being the case, one might question whether there is a possibility that the farms could run afoul of a Waitata farm-like condition (that requires nutrient concentrations beyond 250 m from the farms to remain within the bounds of natural variation for the location and time of year). Our model does not have sufficient spatial resolution to properly address that question, but we note that ammonium concentrations at any given location have fluctuated over a range of about 30 mg N m^{-3} (approx. 2 mmol N m^{-3}) over the years that Marlborough District Council have sampled Pelorus Sound water quality (Broekhuizen and Plew 2015). Of course, some of that fluctuation is seasonal. The range of fluctuation is smaller when data are stratified by season – but it still spans at least several mg N m^{-3}. That is similar to the magnitude of ammoniacal nitrogen increase that the model predicts at distances of a few hundred metres from the pen perimeters for scenario 8 during the winter months. That suggests that even farms as large as those envisaged in scenario 8 may be able to meet Waitata-like 'extent-of-nutrient-plume' conditions.

Chlorophyll

Figure B-3 illustrates the simulated time-series of near-surface chlorophyll at the Marlborough District Council stations in the baseline$_{f2016}$ scenario and in scenario 13 (the one causing the greatest enrichment within Pelorus Sound). Recollecting the summary of MDC chlorophyll data (Section 4.4), it will quickly be apparent that the model is over-predicting summertime chlorophyll concentrations, particularly at the inner Pelorus stations. This is one of the model's deficiencies that was identified in

[33] Though there are a few records of chlorophyll > 5 mg m^{-3} in Beatrix Bay and at Schnapper Point amongst other, earlier data.

our previous work (Broekhuizen, Hadfield et al. 2015). Unfortunately, we have not yet found a solution to the problem.

Certainly, chlorophyll concentrations in the baseline$_{f2016}$ scenario are often greater than 3.5 mg chl m^{-3} (and even 5 mg chl m^{-3}). To a small degree, this may be a result of the two newly approved farms (Waitata and Richmond) but previous modelling suggests that the model tends to over-predict chlorophyll even in the absence of these farms. Relative to the baseline$_{f2016}$, it is scenario 13 which induces the largest summertime chlorophyll concentrations. The biggest concentration increments arise in parts of Mahau Sound, Kenepuru Sound and Tawhitinui Reach/Fitzroy Bay (Figure 3-25o). In those regions, the summer time-averaged chlorophyll increment is circa 0.08-0.1 mg Chl m^{-3}. Marlborough District Council has monitored chlorophyll concentrations within the main channels of these three regions (albeit not at the locations where the model suggests concentrations or concentration increments will be largest) on a monthly basis since July 2012. To date, near-bed chlorophyll concentrations have never exceeded 3.5 mg Chl m^{-3} in any of those three regions. Near surface chlorophyll concentrations have exceeded 3.5 mg Chl m^{-3} on five occasions (of >50) at the Mahau Sound sampling site, three occasions at the Kenepuru (Schnapper Point) site and two occasions at the Tawhitinui (Dart Rock) sites. At these three sites (and all other MDC monitoring sites), the vast majority of sampled near surface chlorophyll concentrations have been less than 3 mg m^{-3} (3 mg Chl m^{-3} has been exceeded on seven occasions in Mahau, six occasions each at Kenepuru and Tawhitinui in near surface samples and one, two and zero occasions in near-bed samples). Given the comparatively small differences evident between scenarios 1 (baseline$_{f2016}$) and 13 (the one inducing the largest changes), we infer that if the model was to more accurately reproduce historical chlorophyll concentrations model, it would not generate frequent breaches of 5 mg chl m^{-3} (or, perhaps, 3.5 mg chl m^{-3}) even under scenario 13. Even if the 'worst' (by TN enrichment within Pelorus Sound) were selected (scenario 13) it seems unlikely that breaches of the 3.5 mg chl m^{-3} threshold (let alone the 5 mg chl m^{-3} one) would become a frequent event. That said, our simulations suggest that all the alternative scenarios will yield a system that is (slightly) more enriched than the present one. This could lead them all to run foul of conditions akin to Waitata's 43(e). Ultimately, much may depend upon how the phrase *'beyond that which is likely to occur naturally'* is interpreted in the future.

4.6 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 eleven different candidate 'future farming scenarios'. We chose to rank the simulations according to the degree of nitrogen enrichment

(Table 3-1) and relative chlorophyll enhancement induced within Kenepuru and Mahau Sounds (i.e., the vicinities of Marlborough District Council sampling sites PLS-11 & PLS-22) because:

- Marlborough District Council monitoring data indicate that chlorophyll concentrations within the main-stem areas of Mahau Sound and Kenepuru tend to be greater than those at other MDC monitoring stations.
- All of the scenarios suggest that the greatest seston changes (concentration increases) will arise within these two regions of Pelorus.
- 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 these parts of the Sound.
- It seems probable that any future farms will be governed by consent conditions that place an upper bound upon acceptable chlorophyll (see sections 4.4).

Whilst neither the chlorophyll maxima, nor the oxygen minima within Pelorus Sound are sufficiently extreme to warrant immediate concern, the collective facts outlined above indicate that the inner parts (Mahau Sound and Kenepuru Sound) may be the most enriched[34] 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 question by ranking the farming scenarios in accordance with the magnitudes of water-quality enrichment they induce within these areas.

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 parts of Pelorus 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 Pelorus).

If, however, one is prepared to accept a small degree of enrichment within inner Pelorus, then at least some of the alternative scenarios may become acceptable. It is our opinion that <u>none</u> of the alternative scenarios will lead to <u>frequent</u> 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 upward through the rank-scores listed in Table 3-1. 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 Pelorus and any

[34] 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 Pelorus would probably fall into the upper part of the oligotrophic/lower part of the mesotrophic categories.

anticipated increased economic value accruing to one or more of: (a) themselves, (b) fish-farm owners, (c) farm-employees and (d) the wider economy[35].

Broadly speaking, those who seek to minimise the risk of a breach of environmental standard within the inner parts of Pelorus will favour scenarios with a smaller rank-score within Table 3-1. The risk of triggering a water-quality breach is minimized by favouring scenarios which:

(i) minimize the net increase in feed loads to the system, and

(ii) place the new/relocated farms closer towards the seaward (Cook Strait) end of Pelorus Sound (i.e., favour shifting farms towards Blowhole point over shifting them towards Richmond Bay South or Horseshore Bay).

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 Pelorus because these appear to be most 'at risk'. Nonetheless, we acknowledge that there are many parts of the Sound (and adjacent coastal regions) for which there are no data - so we have no definitive way of knowing that inner Pelorus is genuinely the most enriched part of the system at present. We also acknowledge that some individuals may prefer minimising water-quality in regions other than inner Pelorus. For example, scenarios which relocate farms to Blowhole Point will tend to induce greater change in adjacent coastal waters (e.g., Admiralty Bay) than those which place the farms around Richmond Bay/Horseshoe Bay.

[35] 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.).

5 Acknowledgements

We are grateful to New Zealand King Salmon Ltd (specifically, Grant Lovell, Kim Hooper and Mark Gillard) for providing us with farm-stocking schedules for each farm in each scenario that we have simulated. The original coupled hydrodynamic and biophysical model was developed with CORE funding to NIWA from the Ministry for Business and Innovation and preceding Government funding to NIWA (FRST research). Its initial application to the Marlborough Sounds was funded by Marlborough District Council and NIWA (CORE funding). The author(s) wish to acknowledge the contribution of NeSI to the results of this research. New Zealand's national compute and analytics services and team are supported by the New Zealand eScience Infrastructure (NeSI) and funded jointly by NeSI's collaborator institutions and through the Ministry of Business, Innovation and Employment. URL http://www.nesi.org.nz

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Appendix A Time-averaged results for near bed layer

Concentration | **Relative concentration** | **Concentration difference**

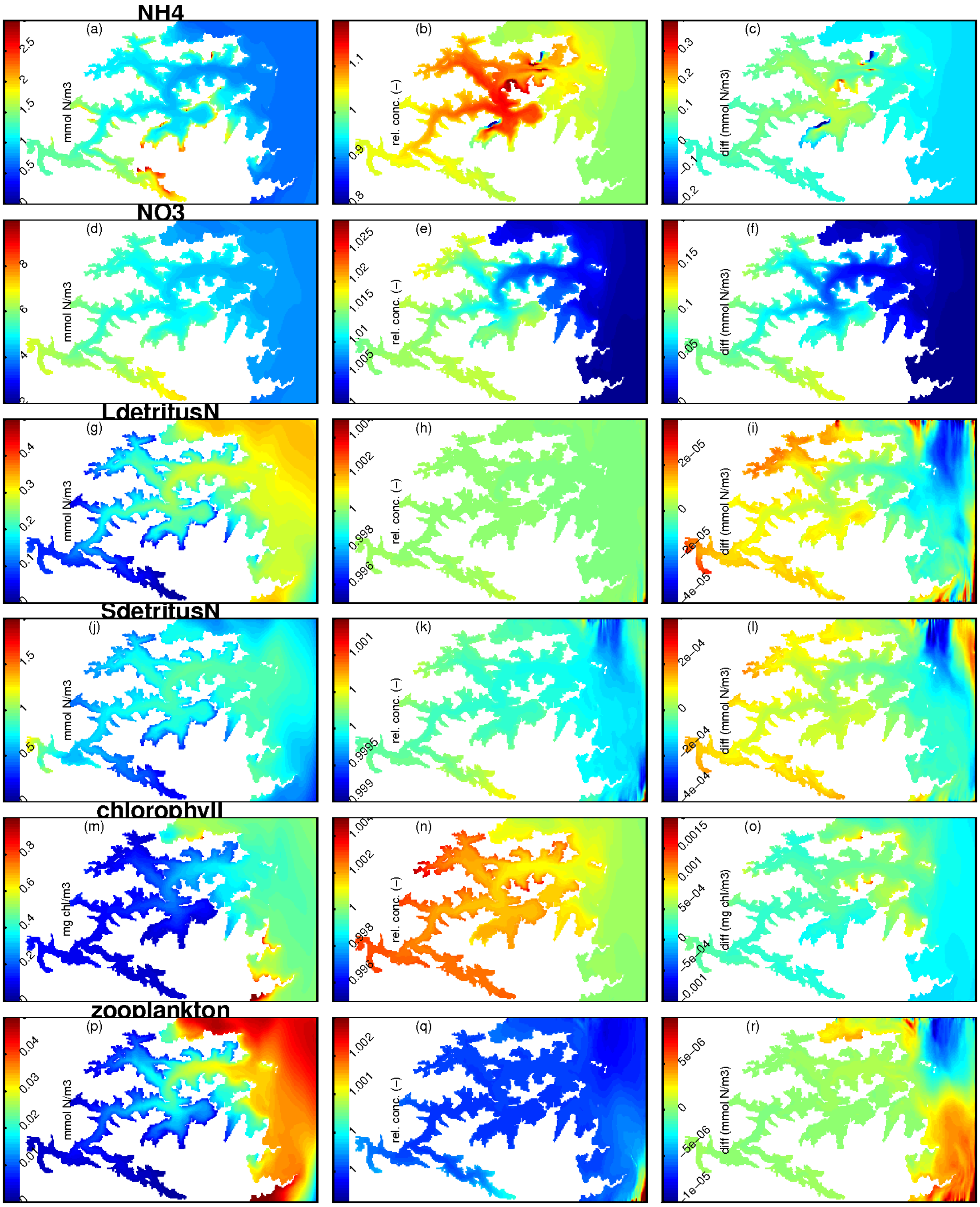

Figure A-1: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 2 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

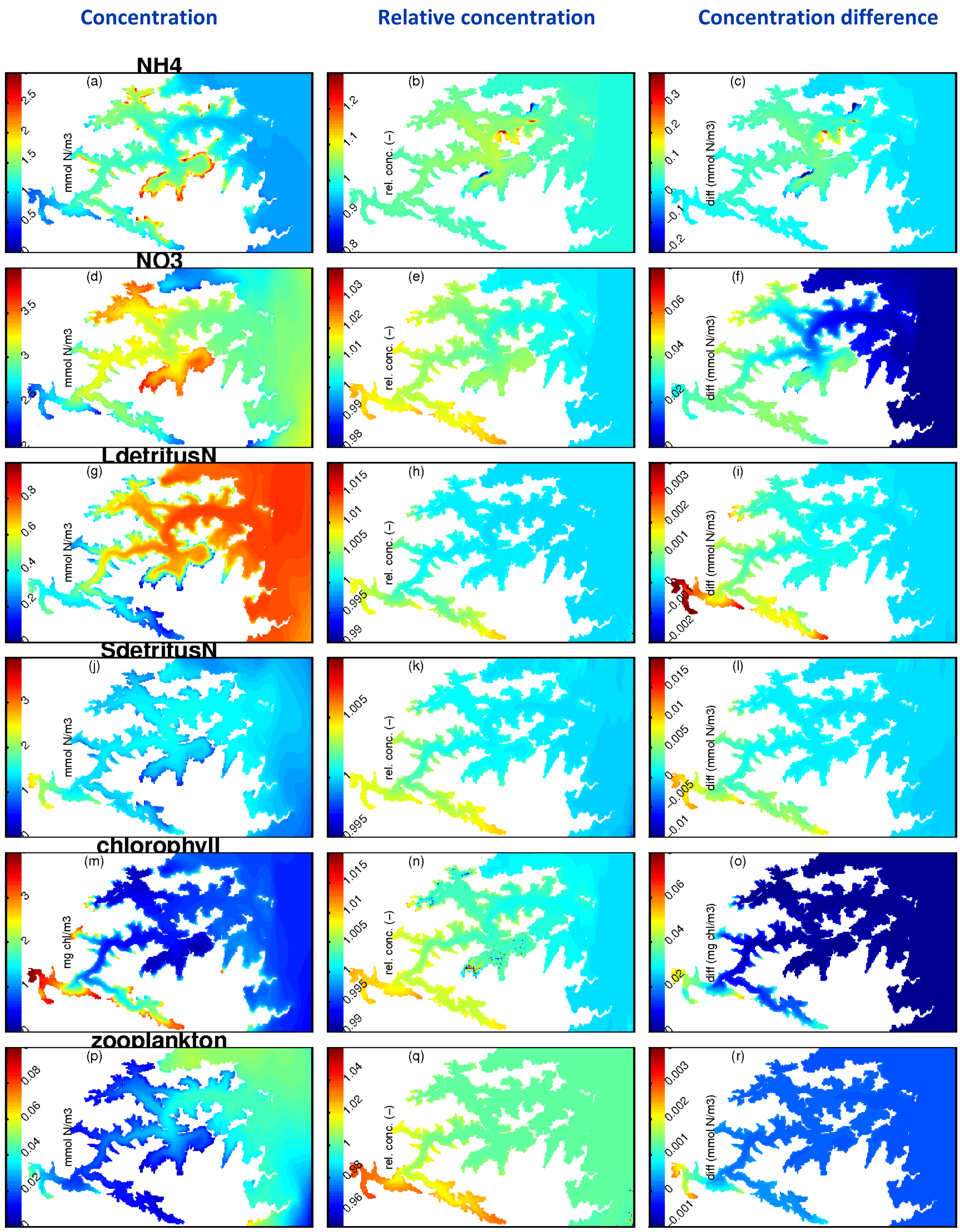

Figure A-2: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 2 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

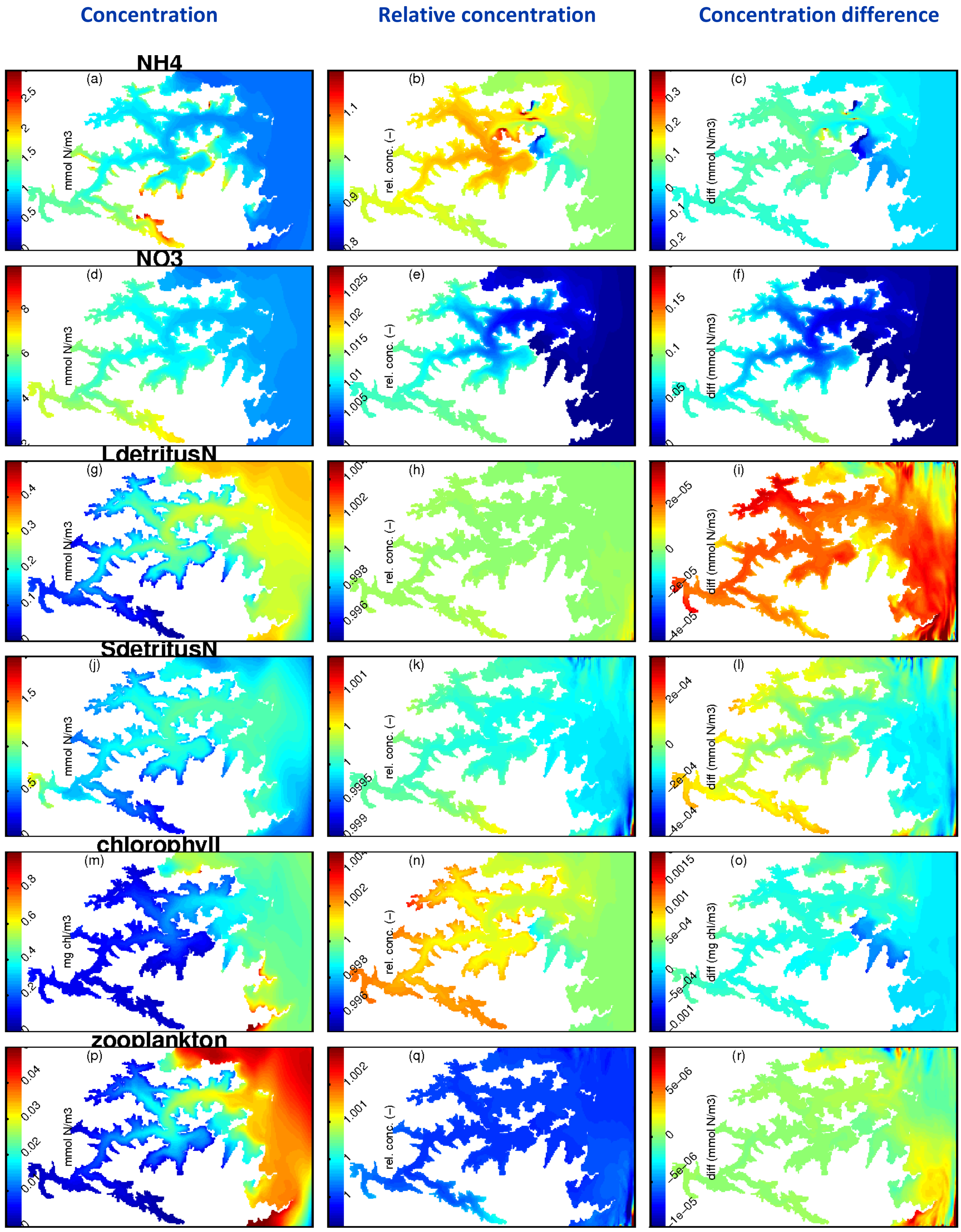

Figure A-3: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 4 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

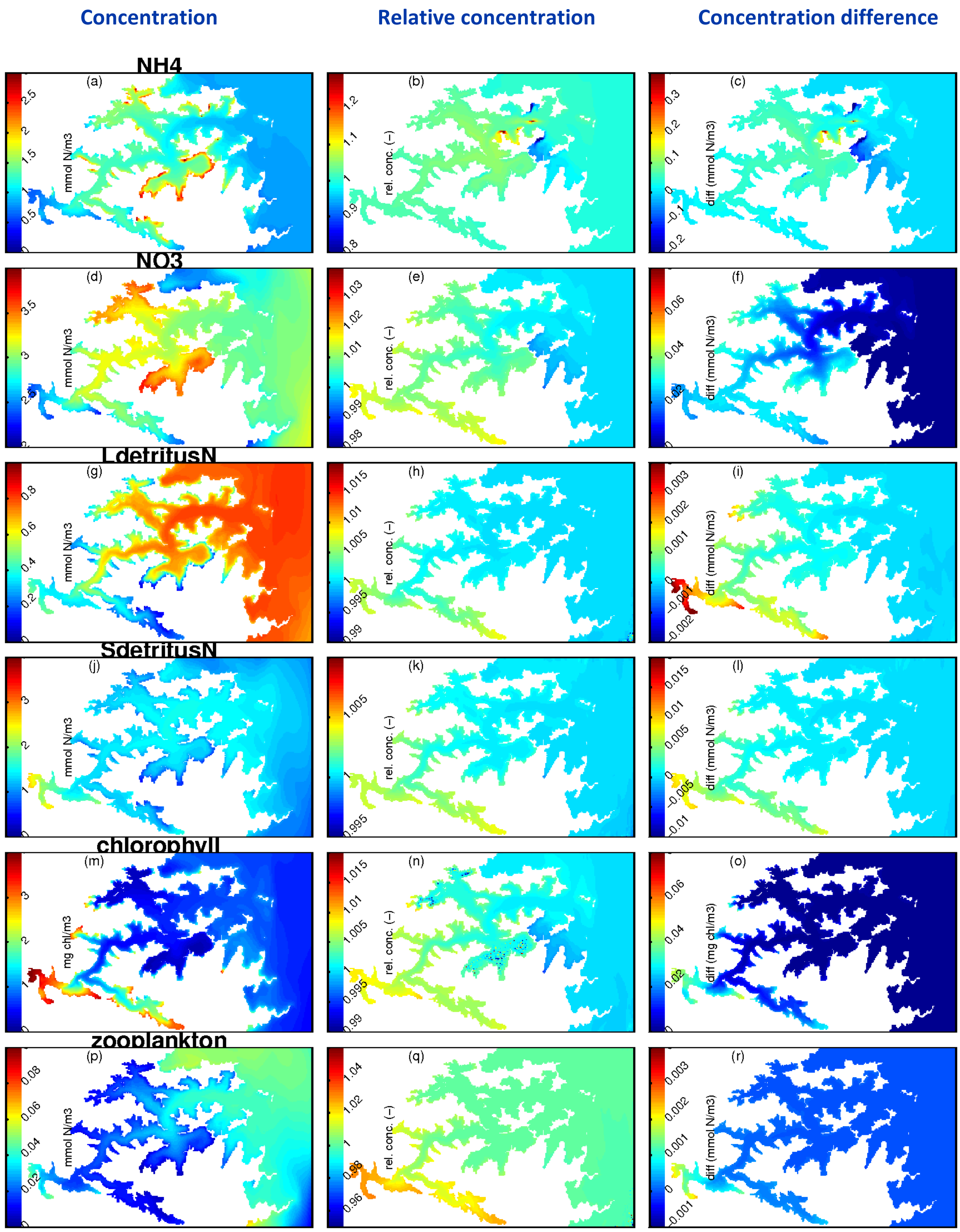

Figure A-4: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 4 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

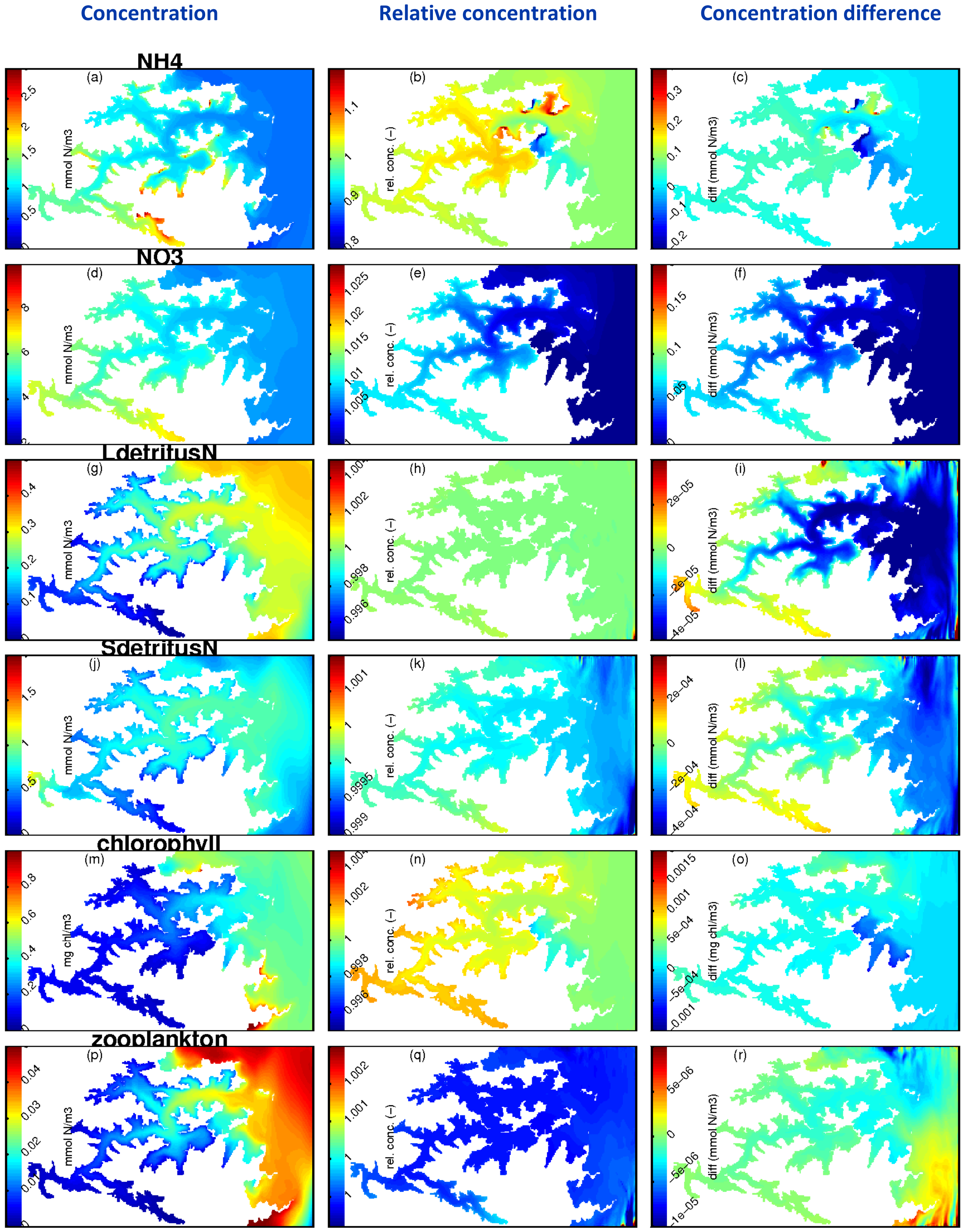

Figure A-5: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 5 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

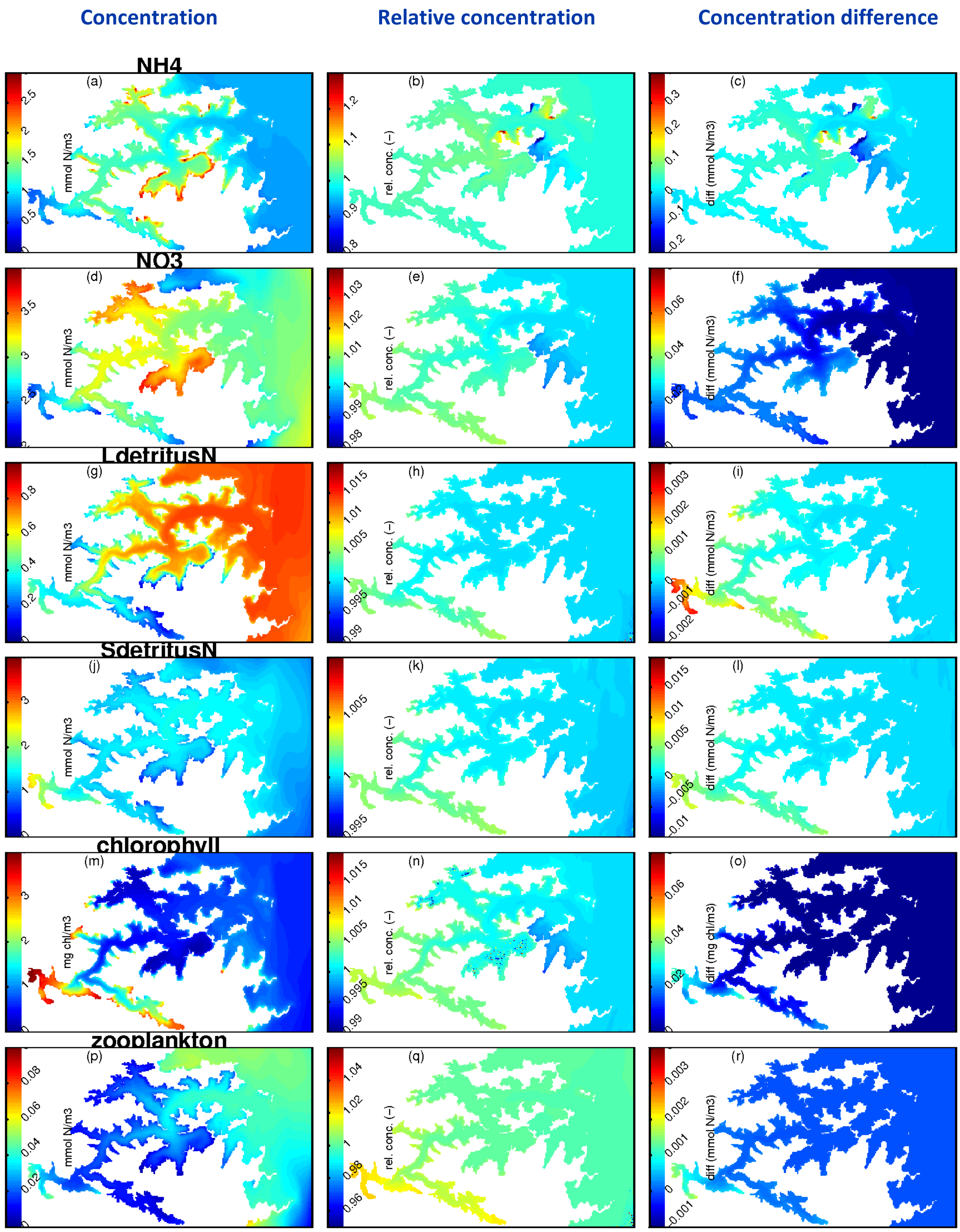

Figure A-6: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 5 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

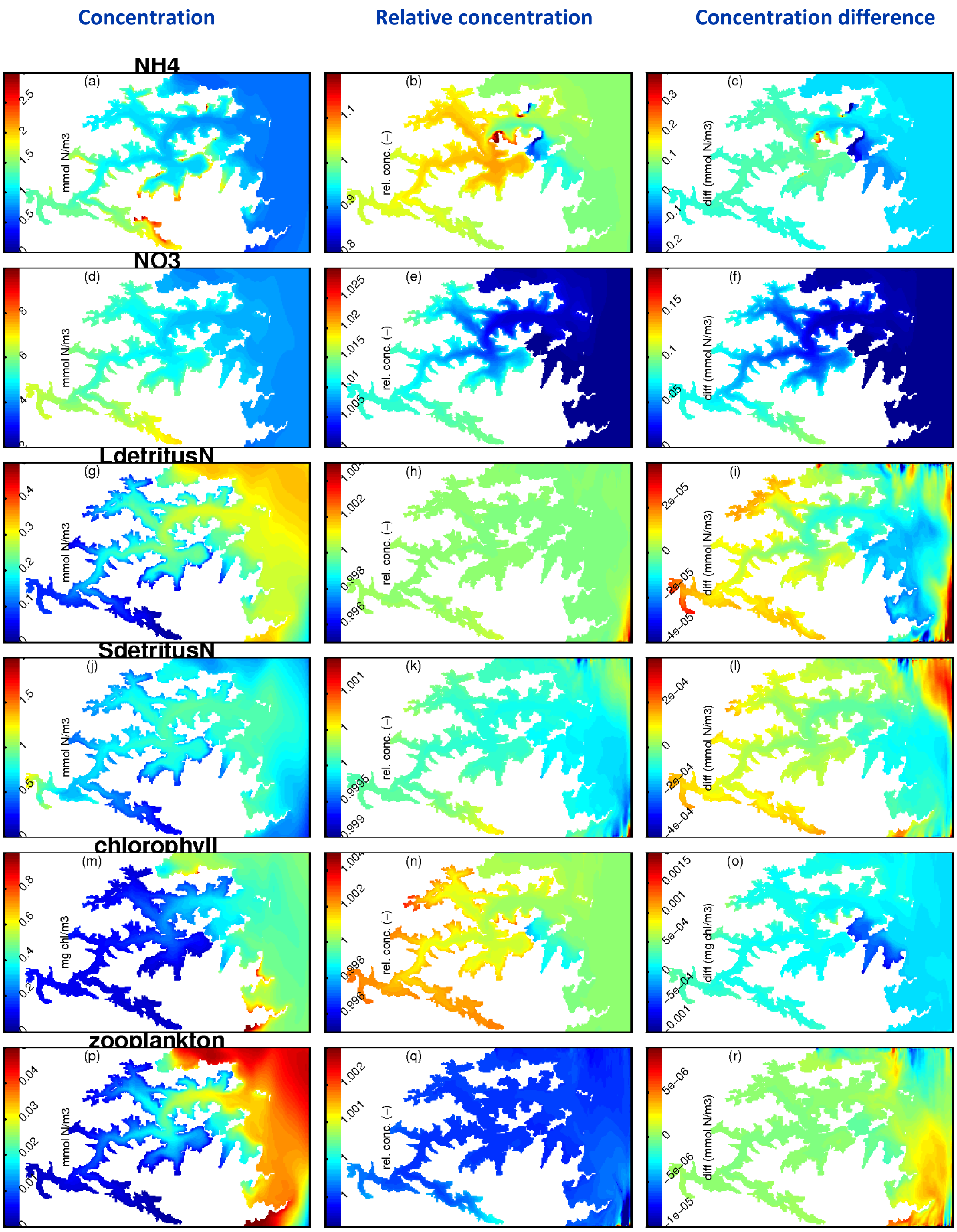

Figure A-7: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 6 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

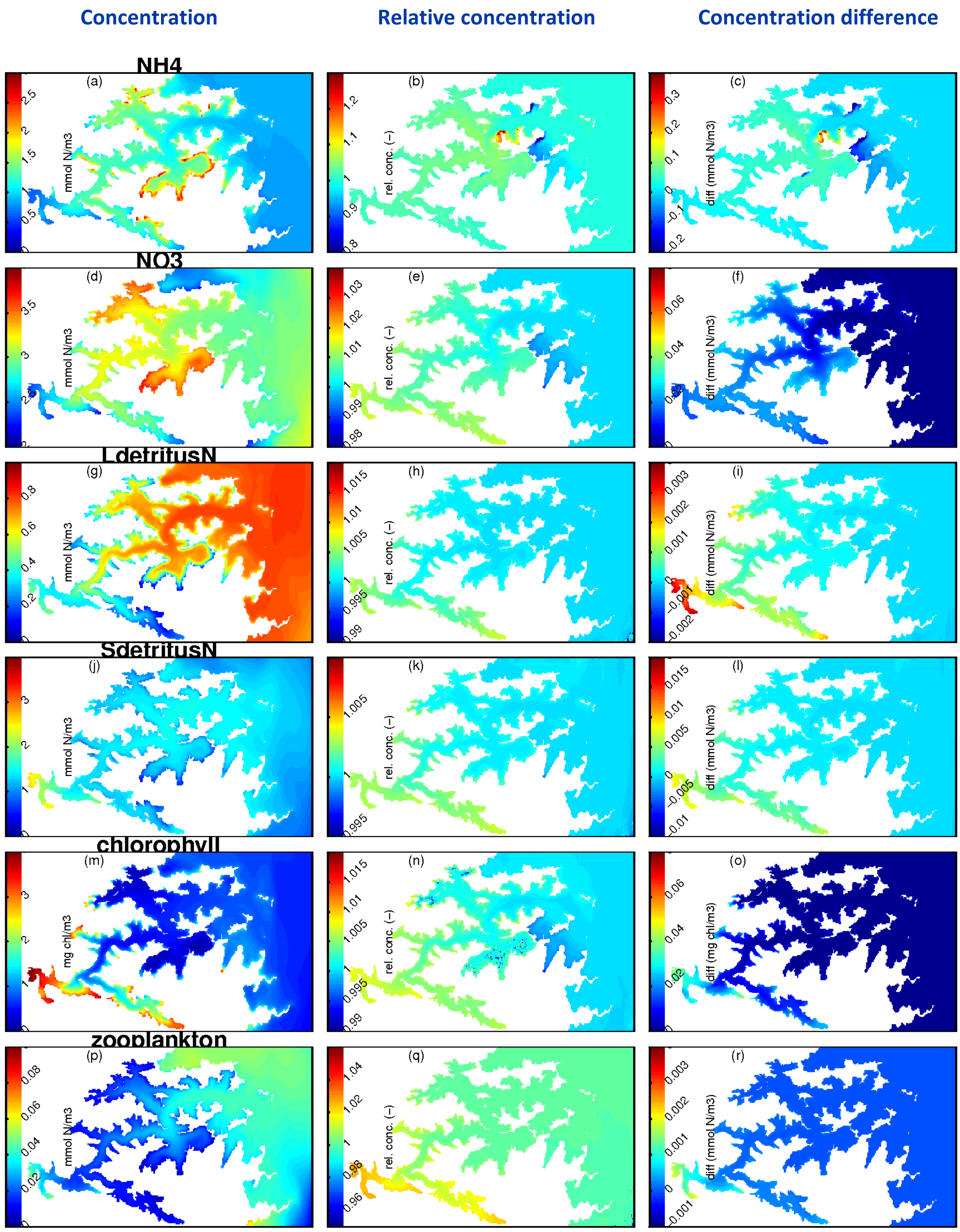

Figure A-8: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 6 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

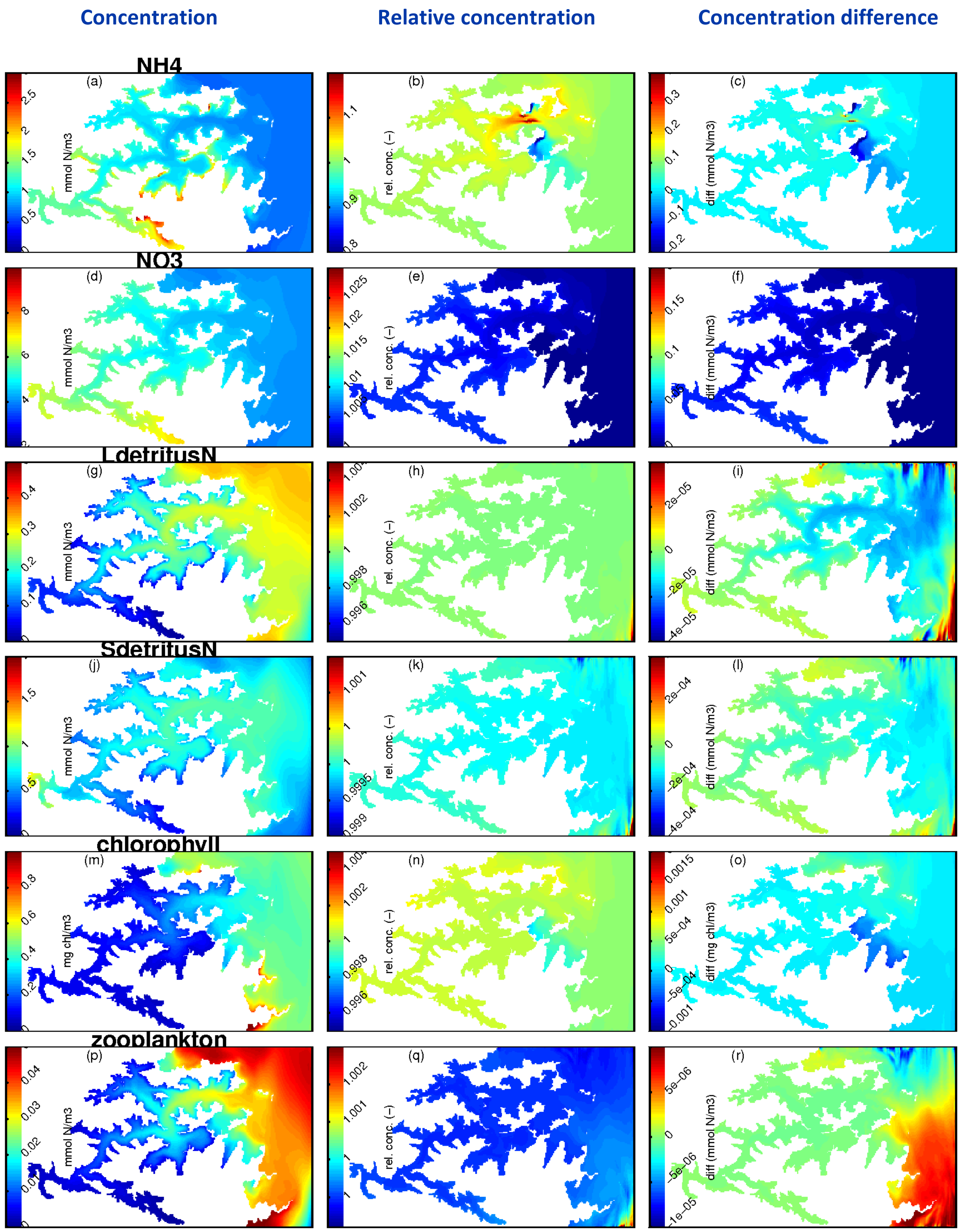

Figure A-9: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 7 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

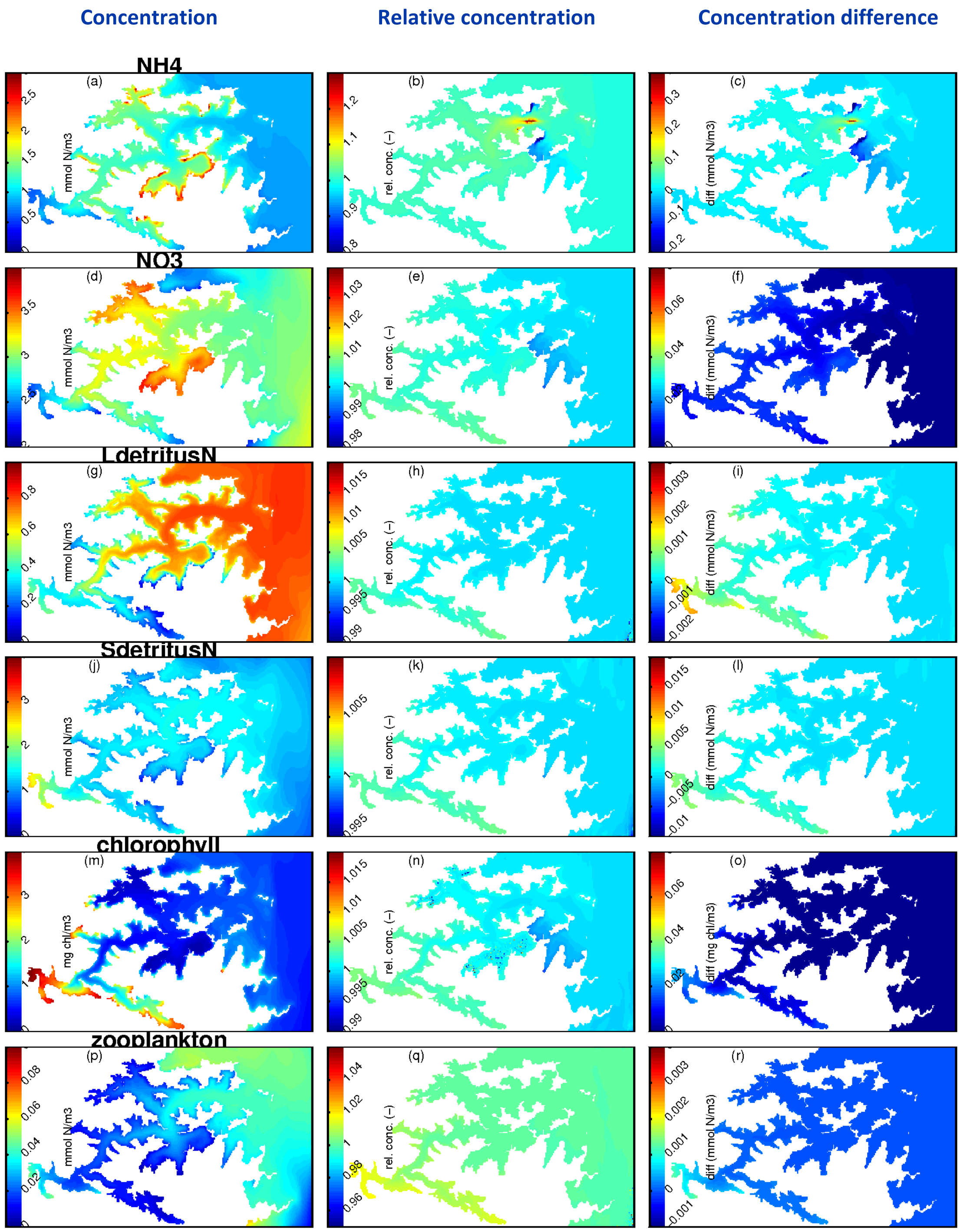

Figure A-10: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 7 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

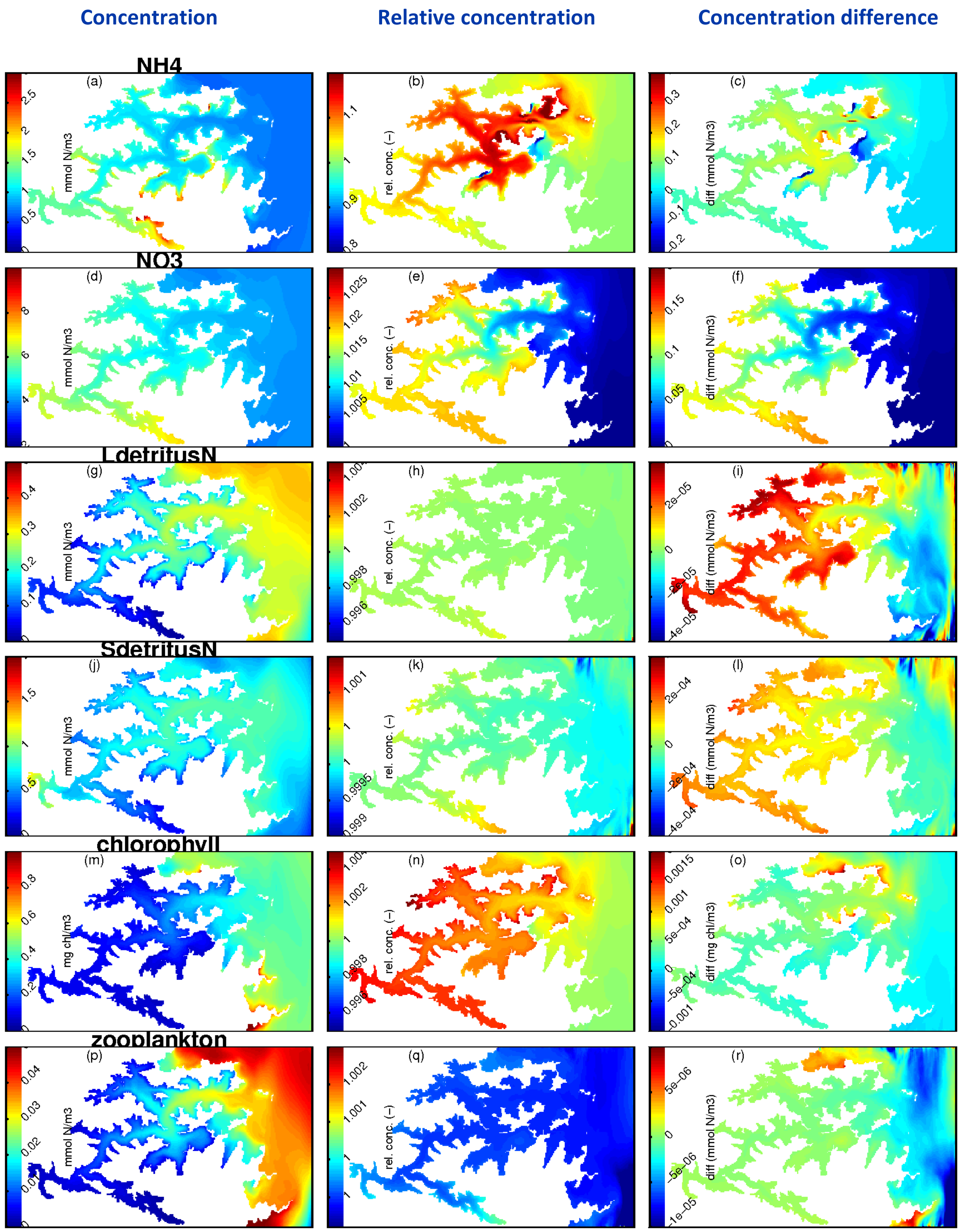

Figure A-11: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 8 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

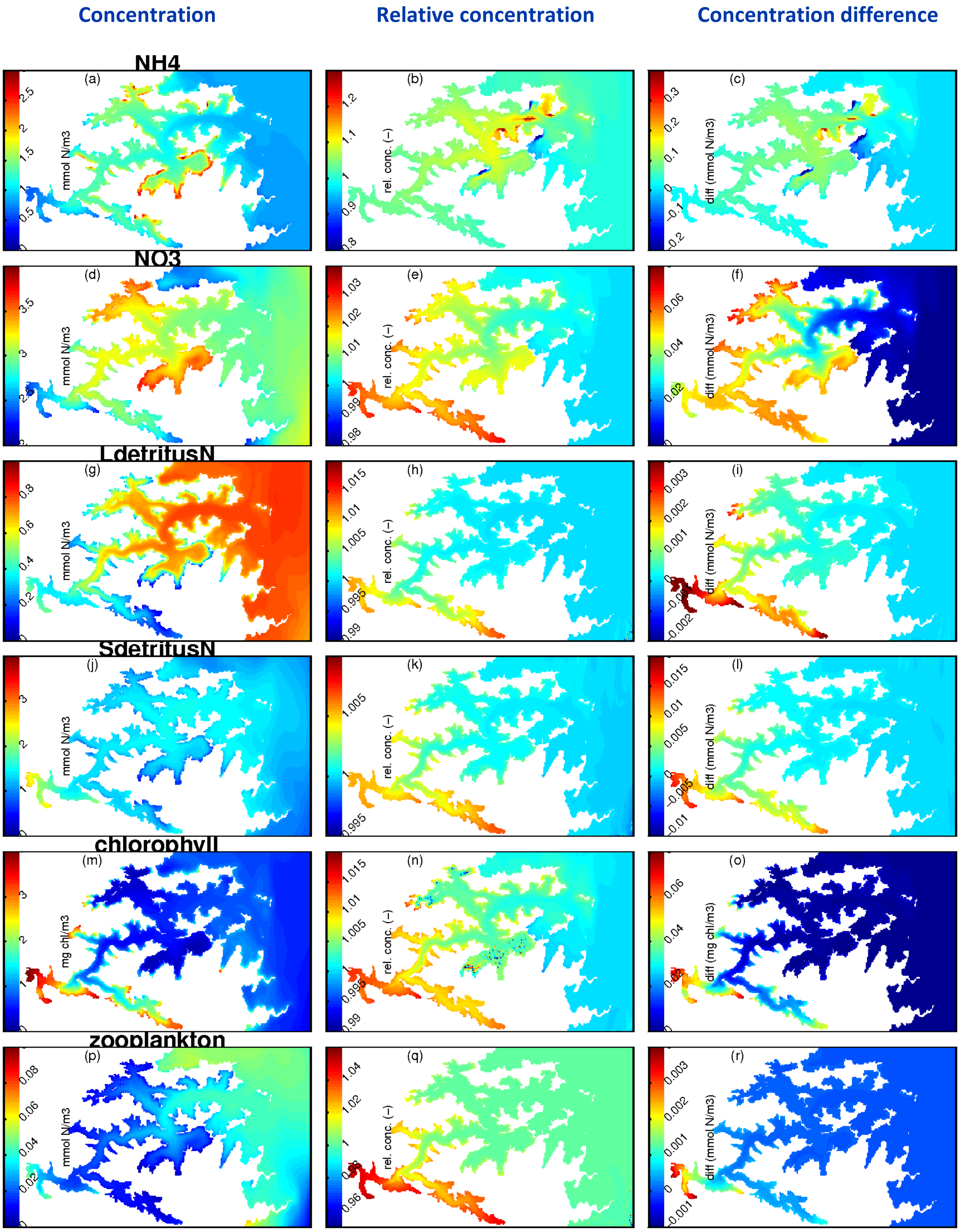

Figure A-12: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 8 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

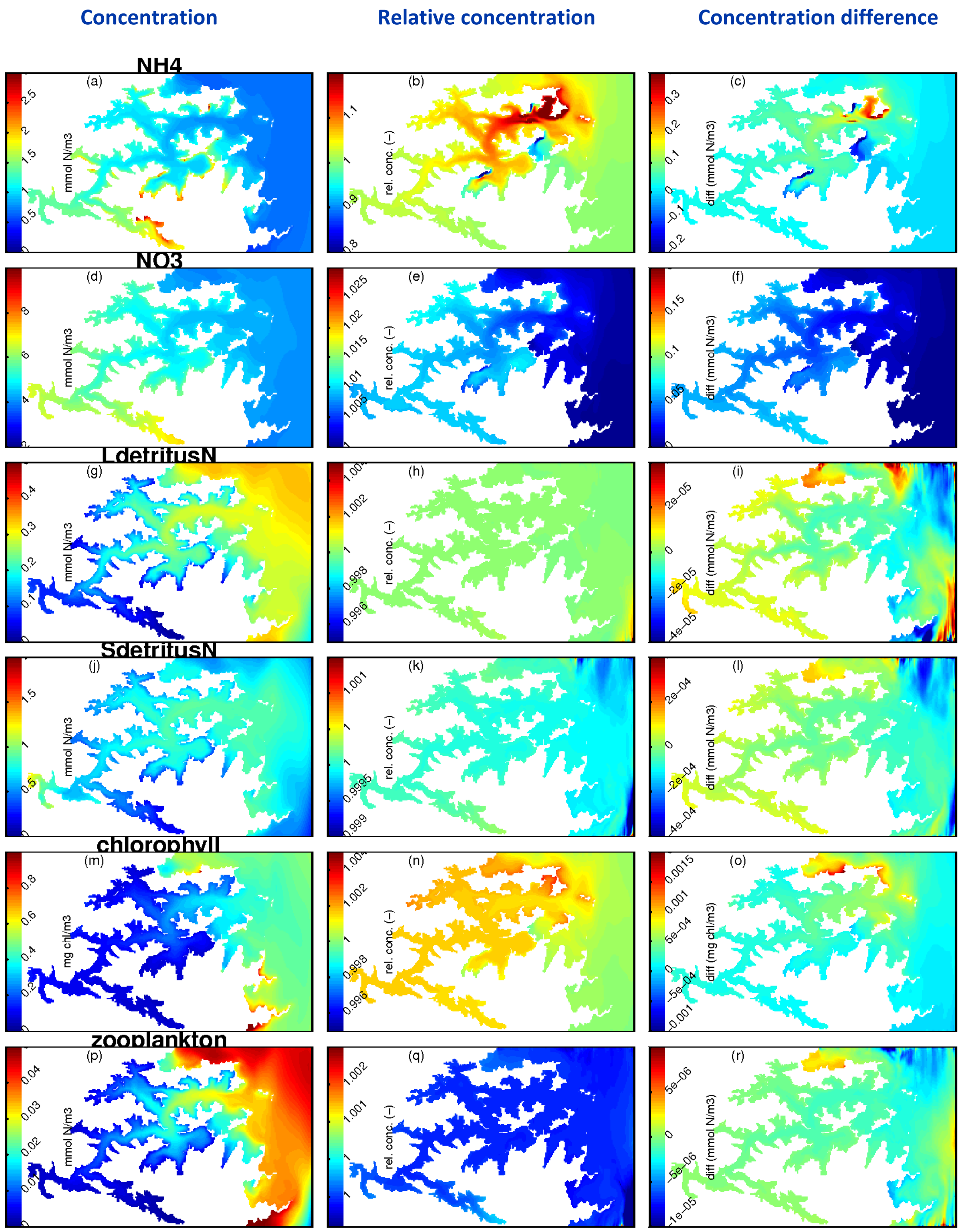

Figure A-13: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 9 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

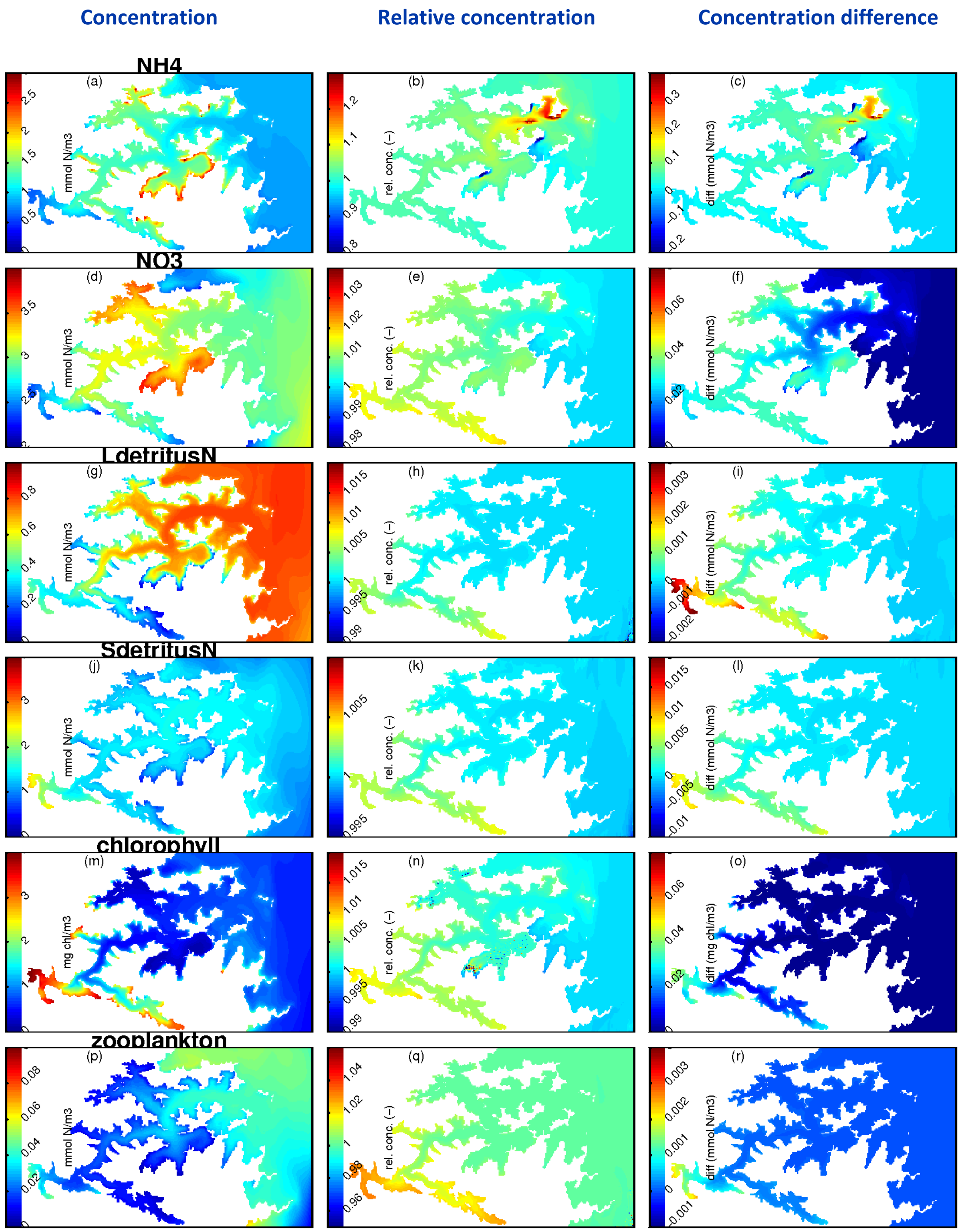

Figure A-14: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 9 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

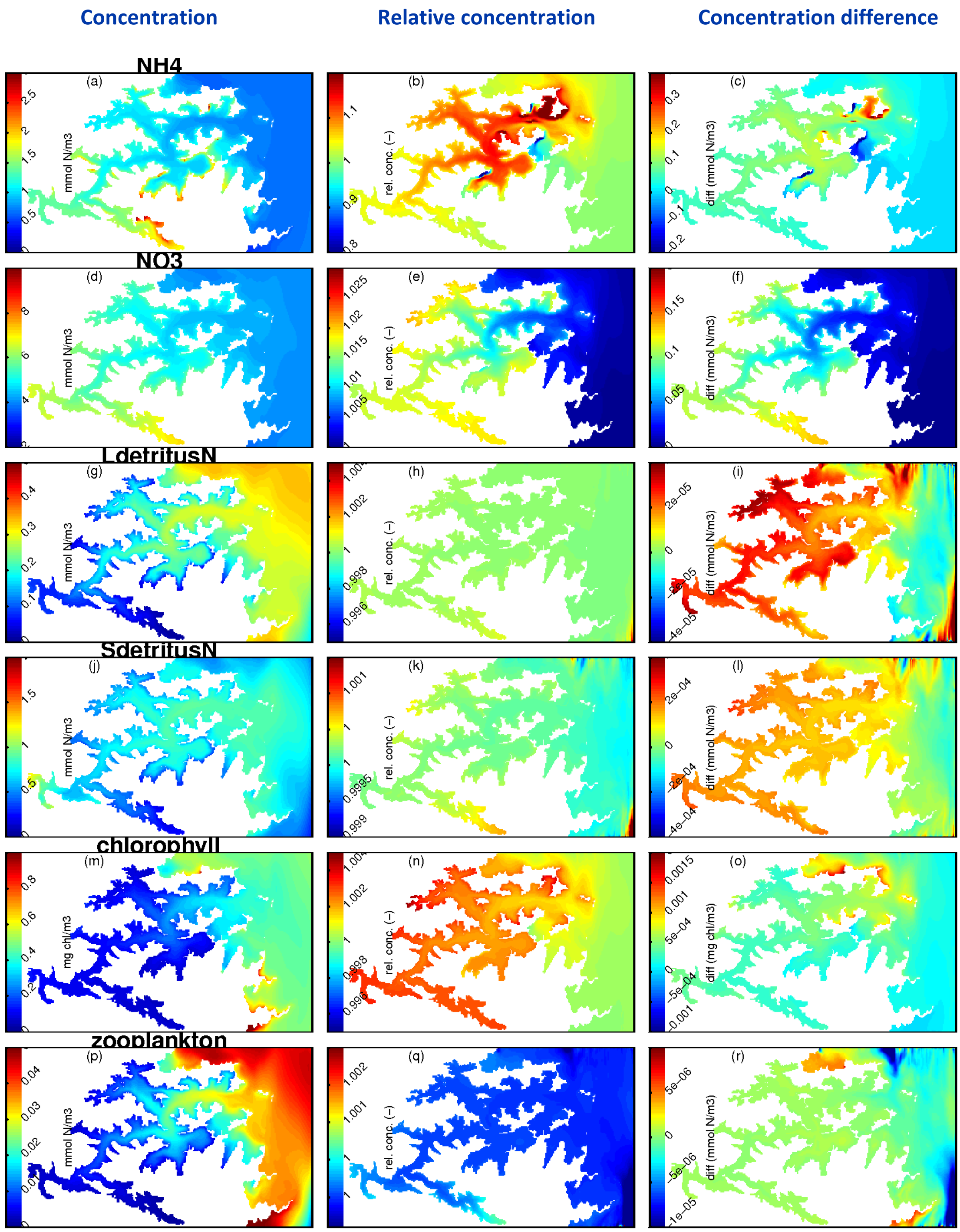

Figure A-15: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 10 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

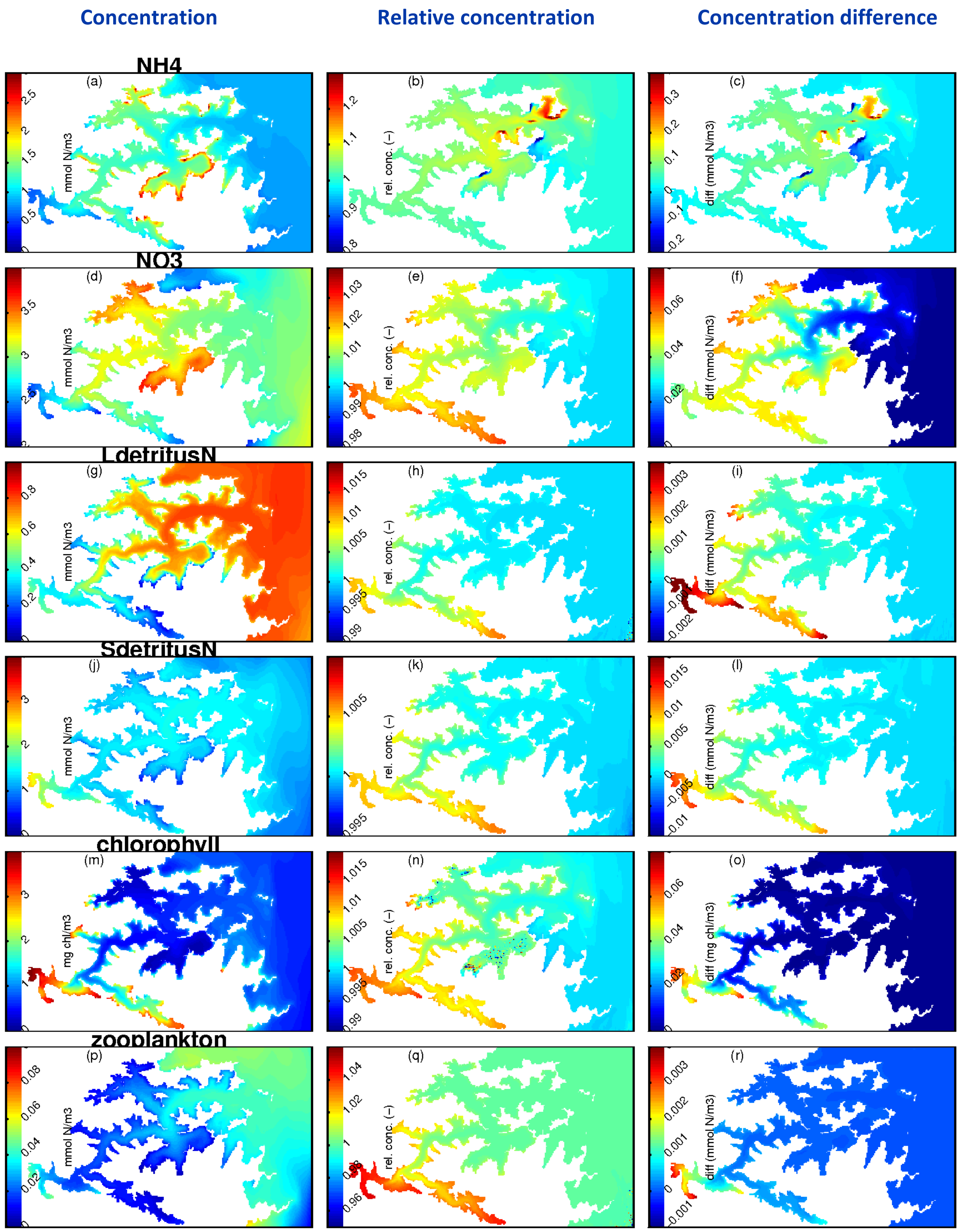

Figure A-16: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 10 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

Concentration	Relative concentration	Concentration difference

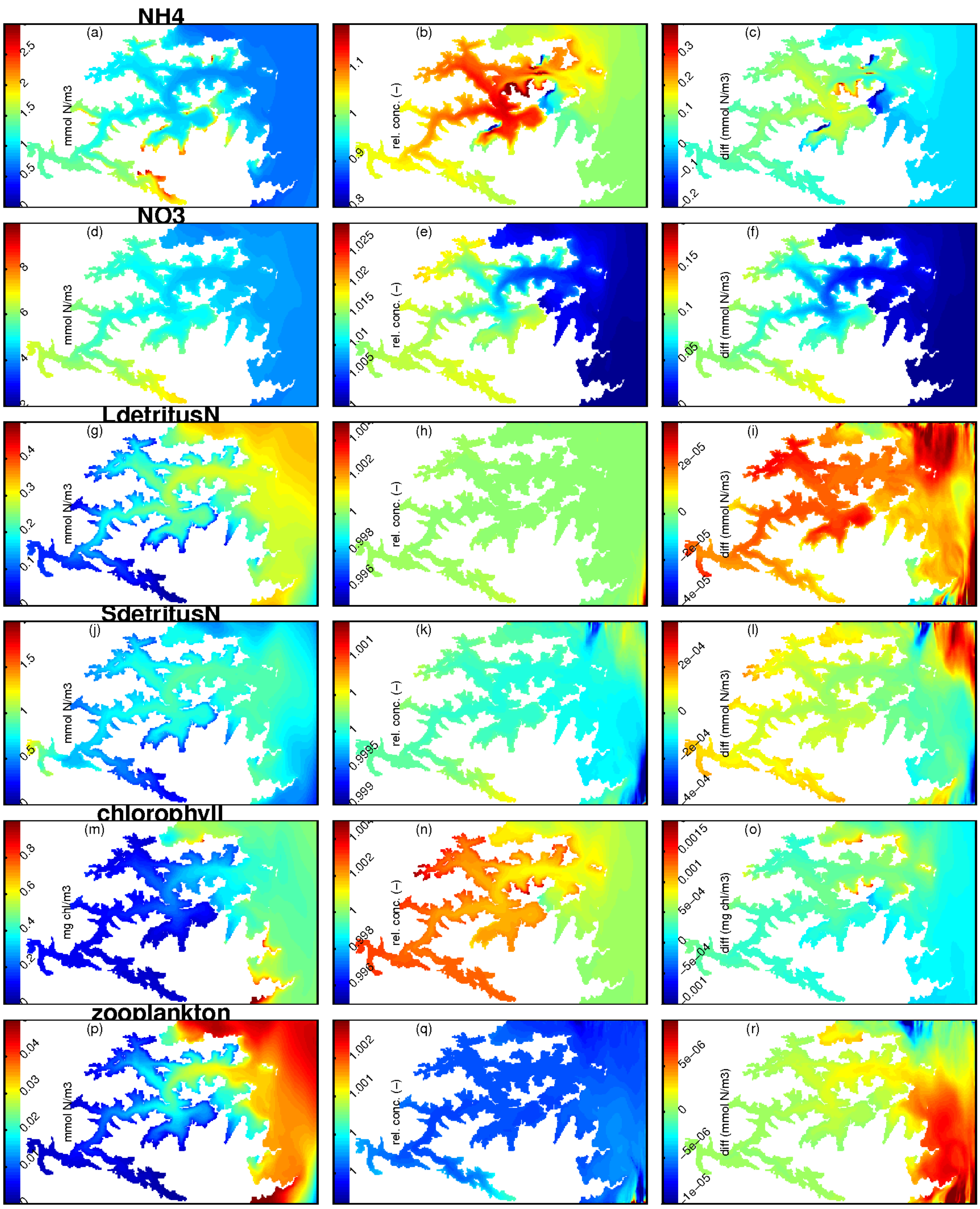

Figure A-17: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 11 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

Concentration	Relative concentration	Concentration difference

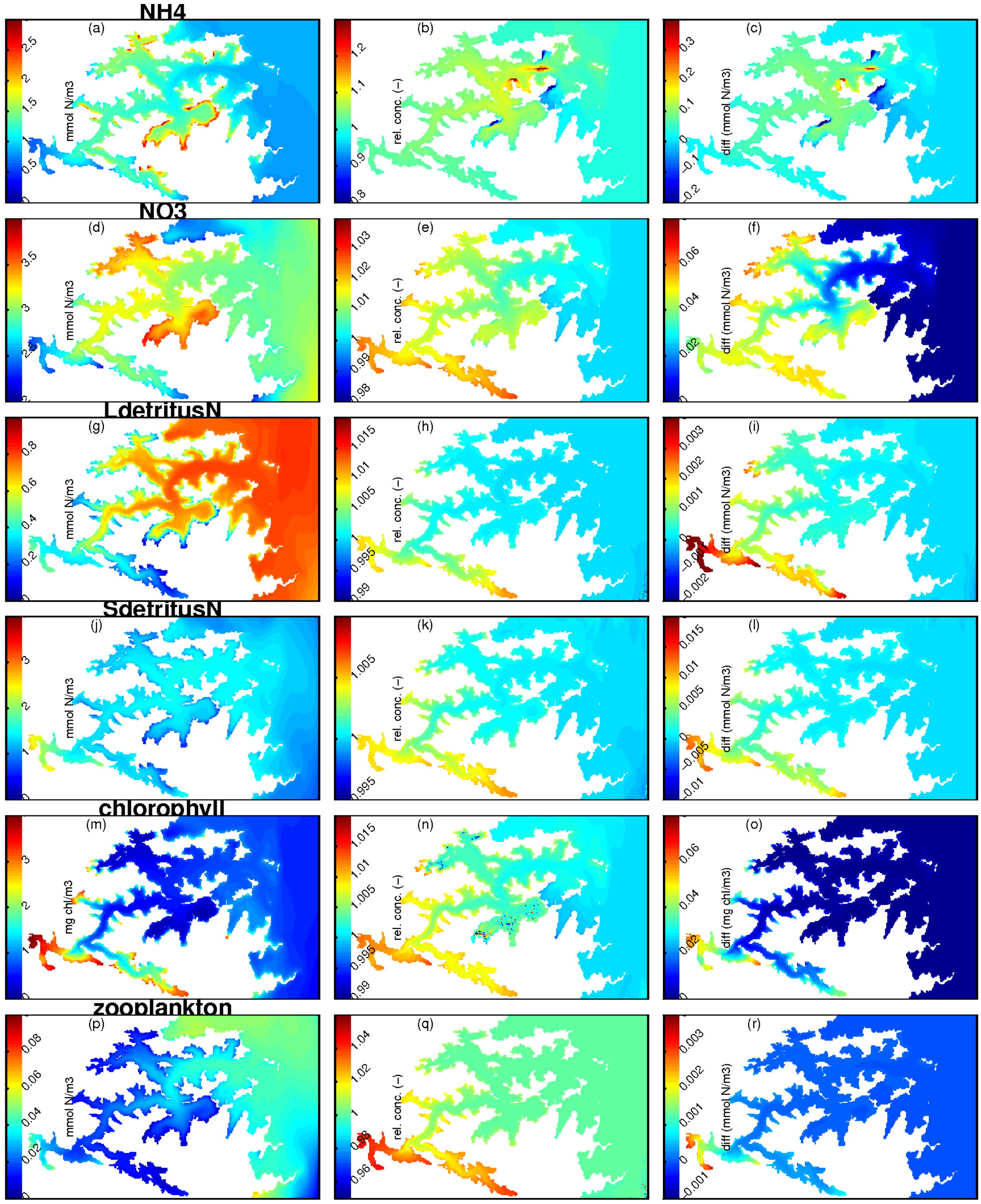

Figure A-18: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 11 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

Concentration	Relative concentration	Concentration difference

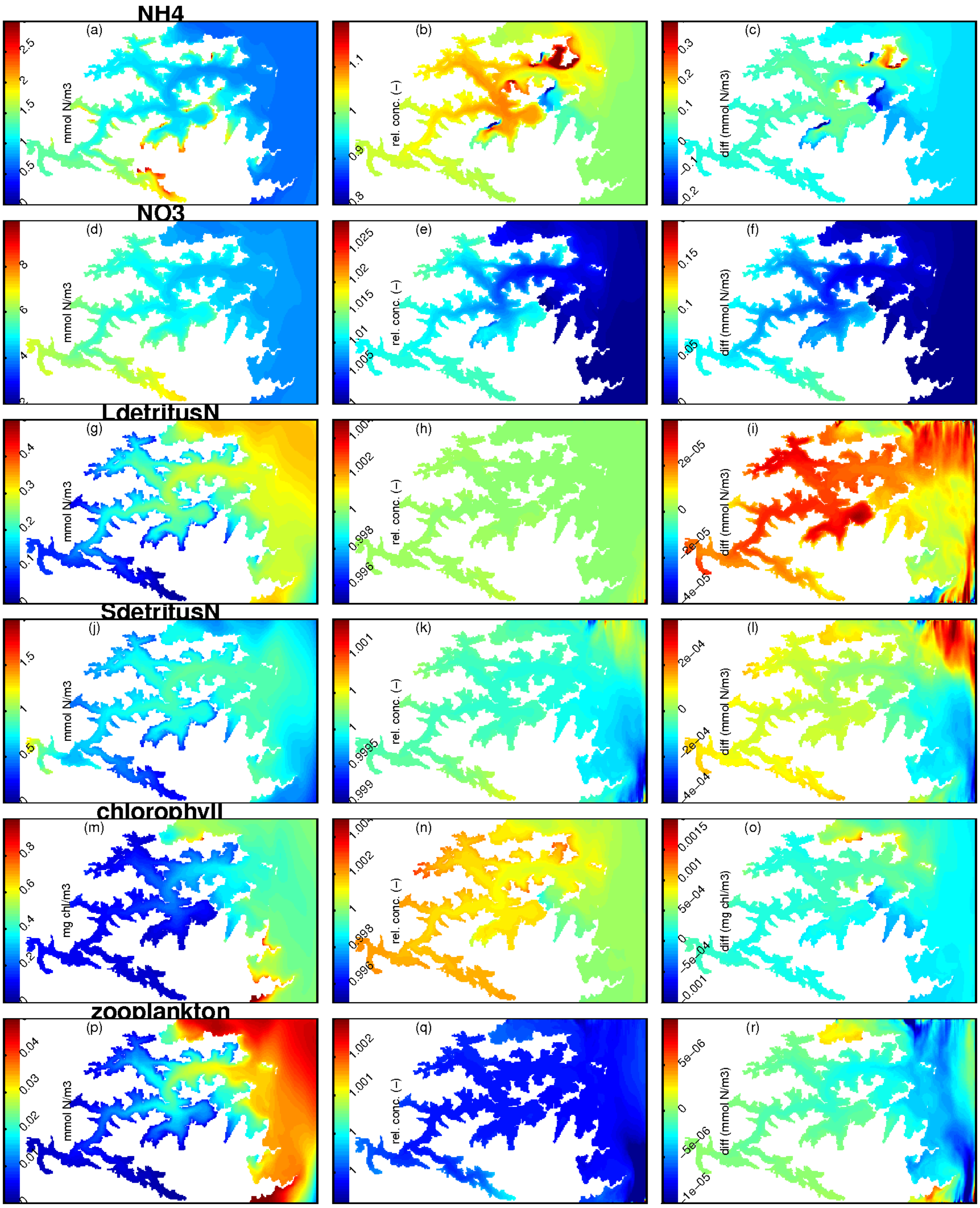

Figure A-19: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 12 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

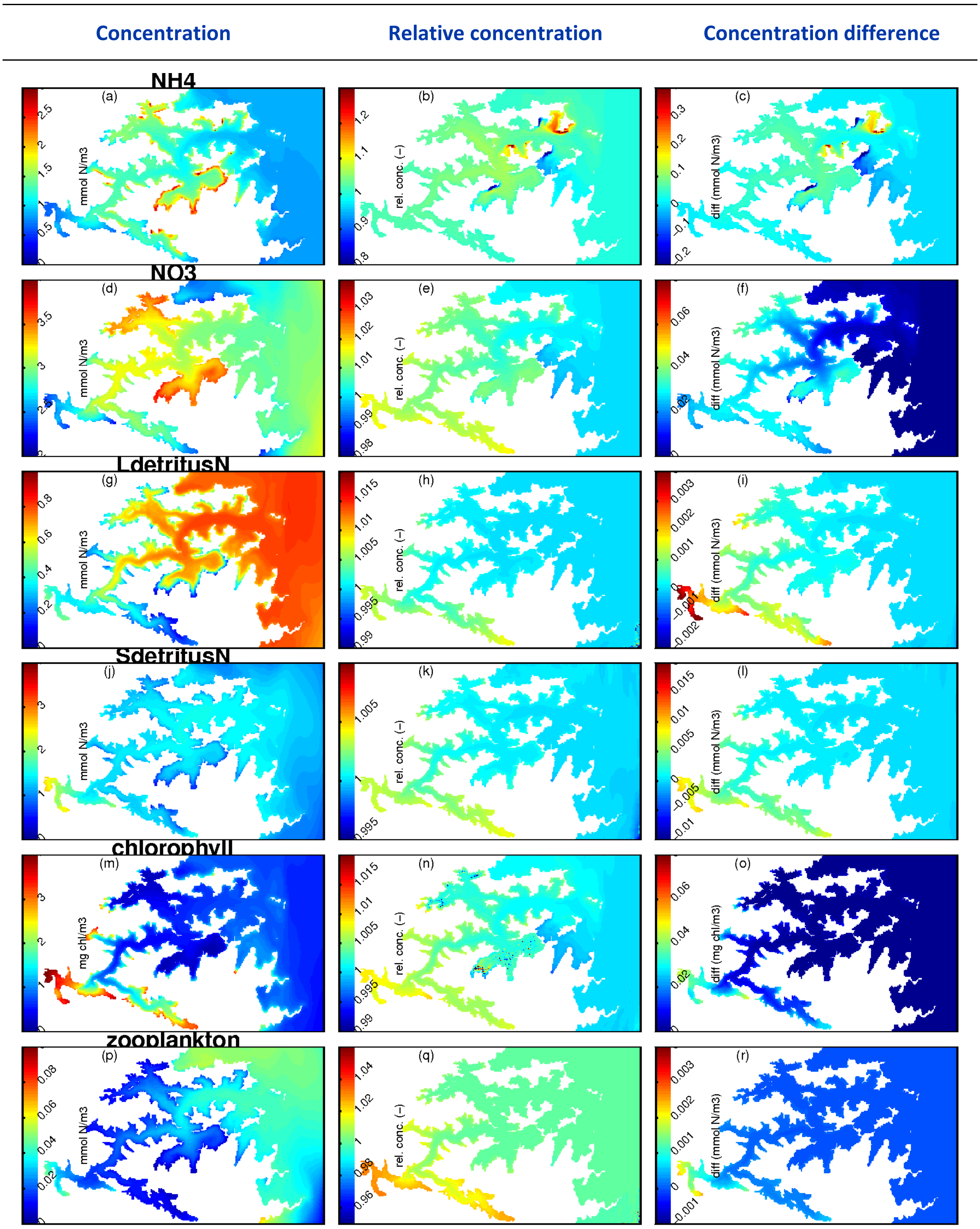

Figure A-20: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 12 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

Concentration	Relative concentration	Concentration difference

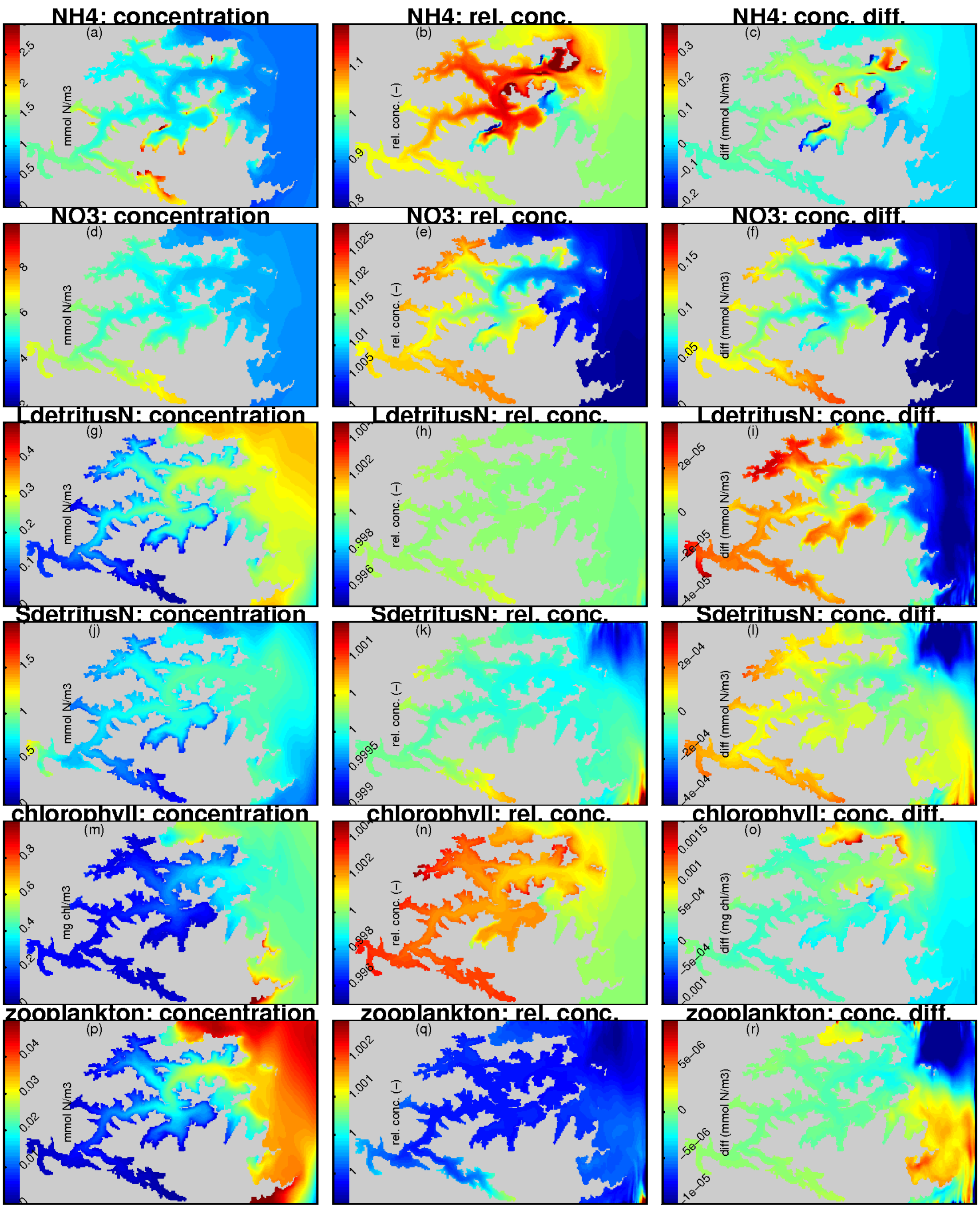

Figure A-21: Time averages for winter-time near-bed: concentrations, relative concentrations and concentration differences (scenario 13 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

Concentration	Relative concentration	Concentration difference

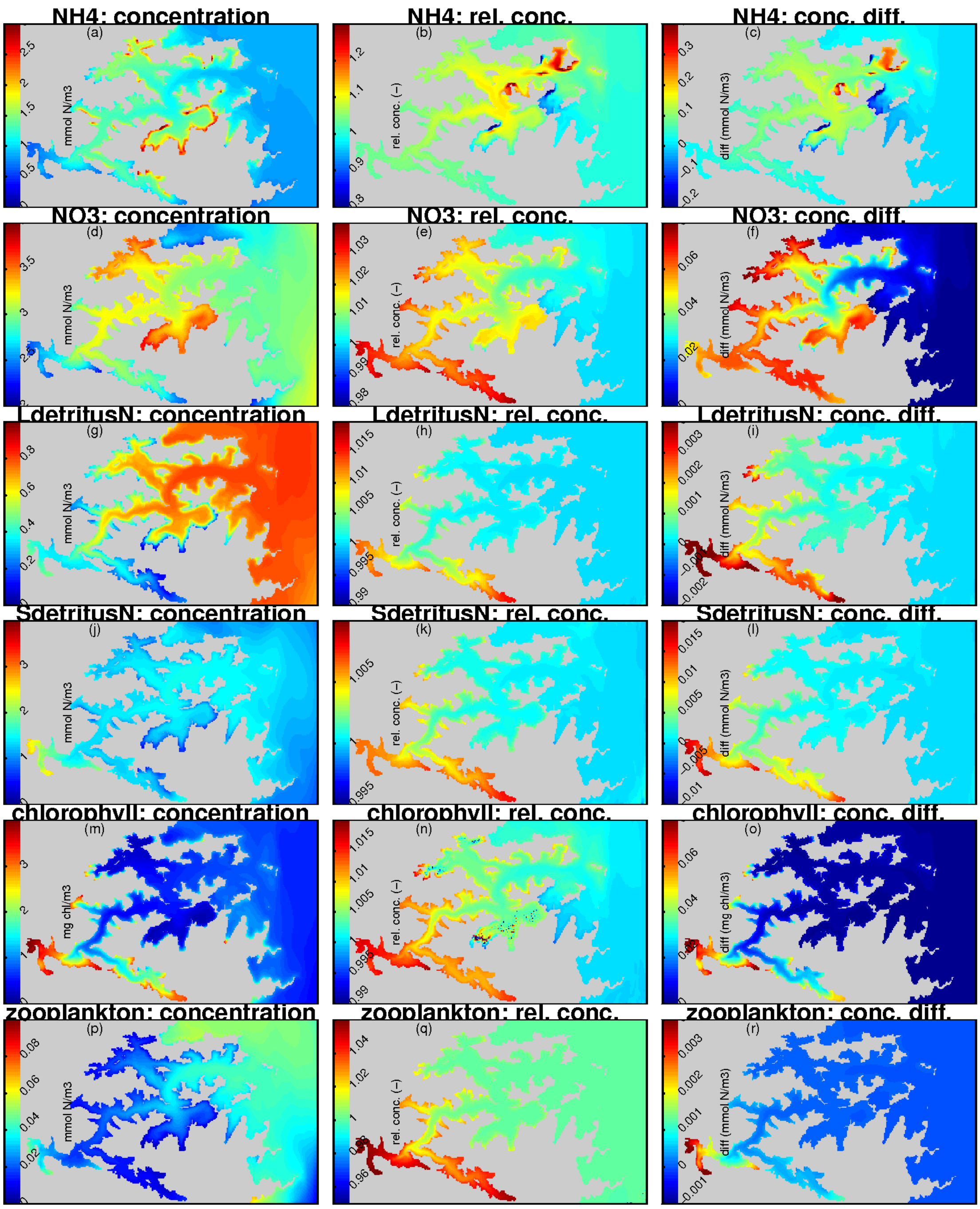

Figure A-22: Time averages for summer-time near-bed: concentrations, relative concentrations and concentration differences (scenario 13 vs scenario 1). The concentrations that are plotted in the left-most column are those of scenario 1. The relative concentrations (central column) are expressed as those of the alternative scenario relative to those of scenario 1. Concentration differences (right-most column) are calculated by subtracting the scenario 1 concentrations from those of the alternative scenario. Relative concentrations (or positive concentration differences) in excess of 1.0 indicate that the alternative scenario tends to yield higher concentrations than scenario 1 (the baseline$_{f2016}$).

Appendix B Time-series of state-variables at specific locations: comparison of Scenario 13 and the baseline$_{f2016}$ scenario

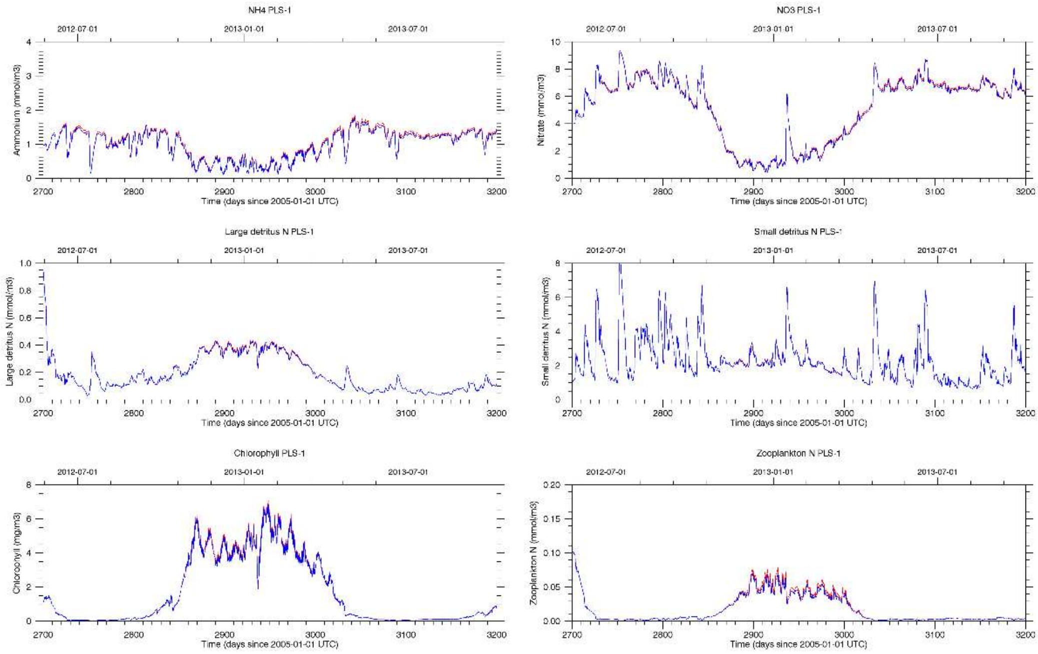

Figure B-1: Simulated near-surface concentrations at the Marlborough District Council site PLS-1. Individual data-points are 12 hour time-averages. Blue curves are baseline$_{f2016}$ results; red curves are Scenario 13 results. Variables are (from top left, by row) NH4, NH3, large detritus, small detritus, chlorophyll and zooplankton.

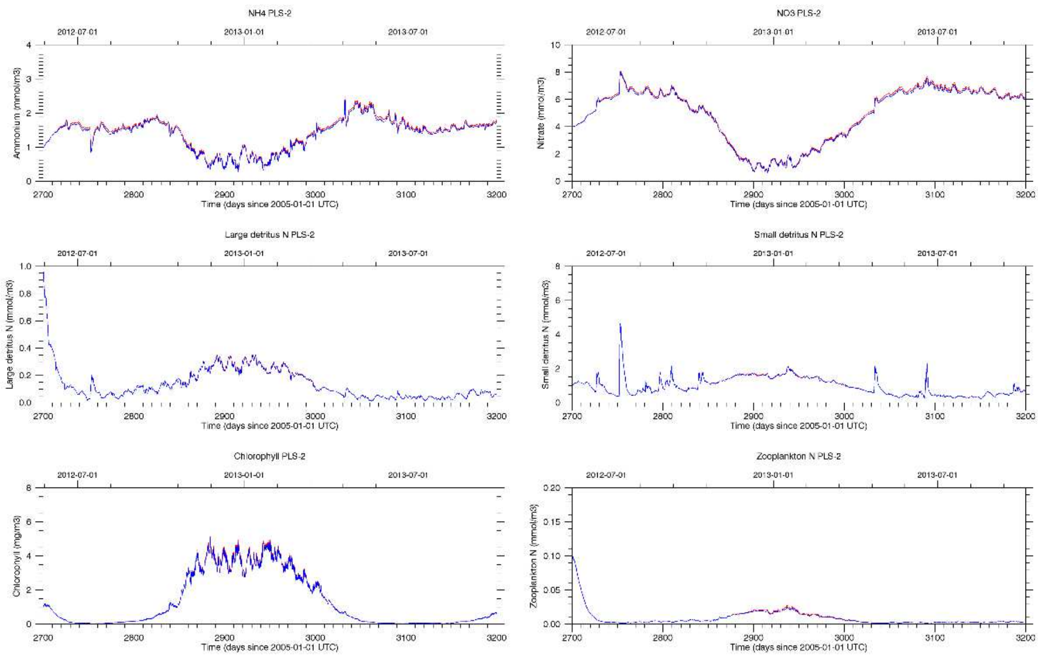

Figure B-2: Simulated near-surface concentrations at the Marlborough District Council site PLS-2. Individual data-points are 12 hour time-averages. Blue curves are baseline$_{f2016}$ results; red curves are Scenario 13 results. Variables are (from top left, by row) NH4, NH3, large detritus, small detritus, chlorophyll and zooplankton.

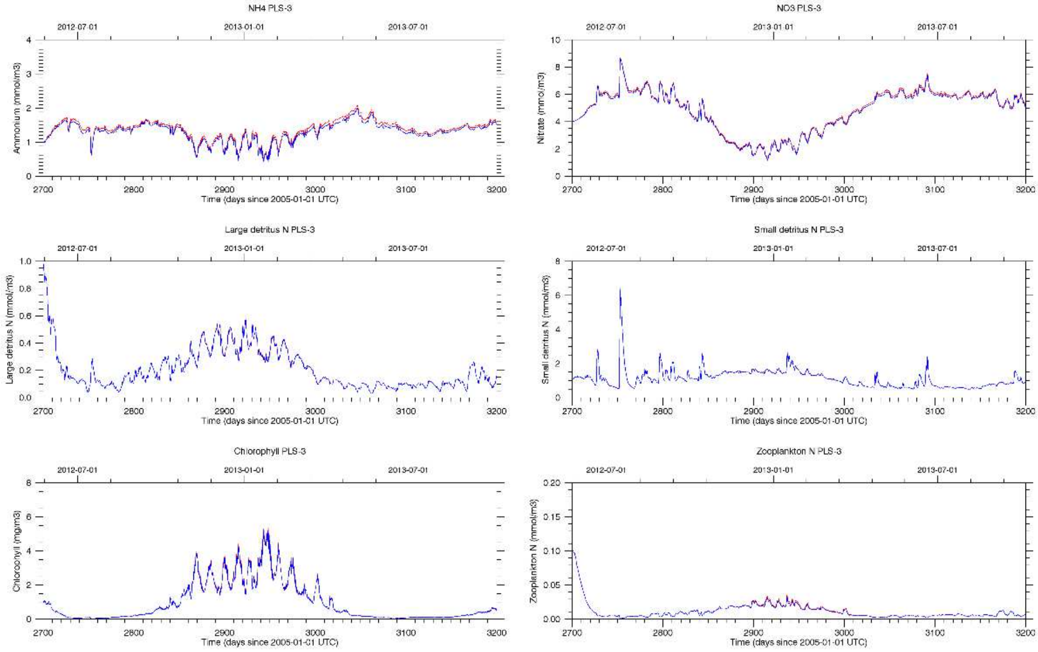

Figure B-3: Simulated near-surface concentrations at the Marlborough District Council site PLS-3. Individual data-points are 12 hour time-averages. Blue curves are baseline$_{f2016}$ results; red curves are Scenario 13 results. Variables are (from top left, by row) NH4, NH3, large detritus, small detritus, chlorophyll and zooplankton.

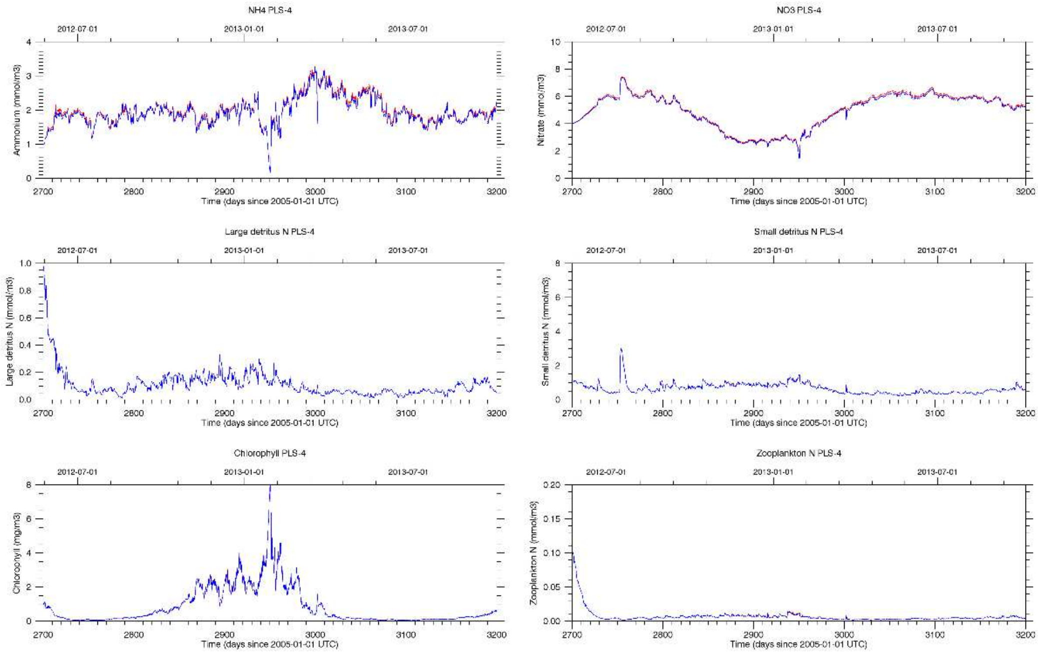

Figure B-4: Simulated near-surface concentrations at the Marlborough District Council sites PLS-4. Individual data-points are 12 hour time-averages. Blue curves are baseline$_{f2016}$ results; red curves are Scenario 13 results. Variables are (from top left, by row) NH4, NH3, large detritus, small detritus, chlorophyll and zooplankton.

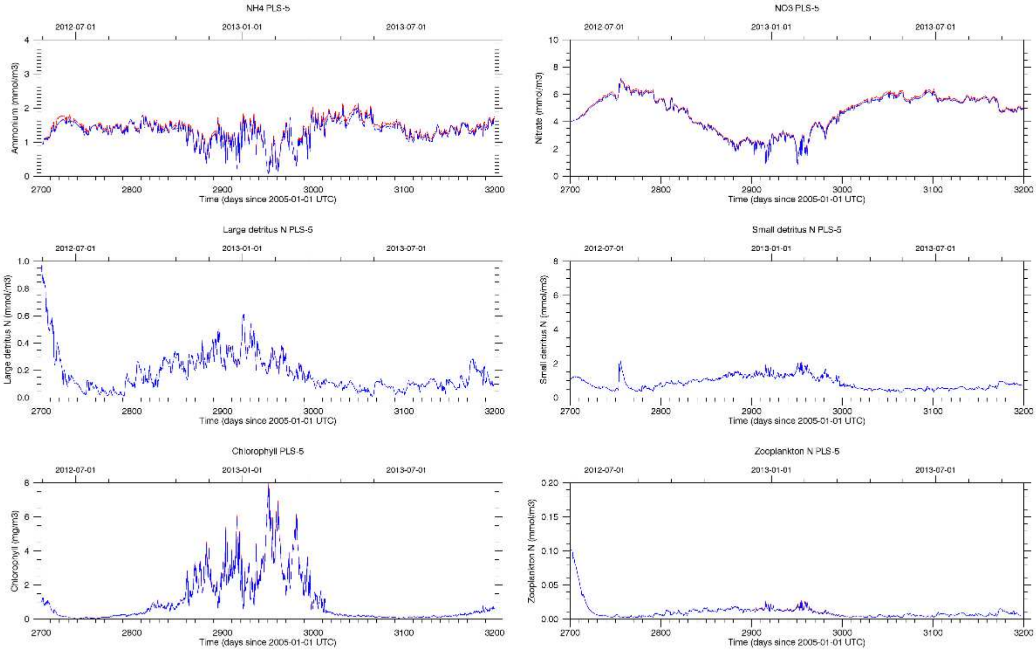

Figure B-5: Simulated near-surface concentrations at the Marlborough District Council site PLS-5
Individual data-points are 12 hour time-averages. Blue curves are baseline$_{f2016}$ results; red curves are Scenario 13 results. Variables are (from top left, by row) NH4, NH3, large detritus, small detritus, chlorophyll and zooplankton.

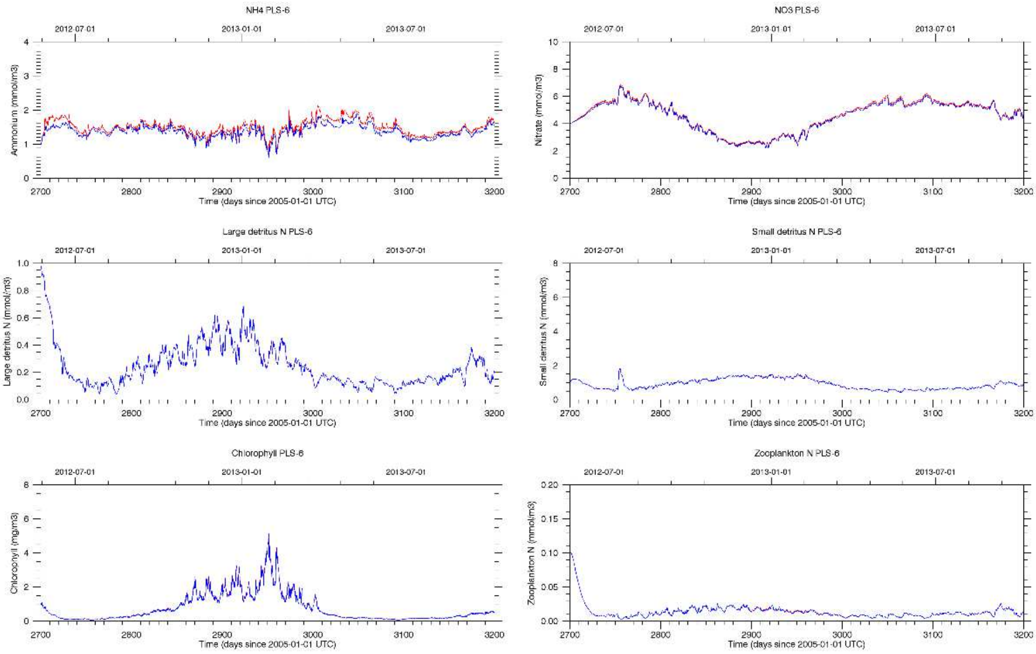

Figure B-6: Simulated near-surface concentrations at the Marlborough District Council site PLS-6
Individual data-points are 12 hour time-averages. Blue curves are baseline$_{f2016}$ results; red curves are Scenario 13 results. Variables are (from top left, by row) NH4, NH3, large detritus, small detritus, chlorophyll and zooplankton.

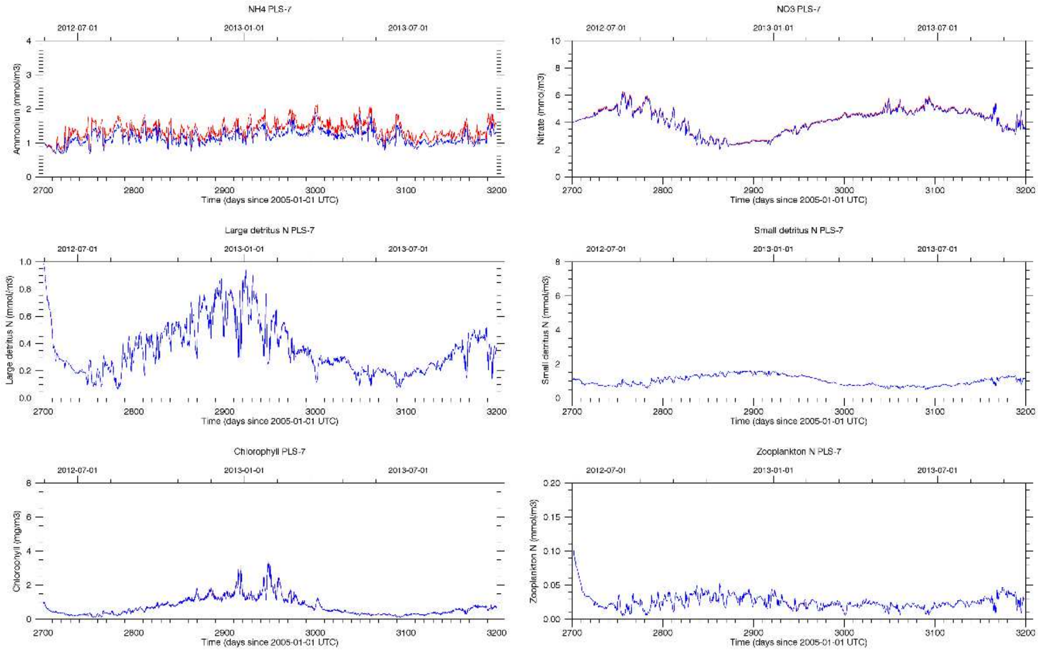

Figure B-7: Simulated near-surface concentrations at the Marlborough District Council site PLS-7
Individual data-points are 12 hour time-averages. Blue curves are baseline$_{f2016}$ results; red curves are Scenario 13 results. Variables are (from top left, by row) NH4, NH3, large detritus, small detritus, chlorophyll and zooplankton.