Table 4

Statistical summary of the with-farms simulated sampling for plankton sub-class 3 (as mg Chl a m⁻) on each of the five days of the synoptic survey.

Property	25 May	26 May	27 May	28 May	29 May
Mean	0.40	0.38	0.37	0.39	0.41
Median	0.37	0.35	0.35	0.38	0.40
Std. Dev.	0.24	0.26	0.24	0.28	0.28
Max.	1.58	1.75	1.61	2.05	1.73
Min.	0.06	0.0	0.01	0.07	0.0
Coeff. of variation	0.60	0.68	0.65	0.72	0.68

6.2.1 Depletion inferred from a comparison of no-farms and with-farms simulations

Table 5 together with Figures 22 and 23 summarise the results of a comparison of the sampling data taken during a no-farms and a with-farms simulation. Averaging across all stations, the mean ratio (with farms/no farms) invariably exceeds one (implying enhancement, though the standard deviations are such that the differences from one are not statistically significant). As one might have expected, the median ratios are less variable, and deviate from 1.0 by smaller margins. The levels of depletion predicted by the model are generally smaller those inferred from the surfaces-method applied to the field data. Recalling that plankton sub-class 3 (our chosen analogue to the field phytoplankton population) had a maximum weight-specific growth rate which was rather greater than that which we believe to have prevailed in the field population, we take the predicted lesser depletion to be (weak) evidence in favour of the argument that the model's qualitative performance is correct (quantitative agreement cannot be expected given that the prescribed phytoplankton growth rate was twice that inferred from the field).
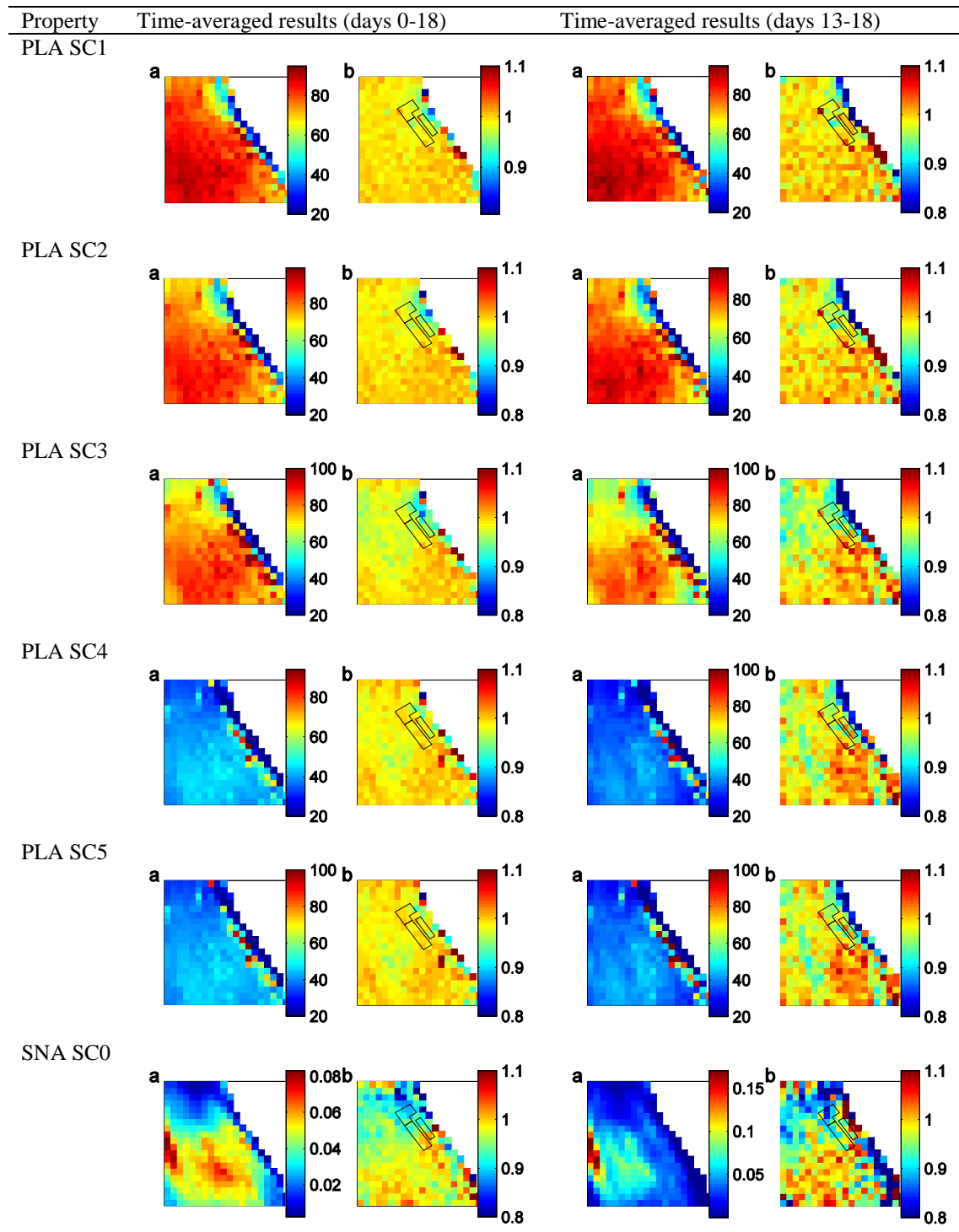
Table 5

Comparison of virtual sampling for the 'no-farms' and 'with-farms' simulation results. The rows 'mean', 'median' and 'std. dev.' refer to the mean (median, standard deviation) of the ratio (1+(with farms-no farms)/no farms) for corresponding sampled values of the concentration of plankton sub-class 3. NaN denotes 'not a number' and arises when one endeavours to calculate the ratio 0/0 (ie when both the with – farms and no-farms simulations predict zero cocnentration); ∞ indicates infinity and arises when the no-farms simulation predicts a concentration of zero.

| Property	25 May	26 May	27 May	28 May	29 May	25-29 May
Mean	0.93	-∞	1.05	-∞	0.65	1.0
Median	1.07	1.07	1.10	0.98	0.98	1.03
Std. Dev.	0.60	NaN	0.45	NaN	1.59	0.25

Figure 22

Time and depth-averaged simulated concentrations of five logistically growing plankton sub-classes (mg C m-3), and of 8 d old snapper (larvae m-3) (image columns 1 and 3) under a no farm scenario; image columns 2 & 4 illustrate the 'with-farms' time-and-depth-averaged concentrations relative to those of the 'no-farms' situation. Image columns 1 & 2 present averages over the entire duration of the simulation. Image columns 3 & 4 present averages over the period corresponding to the field-survey. Each small pixel corresponds to an area of 750 m x 750 m.

Property	Time-averaged results (days 0-18)	Time-averaged results (days 13-18)
PLA SC1		
PLA SC2		
PLA SC3		
PLA SC4		
PLA SC5		
SNA SC0		

Figure 23

Bubbleplot illustrating the simulated spatial distribution of plankton subclass 3 on each of the five days (upper five rows) of the synoptic survey. The lower-most row presents the five-day average results. Left-hand column: no-farms abundance (mg Chl m⁻); centre column with-farms abundance (mg Chl m⁻); right-hand column relative abundance (with farms/no farms). In the abundance plots the concentric circles on the left-hand side of each plot correspond to concentrations of 0, 1 and 2 mg Chl m⁻. In the ratio plots they correspond to ratios of 0, 2 and 4.
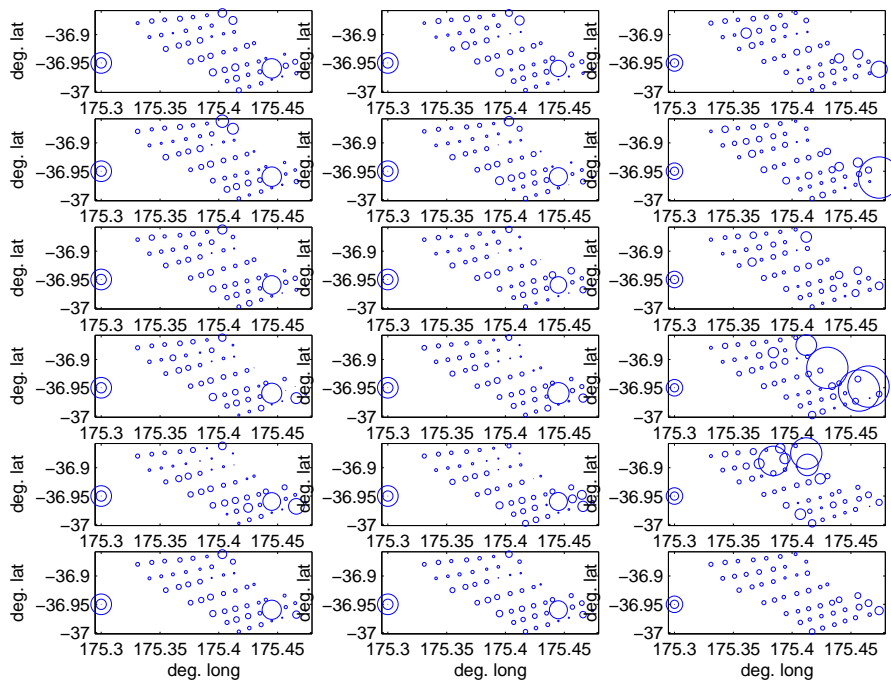
6.2.2 Depletion inferred from the surfaces method applied to the simulation results from the logistic model

As with the biophysical model, it proved inappropriate to apply the surfaces method to the virtual sampling data stemming from the with-farms simulation.

7   Discussion

7.1   A comment upon carbon:chlorophyll ratios

Both the biophysical model and the empirical model measure phytoplankton abundance in terms of carbon. The synoptic survey measured phytoplankton abundances in terms of chlorophyll. To render the model results more directly comparable with the field data, we have converted from carbon to chlorophyll by assuming fixed C:Chl ratios. For the biophysical model, we adopted values of   50:1 for the diatoms and phytoflagellates, and 100:1 for dinoflagellates. For the empirical model, we adopted a ratio of 50:1. Unfortunately, it is well known that, even within a single cell C:chl ratios can vary by a factor of two or more (EPA 1985) in response to a variety of factors including: recent intensity of light experienced by the cell, water temperature and nutrient-status of the cell (Chan, A.T. 1980,Geider, R.J. 1987,Geider, R.J. et al. 1997). Clearly, this variation constrains the degree of resolution at which we can compare observed and simulated phytoplankton biomass.

7.2   'Sampling Error in the simulations'

Broekhuizen (2004) emphasize one of the limitations of the particle-tracking approach that is used in both the biophysical model and the empirical model. Namely, that the accuracy with which concentration can be resolved is dependent upon the number of particles contributing to the average. In effect, 'sampling error' becomes a significant problem when there are few particles in a control-volume. If one is interested in time-averaged results (as we were when making the scenario simulations of Broekhuizen (2004)) this limitation becomes less important (because one consequence of the time-averaging is to increase the number of particles contributing to the sample). From the outset, we feared that it would represent a significant hurdle when endeavouring to estimate instantaneous abundances. This has proven to be the case – particularly for the empirical model. The practical implication of this 'sampling error' is that, in the instantaneous estimates of simulated abundance (but not the long-term average estimates), 'sampling error' in the simulations appears to be of a magnitude approaching that of the farm-induced signal that was inferred from the field data. This makes it difficult to definitively accept, or falsify the models. Nonetheless, we believe that the balance of evidence is in favour of accepting their local-scale predictions. Equally, however we believe that the results imply that the far-field predictions of the Broekhuizen (2004) version of the biophysical model should be held in doubt – we believe those of the more recent version (see Appendix 2) of that model are much more plausible.

Sampling error has proven to be a more obvious problem in the empirical model than in the biophysical model. There are three reasons for this. The first is that the latter model suffers from another, perhaps, more fundamental problem – the excessive onshore offshore chlorophyll gradient referred to previously. The second is that, as an

emergent property, the biophysical model predicts high concentrations inshore and low concentrations in the central firth. In contrast, as a prescribed property, the empirical model assumes that abundances are lower near the coast than they are in the northern, central firth. Thus, the sampled biomasses in the vicinity of Area A are based upon fewer particles (are less robust) in the empirical model than they are in the biophysical model. The third reason is that, within the biophysical model, considerable effort is devoted to ensuring that diatom (and phytoflagellate and dinoflagellate) particles that are in close proximity to one another are of similar size (represent similar quantities of material), but less care is taken in the logistic model. At the level of an individual sub-class of plankton on an individual particle, the logistic-plankton model assumes that the net rate of population growth is governed by (ignoring additional mortality due to mussel-feeding):

$$\frac{dn_i}{dt} = rn_i \left(1 - \frac{\sum_{j=1}^{m} n_j}{VK} \right) \tag{1}$$

in which n_i denotes the biomass associated with the ith particle, V denotes the volume of the control-volume within which the particle finds itself, r denotes the maximum weight-specific growth rate, K denotes the local carrying capacity and m denotes the number of plankton particles within this control-volume. The rate of change of total population biomass (N) within the control-volume is given by:

$$\frac{dN}{dt} = \sum_{i=1}^{m} rn_i \left(1 - \frac{\sum_{j=1}^{m} n_j}{VK} \right) \tag{2}$$

Should a particle grow to exceed a prescribed biomass, it is split into two 'daughters', each receiving half of the parent's mass. This ensures that there is an upper limit to particle size (there is an implicit lower limit because both logic and the logistic growth model itself dictate that particle-specific biomass cannot fall to zero). Nonetheless, the realised weight-specific growth rate of all particles within a given control-volume $\left(= r \left(1 - \sum_{j=1}^{m} n_j \middle/ VK \right) \right)$ is identical. Thus, neighbouring particles of differing size (because they have originated from differing locations), will not converge in size.

One could reformulate the logistic model slightly to achieve size-convergence. In the reformulated form, the analogous equation to Eq (1) is:

$$\frac{dn_i}{dt} = rn_i \left(1 - \frac{mn_i}{VK} \right) \tag{3}$$

The control-volume-specific rate of biomass change corresponding to Eq. 3 is the same as that corresponding to Eq 1 (namely, Eq. 2).

We have made a pair of simulations (not shown) using the reformulated model. As one would expect, the time-averaged results remain very similar to those illustrated in Figure 22. Unfortunately, applying the surfaces method to the new simulations does not yield results that are in markedly better quantitative agreement with those derived from the field data.

7.2.1 Biophysical model

We have noted that, though the average simulated chlorophyll concentrations on each of the five days generally do not differ significantly from the field mean, they invariable fall below the corresponding mean. Nonetheless, given the approximate nature of the conversion between chlorophyll and carbon, we conclude that the model is reproducing spatial-average chlorophyll concentrations within the Wilson Bay area satisfactorily. Given the simple nature of our initial conditions (in the absence of firth-wide data, we assumed spatial homogeneity) and (Firth/Gulf) boundary conditions (spatially and temporally constant), we are pleased to find that the model reproduces the averages with such fidelity after changing only the initial and boundary conditions to better reflect the conditions that prevailed at the start of the simulation period. Nonetheless, at this level of comparison, the model appears to fail in two respects. Firstly, it predicts a gradual decline in phytoflagellate biomass, whilst the field-data suggest that the abundance of these phytoplankton was near constant. Secondly, chlorophyll concentrations inferred from the model show a much larger and more abrupt onshore/offshore decline than is evident in the field data.

The phytoflagellate decline is relatively slow, and could have been corrected by reducing the 'background weight-specific mortality rate' (which is assumed to be constant in the model) by only ~ 0.05 d^{-1}. Such a change is small in comparison with the extremely wide range of mortality-estimates that have been derived for the total (*cf* phytoflagellate) phytoplankton in the Hauraki Gulf region: 0.2 d^{-1} to 0.9 d^{-1} (Hall, J.A. et al. in review).

In part, the excessive onshore/offshore gradient of simulated chlorophyll can be attributed to the fact that we have assumed that each taxon has a constant carbon:chlorophyll ratio whilst the field data indicates that this was not the case. Nonetheless, the onshore/offshore gradient inferred from the model is greater than can be explained by the Chl:C gradient in the field-data. Thus, the model is exhibiting a residual, systematic error.

There are several processes that might be driving the systematic error. These include: (a) incorrect specification of initial and boundary conditions, (b) overly-strong light-limitation of the (offshore) phytoplankton population, (c) spatially varying losses to zooplankton grazers and (d) erroneous patterns of horizontal transport. Inspection of the spatial patterns of zooplankton abundance at stations A1-G1, A5-G5 and A7-G7 (inferred from counts made upon preserved water-samples made on the first and last days of the synoptic survey) reveal substantial between-station variability, but there is no evidence of an onshore/offshore gradient in zooplankton density. Thus, we discount the third explanation. This step-like transition is evident both when the biophysical model is driven by currents etc. stemming from the hydrodynamic model with the default parameterisation, and when it is driven by currents etc. stemming

from the recalibrated version (see Appendices 1 & 2). Thus, we do not believe that it is a result of having a false current-driven circulation pattern. It may, however, be indicative of false patterns of transport stemming from other mechanisms. Phytoplankton horizontal transport also depends upon their vertical position within the water-column and the assumed horizontal eddy dispersion coefficient. The former is influenced by their 'swimming' behaviour. We have not made a rigorous comparison of simulated and observed vertical phytoplankton distributions – though we note that, down to 15 m (the depth to which depth-resolved field-data extend), neither show strong vertical gradients. A simpler 'transport-related' means of promoting a less extreme onshore/offshore gradient of phytoplankton abundance would be to apply a larger horizontal turbulent dispersion coefficient than was adopted in this study (0.1 m^2 s^{-1}). Whilst this is consistent with empirical evidence (Okubo, A. 1971), the empirical data would also support a number larger than this.

There are also other possible explanations for the false abundance gradient. We know that our initial- and boundary conditions are simplistic. It is conceivable that introducing spatial variation into either, or temporal variation into the latter could correct the apparent systemic error in the spatial distribution of algal biomass during the period of the synoptic survey – however it is far from clear what spatio-temporal pattern would be required, or whether this pattern would be plausible.

Light intensity drops approximately exponentially with increasing depth-within-water-column. Whilst photosynthetic rates are non-linear functions of light intensity (as light intensity rises, rates rise to a plateau and even fall at sufficiently high intensities) it is clear that depth-averaged phytoplankton population growth rates will tend to be lower in deeper water than they are in shallow water. During the period of the synoptic survey, depth-integrated phytoplankton growth would have been light limited in deeper waters. Thus, the model has a tendency to yield lower depth averaged biomass offshore. The gradient of this decline will be sensitive to three different parameter groups: those governing population loss rates (respiration, cell-leakage and mortality), those governing the shape of the photosynthesis/irradiance curve (maximum weight-specific photosynthetic rate and half-saturation coefficient) and those governing the rate at which light attenuates through the water-column. In particular, small reductions in the attenuation-rate parameters or the (taxon-specific) half-saturation coefficient for light-capture can be expected to increase offshore phytoplankton production rates disproportionately relative to those inshore.

7.2.2 Empirical Model

As was expected *a-priori*, the logistic model yields plankton densities that are lower than those measured in the field. Unlike the biophysical model, it does not yield an excessively large onshore/offshore chlorophyll decline; however the between station variability still exceeds that measured in the field data. Seemingly as a result of this (non-farm-driven) variability, the degree of quantitative congruence between the depletion surfaces inferred from the field data and the simulated data is poor. Thus, as with the biophysical model, we are forced to conclude that the logistic model is not reproducing the observed spatial patterns with sufficient fidelity to enable us to reproduce the surfaces S_{all}, $S_{outside}$ and S_{perim} with any accuracy. Despite this failure, a comparison of the no-farms and with-farms simulation results indicates that plankton

sub-class 3 is predicted to suffer almost no depletion (<5% in the 18 d and 5 d time-averages) as a result of the presence of Area A farms (indeed, the virtual sampling results indicate that enhancement may occur – though this must be an artefact, see below). Depletion of 5% is consistent with the level of depletion inferred from the surfaces method applied to the field data.

The virtual-sampling data stemming from the no-farms and with-farms simulations indicates that the farms may enhance phytoplankton biomass. To a lesser extent, this pattern is also found in the time-averages. Whilst enhancement has been noted in the field (Ogilvie, S.C. et al. 2003), and is a plausible outcome in the biophysical model, the logistic model *per-se* does not have any mechanism that can permit enhancement. Rather, seeming enhancement is an artefact arising from 'sampling error'. Particles within the farms exhibit slightly lower net weight-specific growth rates. Thus, the temporal pattern of particle fission changes. Particle trajectories are driven by a combination of (deterministic) currents and turbulence (simulated by introducing pseudo-random perturbations into particle trajectories). Changing the temporal pattern of particle fission, changes the sequence of random perturbations experienced by each particle (and the total number of particles within the system). Thus, the trajectories of individual particles change and corresponding virtual-samples in the no-farms and with-farms simulations are not necessarily based upon corresponding underlying particles. Our contention that sampling error underlies the apparent enhancement is supported by the observation that enhancement is less marked (results not shown) when the simulations are made using the modified version of the logistic model (Eq. 3 vs. Eq. 1).

Based upon the time-averaged results, the biophysical model usually yields depletion estimates that are somewhat larger than those stemming from the logistic model. In small part, this is a consequence of the differing concentrations of suspended particulates (which influences mussel filtration rates) in the two models, however the main reason is that the net phytoplankton weight-specific growth rate yielded by the biophysical model (as an emergent property) is only ~0.01 d^{-1} (somewhat lower than inferred from the field data) whilst plankton sub-class three of the logistic model has a prescribed weight-specific growth rate of 0.2 d^{-1} (somewhat higher than that inferred from the field data).

8 Implications for confidence in the earlier, scenario simulations

8.1 Biophysical model

We have found that the model reproduces average nutrient and phytoplankton concentrations within the Wilson Bay region well, but with a systematic spatial bias that we tentatively attribute to either: (a) having adopted a horizontal turbulent dispersion coefficient which was low in comparison with reality, or (b) overly-strong light limitation of phytoplankton growth. If the former explanation is correct, it implies that the maximum levels of local-scale farm-induced change are likely to be less extreme than those predicted, but that such change may instead become spread over larger areas than has been predicted. If the light-limitation explanation is correct, it indicates that the model may be under-predicting phytoplankton growth rates a little when light intensities are low (during late-autumn, winter and early spring and during periods of high water-column sediment load). On the other-hand, almost by definition, such under-prediction will be irrelevant during periods of nutrient limitation (late spring - early autumn).

The excessively high variability (in time and space) generated by the biophysical model has made it difficult to determine how well the model is reproducing the patterns of farm induced change that were inferred from the field data. Based upon a like-with-like comparison (ie the virtual sampling data), the model is clearly under-estimating depletion; however the pattern of depletion evident around the NE of Area A in longer-term space-time averages is more consistent with inferences drawn from the field data – though the spiral pattern of depletion and enhancement to the SW of the farm is not.

In summary, whilst the combination of erroneously large spatial gradients and excessive 'sampling error' implies that the version of the biophysical model used in the Broekhuizen (2004) report was not performing as well as one could wish, we believe that there is no evidence that it dramatically over-predicts, or dramatically under-predicts the local time-averaged phytoplankton change in the vicinity of Area A during the period of the synoptic survey. There is, however, some evidence of systematic failings in the near-field. By implication, there may also be failings in the predicitons for the far-field. The revised version of the biophysical model (see Appendix 2) performs better than the original in both the local- and near-fields. We infer that it is also likely to perform better in the far-field.

8.2   Logistic Model

During the period of the synoptic survey, sub-class three of our logistic model appears to have provided the closest analogue to the field phytoplankton population and we have based our analysis upon this sub-class. As with the Biophysical model, the logistic model fails to reproduce the observed spatial pattern of chlorophyll with sufficient fidelity to make it possible to adequately reproduce the results stemming from the surfaces-method applied to the field data.   Nonetheless, comparison of the 'with-farms' and 'without farms' simulations provides strong evidence that the extent of depletion is not substantially greater than that inferred from the field-measurements. Indeed, it may be a little lower – which is to be expected given that the prescribed weight-specific growth rate for sub-class 3 (our chosen phytoplankton analogue for the survey period) was more than twice that inferred from the field data.

It is important to remember that phytoplankton net growth rates are very variable in time and in space. Thus, there are undoubtedly locations and times for which sub-class three will provide a poor analogue of the field phytoplankton population. In the model, the descriptions for faster and slower-growing plankton are structurally identical to those for sub-class three, but differ parametrically. Our analysis demonstrates that the underlying assumption of logistic growth in the plankton, combined with the chosen model of mussel feeding does permit adequate duplication of time-averaged near field patterns of depletion.

8.3   General comments

Simulated levels of plankton depletion are relatively insensitive to changes in phytoplankton biomass. The fundamental reason for this is that, whilst mussel filtration rates are influenced by the concentration of both organic and inorganic particulates within the water-column, plankton represent only a comparatively small component of the total particulate content in the water (suspended sediment and organic detritus dominate). Thus, even relatively large changes in plankton abundance have only a small influence upon mussel filtration rates. The implication of this is that, despite the evidence that the models may be generating some systematically erroneous plankton distributions, the magnitude of predicted near-farm plankton change will not be very different from those that would be predicted were the spatial patterns of abundance rendered with greater fidelity. It is, therefore, more important that the models adequately predict the patterns of farm-induced near-field change, than it is that they predict absolute abundance adequately. We believe that we have demonstrated that, at the scale of the entire 49-station sampling grid, the biophysical model is predicting near-field depletion patterns that are similar to those inferred from the synoptic survey data. The logistic model is under-predicting depletion but this is to be expected given that our chosen analogue (sub-class 3) to the real phytoplankton population had a growth rate somewhat greater than that inferred to have prevailed in the phytoplankton population at the time of the survey (recall, that because this was a verification exercise, we did not modify any of the model's parameters).

Predictions regarding the spatial extent and magnitude of change in the near- and far-fields are dependent not only upon mussel filtration rates, but also upon several other

factors. These can be separated into two components: (a) those which influence the rate of demographic recovery (details of cell physiology, nutrient-regeneration, water-temperature, irradiance, predation etc.) and (b) those which influence the (horizontal) direction of transport following passage through a farm (quality of the hydrodynamic simulations and the fidelity with which our assumed 'swimming rules' generate the correct vertical distributions of plankton). Whilst the hydrodynamic model performed moderately well (even with the original parameterisation) during the verification period, the validity of the swimming rules is less certain. Similarly, we recognise that all our biological models have simplistic representations of nutrient-regeneration and predation. The corollary must be that we are less confident in the veracity of the predicted near- and far-field changes than we are in the predicted local ones. We take this opportunity to remark that preliminary results stemming from the most recent iteration of the biophysical model (see Appendix 2) indicate that though the local patterns of change are similar to those produced by the original version of the biophysical model (as used in the main body of this report and in Broekhuizen et al. (2004)), the patterns of change in the near- and, more especially, far-field do differ. The change 'halos' tend to be more contiguous/continuous than those in Broekhuizen et al. (2004) and it is much less common for far-field signals to appear 'out of nowhere'. The revised model still predicts the step-like onshore offshore chlorophyll-abundance transition. Predicted levels of depletion in and to the north of the Wilson Bay farms are similar to those of the orginal model, but the inshore enhancement and the 'enhancement/depletion spiral' to the the SW of the farmed area are both absent – in better accord with inferences drawn from the field data.

8.4   Implications for interpretations of the earlier 'scenario simulations'

This verification exercise was undertaken in order to gain an indication of how much credence should be given to the results of the scenario simulations described in Broekhuizen et al. (2004). We believe that our verification analysis demonstrates:

1. Using the parameterisation that underlay the simulations in Broekhuizen (2004), the hydrodynamic model reproduced tidal and wind-driven circulation patterns and temperature/salinity gradients during the synoptic survey period moderately, but improvements are possible (see Appendix 1 of this report).

2. Though the biological models are over-estimating the fine-scale variability in nutrient and phytoplankton biomass, and perhaps also yielding some systematic error in the spatial distribution of phytoplankton abundance, they neither dramatically over-predict, nor dramatically under-predict the area-average levels of farm-induced phytoplankton change in the immediate vicinity of Area A.

3. We do not have the data to permit us to verify the models' far-field predictions of phytoplankton change. The performance of the (original versions) models in the near-field is equivocal. Whilst they correctly indicate depletion in the NE area of the farmed zone, the amount of depletion is at the lower end of what was inferred from the field data (and often less than that inferred). Similarly, there is also evidence that the (original version of the) biophysical model makes some false predictions in the near field. This failing in the original version of the biophysical model has now been remedied (Appendix 2). Preliminary results

stemming from the new model applied to a western firth AMA indicate that the far-field predictions ascribed to the Western Firth AMA in Broekhuizen et al. (2004) may be unreliable – though the local-scale changes remain similar.

4. Whilst this verification exercise indicates that the biological models are capable of performing moderately well in the region of Wilson Bay, that farm-area is comparatively small in comparison with the one that Broekhuizen et al. (2004) were asked to consider for the Western Firth. There is mounting evidence that large-scale mussel farms can have an influence upon water-speed and mixing conditions within and around the farms. None of our models (hydrodynamic, biophysical or empirical) take any account of possible current/mixing changes. We have been able to generate satisfactory simulation results for the Wilson Bay area without considering the hydrodynamic influence of the farms, but it is not clear whether or not this would prove to be the case for a large farm area in the western firth.

9 Acknowledgements

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