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Exploring the Carrying Capacity of the Firth of Thames for Finfish Farming: A Nutrient Mass-Balance Approach

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June 2008

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Executive Summary

Environment Waikato is currently scoping a possible plan change to allow for the diversification of aquaculture within existing aquaculture management areas (AMAs) in the Region. This plan change would allow for the cultivation of species other than mussels, including finfish. The most likely site initially for this would be at the Wilson Bay Marine Farm Zone (WBMFZ) in the Firth of Thames, which is currently consented for mussel aquaculture only (total area about 1200 ha). For eco-physiological and economic reasons, the yellowtail kingfish (*Seriola lalandi lalandi*) is the most likely candidate for the cultivation of finfish in the Firth of Thames and is the focus for this analysis. However, effects of finfish farming are likely to be similar for most of the species that could be farmed in the Firth, assuming similar farming intensities.

To assist Environment Waikato in considering the proposed plan change, this study compares new N additions from finfish farming with aquatic ecosystem processes of the Firth, riverine and oceanic additions, and losses through hydrographic export, denitrification (the microbially-mediated loss of N to the atmosphere) and mussel harvest. It combines information from a nutrient mass-balance budget for the Firth and estimates of Firth primary production (both obtained using field surveys made in the last decade funded by the Foundation for Research Science & Technology), with estimates of N discharged to the marine environment during fish feeding calculated using feed input, composition and feed conversion ratios (FCRs) provided by NIWA aquaculture specialists. It also compares N discharges from finfish farming with potential N removal caused by existing and future farmed mussel harvests at the WBMFZ. The purpose of the report is to provide perspectives on the relative magnitudes of ecosystem and farm processes under various intensities of finfish farm development, to inform Council decision-making about sustainability of finfish culture in the region. The primary focus of the study is at the Firth-wide scale, but makes inferences about impacts at the local AMA scale.

Key findings are:

1. On average, riverine supply of inorganic and organic N to the Firth is greater than the supply arising from mixing across the boundary between the Firth and the Hauraki Gulf. During periods when ocean downwelling is dominant over the adjacent continental shelf, rivers contribute about 70% of the dissolved inorganic N (DIN) load, and when upwelling is active, 50% of the load arises from rivers.

2. The Firth is a strong net sink for inorganic N, indicating that it denitrifies large amounts of nitrogen gas to the atmosphere on a net basis (about 10,800 t N y^{-1}). DIN inputs to the Firth accounted for only about half of this. Particulate and dissolved organic nitrogen (PON, DON) made up the shortfall, originating from riverine (mainly) and oceanic

sources. The mean Firth primary production value was about 28,000 t N y^{-1} incorporated into organic material.

3. Nitrogen discharged to the marine environment from fish farming is estimated at 60 kg N per tonne of fish production, using a feed conversion ratio of 1.3 (FCR: defined as dry weight of feed added to harvested wet weight of fish) based on kingfish culture results from Australia and New Zealand. For FCR = 1.5, which is within the range of current practice for kingfish culture, about 75 kg N is discharged per tonne of fish produced. About 85% of this will be in dissolved forms (ammonium, urea, nitrate, the sum of which is called dissolved inorganic nitrogen DIN here), and the rest is in particulate form.

4. To place the potential N discharged by fish farming into context, scenarios ranging from 1,000 to 10,000 tonnes of fish production[1] per year were evaluated at the two FCRs. At a production of 2,000 tonnes and FCR = 1.3, N discharged was estimated to be small relative to other Firth-wide N processes, sources and sinks: 0.4% of the Firth system N primary production, 1.1% of its denitrification rate, 1.1% of inputs of total N (inorganic plus organic) to the Firth from rivers and the ocean and 1.7% of the input of total N from rivers alone. In terms of loads of dissolved inorganic nitrogen (DIN), which is the most bio-available form of N for primary production, discharges from 2,000 tonnes per year fish production were estimated to be 2.7% of DIN inputs from rivers and the ocean, and 3.8% of the loading from rivers alone. These percentages increase by about 25% for FCR = 1.5. For the 10,000 tonnes per year (FCR = 1.3) scenario, N addition from fish farming is estimated at 5.7% of total N inputs to the Firth and 13.4% of DIN inputs, potentially significant relative to Firth-wide loading and other ecosystem processes.

5. The analyses of this report consider the sizes of fish farm discharges relative to Firth-wide ecological processes, sources and sinks involving N. It is certain that N discharged from fish farms, as proportions of areal primary production, denitrification, and loading from other sources (rivers and oceanic) will be much higher local to the WBMFZ than over the Firth-wide scale. As an example, in principle, the proportions could be 10-fold higher over an area 1/10th the Firth area, (i.e., 1100 km^2/10 = 110 km^2) surrounding the WBMFZ. The actual degree of this focussing of effects will depend on fish farming intensity and hydrodynamic dispersal of discharged N, and also on any functional effects that discharged N may have on the ecological rates themselves.

6. If, at the local AMA scale, such discharged N causes significantly increased organic supply (from new phytoplankton and from waste solids directly) sub-oxic conditions could form. This could threaten fish farming, as well as suppress nitrification, a key

[1] Depending on farm layout, stocking density, and site factors, 1,000 t/year would require a total consented area of 5 to 10 ha, 3,000 t/y would require a total consented area of 20 to 30 ha, and 10,000 t/y would require a total consented area of 70 to 100 ha.

element of denitrification. On the other hand, if the scale of these loading effects is small relative to hydrodynamic dispersal, such feedback may not occur.

7. Mussel harvesting removes N from the ecosystem, estimated at about 6 kg N per tonne of green weight mussel harvested. Discharge of N from fish farming is estimated at about 60 kg N per tonne of fish production (FCR = 1.3), such that the harvesting of 10 tonnes of mussels will remove the same amount of nitrogen as added by the growth of 1 tonne of fish. The 2006 Coromandel region annual mussel harvest (21,000 tonnes, 95% of which is in the budgeted Firth area) would remove slightly more N than that discharged by about 2000 tonnes fish production at FCR = 1.3.

8. Because of the focussing of N discharge at the local scale (described above), only mussels growing within the perimeter of effects caused by that focussing will be relevant for remediation. If, for example, N removal by mussels harvested only at the WBMFZ are relevant in this sense (currently 14,000 tonnes) the equivalent N discharge arises from about 1300 tonnes fish production (FCR = 1.3).

9. The uncertainties introduced by the focussing of effects (which are not resolved by the mass-balance approach used here) mean that the local-scale effects of discharged N need to be examined more closely, and are a strong reason to support better-resolved dynamic bio-physical modelling of the local area, including coupling with sedimentary and oxygen dynamics and effects of mussel harvest. Remediation by other forms of co-culture (e.g., algal, deposit feeders) should be also be considered.

10. It is recommended that defensible, locally applicable 'limits of acceptable change' are designated for adaptive management of WBMFZ fish farm development. This should be informed by the modelling and by meta-analyses of known fish farm effects from other studies.

1. Introduction

Environment Waikato (EW) is currently scoping a plan change to allow for the diversification of aquaculture within existing aquaculture management areas (AMAs) in the Region. This plan change will potentially allow for the cultivation of species other than mussels, including finfish. The most likely area for this is the biggest AMA in the Region, the Wilson Bay Marine Farming Zone (WBMFZ), located in the Firth of Thames (Fig. 1, Turner and Felsing 2005). Currently, Area A of the WBMFZ is consented for 470 ha of mussel longlines, and Area B of the Zone, once developed, will comprise an additional 520 ha. In addition to this, 220 ha of older farms exist within Wilson Bay.

The Hauraki Basin catchment adjacent to the Firth is one of New Zealand's most intensively farmed areas, and terrestrial nutrient input into the Firth is substantial (Broekhuizen and Zeldis 2005; Zeldis 2008). In addition, the Firth receives water and nutrients from the adjacent Hauraki Gulf, which opens onto the narrow north-eastern North Island continental shelf (Fig. 1). This shelf is subject to periodic Ekman wind-driven upwelling (Zeldis et al. 2004) which can influence nutrient loading into the Firth (Zeldis 2005). Finfish farming pesents another potential source of nutrient input into the Firth. To provide background information for the aquaculture diversification plan change, EW is seeking to compare the magnitudes of natural nutrient inputs (including terrestrial runoff from farm land) with finfish farm-derived nutrient fluxes in the Firth of Thames.

NIWA have previously carried out a comparison of natural and mussel farm-derived nutrient fluxes associated with various scenarios of mussel farming intensity in the Firth at Area A (Zeldis 2005). Using mass-balance budgeting and primary production information, the study estimated Firth system incorporation of carbon (C) and nitrogen (N) into organic material through primary production, and losses of C and N through system respiration, denitrification, and hydrographic export. These were compared with C and N assimilation and respiration by mussel farms, at the various AMA development intensities. The study provided perspectives on the relative magnitudes of ecosystem and farm processes, under the various intensities of AMA development, to address the issue of aquaculture sustainability from a systems-level perspective.

The current contract is a similar analysis, except in this case it is applied to potential scenarios of finfish farm development in the Firth. Unlike the mussel farm case, where the farm effect on a Firth-wide scale is manifested through a loss of C and N through mussel harvest, in the finfish farm case the effect is manifested largely through a nutrient subsidy to the system, in the form of feed addition of which a proportion is not fixed into fish biomass and is discharged into the water column. The sizes and impacts of such additions will depend on the magnitude and management of the aquaculture development.

The study compares nutrient additions calculated using typical stocking densities, feed input, composition and conversion ratios, with ‘natural’ ecosystem processes of the Firth, including riverine and oceanic nutrient loadings, nutrient losses through hydrographic export, denitrification and crop harvests. It also compares these with fluxes associated with mussel harvests, in a consideration of potential remediation of fish farm effects. The intention of the study is to provide perspectives on the relative magnitudes of ecosystem and farm processes under the various intensities of development, to inform Council decision-making about sustainability of finfish farming in the region.

Over the last few years management of aquaculture in the Firth by EW has been addressed at Firth-wide, as well as local AMA scales, because of the importance of maintaining the Firth as a healthy ecological entity (Turner and Felsing 2005). The Firth-wide scale is the primary focus of this study, but it also makes inferences about impacts at the local AMA scale, for the water column. Local benthic effects are addressed in accompanying reports by Giles (2007) and Oldman (2008), which examine potential benthic impacts within and immediately surrounding potential finfish farm developments within the WBMFZ.

The present study compares nitrogen (N) discharges to the Firth originating from unassimilated feed (uneaten food, and dissolved and faecal metabolic waste) relative to Firth-wide N loading from rivers and the ocean, biogeochemical processes, (namely primary production and denitrification) and potential removal through mussel harvest. It combines information from three sources, detailed in Zeldis (2005) and in the following Methods section and appendices. The first is a water, salt and nutrient mass-balance budget for the Hauraki Gulf and adjacent Firth of Thames, based on ship samples obtained in 2001—2002 and protocols developed within the ‘Land-Ocean Interactions in the Coastal Zone’ (LOICZ) programme of the International Geosphere-Biosphere Programme (Gordon et al. 1996). The budget calculated the flows, sources and sinks of carbon and nutrients through the Firth, arising from ocean mixing, riverine inputs and biological processing. The second data source is Firth primary production, i.e. organic matter fixation, determined from ship samples (Gall et al. 2002; author’s unpubl. information). The third describes N additions associated with kingfish aquaculture from information provided by finfish aquaculture specialists in New Zealand and Australia. Information on N removal associated with mussel farming is also considered. The combination of these data sources provides perspective on relative magnitudes of ecosystem and farm processes, toward assessing potential influence of finfish farms on the Firth of Thames ecosystem.

2. Methods

2.1. Finfish species

Presently, the New Zealand marine finfish industry is dominated by sea-cage farming of King salmon (*Oncorhynchus tshawytscha*) in the Marlborough Sounds, Akaroa Harbour and Stewart Island (Forrest et al. 2007). However, this species is not considered biologically suited for cultivation in the Firth of Thames. The yellowtail kingfish (*Seriola lalandi lalandi*), on the other hand, has been identified as being biologically suitable to New Zealand aquaculture conditions (particularly those prevalent in the Firth of Thames) and as having strong economic and marketing prospects (Poortenaar et al. 2003; New Zealand Aquaculture Council 2006). Water temperature in the Firth ranges from about 13 to 22 °C (Broekhuizen et al. 2002), which is within the optimum range for kingfish culture. Thus, this species appears to be the most likely candidate for the cultivation of finfish in the Firth and is the focus for the present analysis. It should be noted, however, that effects of finfish farming are likely to be similar for most of the species that could be farmed in the future in the Firth (Forrest et al. 2007), assuming similar farming intensity.

2.2. Budgetary approach

The budgetary approach employed here is a "stoichiometrically-linked water-salt-nutrient budget" (Gordon et al. 1996). The nutrients of specific interest here are carbon (C), nitrogen (N) and phosphorus (P). The budget was based on salinity and nutrient samples collected in quarterly oceanographic surveys on the continental shelf outside the Hauraki Gulf, and within the Hauraki Gulf and Firth of Thames (Figure 1), obtained within the Cross-shelf Exchange (C-SEX) project of the NIWA Coasts and Oceans Outcome-Based Investment Programme. In the annually averaged budget presented here, salinity and nutrient data from all depths on all stations on each transect over all voyages were averaged, to estimate annually-averaged salt and nutrient concentrations in shelf, Gulf and Firth systems. This involved 96, 108 and 50 samples taken in the shelf, Gulf and Firth systems, respectively, divided nearly equally between the 4 surveys. Other details of the sampling and budget methods and results are given in Zeldis (2005) but a general overview of the budgetary approach is given here. This is followed by a description of the results for the Firth, and how these were interpreted in the present investigation of finfish aquaculture effects. The method comprises a series of budgets which are solved in a prescribed order (after Gordon et al. 1996), described below.

2.2.1. Water budget

A budget is established of freshwater flows with respect to the Firth system (river runoff, precipitation, groundwater, sewage and evaporation). There must be compensating outflow to the adjacent system, i.e. the Gulf, to balance the water volume in the Firth system. This is the 'residual' flow (Figure 2).

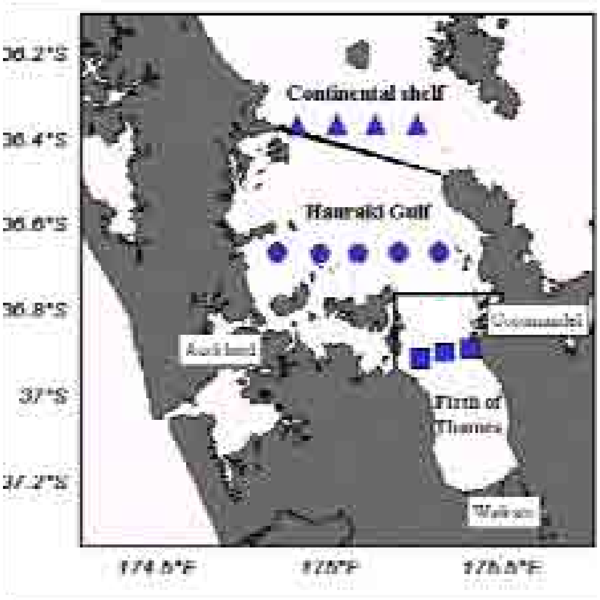

Figure 1: Place names, sampling stations and system boundaries used for the water-salt-nutrient budget in Zeldis (2005). Shelf stations are triangles, Gulf stations are circles and Firth stations are squares.

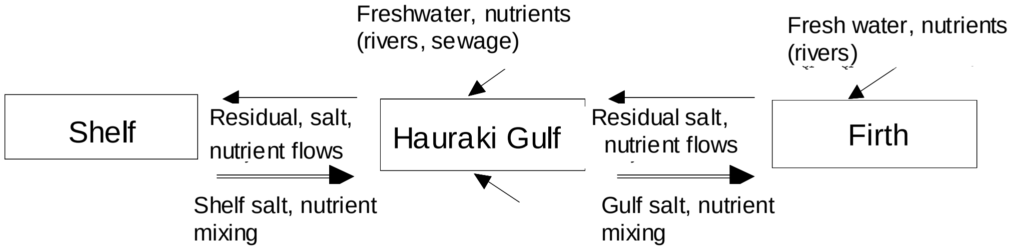

Figure 2: Schematic diagram of system boxes used in LOICZ budget of Zeldis (2005). Main flows of freshwater, salt and nutrients are indicated.

2.2.2. Salt budget

Salt must be conserved in the system when system volume and salinity are at steady state. Therefore, salt removed from the Firth by the residual flow to the Gulf must be replaced by mixing between the Gulf and the Firth, to sustain the salinity difference observed between the two systems (Figure 2). The water and salt budgets describe the exchange of water between the Firth and Gulf systems by the processes of advection and mixing.

2.2.3. Budgets of non-conservative nutrients

Dissolved C, N and P will exchange between the Firth and Gulf systems due to the residual and mixing flows described above. Deviations of material concentrations from predictions based on the previous steps are quantitatively attributed to net non-conservative reactions of materials in the system (Figure 2). Although the C budget is very important in terms of describing net metabolism of organic matter, in this report we are primarily interested in the N budget and its relationship with finfish farm-related N inputs. Details of estimation of net dentrification and of primary production are given in Appendix 1.

2.3. Fish feed N discharged to the marine environment

The amounts of N discharged to the marine environment by the culture of kingfish were estimated based on the information in Appendix 2. With Feed Conversion Ratio (FCR) = 1.3, discharge of 60.2 kg N (dissolved + particulate) to the marine environment per tonne of fish produced was determined. The value for FCR = 1.5 was 74.6 kg N t^{-1}.

2.4. Nitrogen content of mussels

This value was determined as described in Appendix 3 and was used to assess the removal of N from the Firth due to extant and potential future mussel harvests. A best estimate of the nitrogen (N) content of whole freshly harvested mussels (i.e., green weight: GW) of 5.9 kg N per tonne GW of harvested mussels was determined.

2.5. Scenario designation

Scenarios of kingfish production biomasses investigated were: 1,000, 2,000 3,000, 5,000 and 10,000 t. For each harvest tonnage, FCRs of 1.3 and 1.5 were used (Appendix 2). It was assumed that these tonnages refer to the amount of kingfish production harvested per annum, to enable comparison with annual estimates of ecosystem fluxes (e.g. annual primary production, annual river N loading) in the Firth.

3. Results

3.1. The Firth N cycle

To place the results for fish feed N discharges to the Firth in context of the nutrient budget and primary production results, it is useful to posit a conceptual model for N-cycling in the Firth which includes these elements (Figure 3). The model shows the major net fluxes of N, including the loading of new particulate organic N (PON) and DIN to the system (including fish food), the uptake of DIN by autotrophs in primary production to form PON, decomposition of PON by heterotrophs (including finfish and mussels) to DIN, and recycling of the DIN *via* autotrophs to PON. Competing with the internal production:decomposition cycle is the major atmospheric N_2 sink through denitrification, and a lesser export of dissolved organic N (DON). Primary production in the Firth is N-limited over most of the year (Broekhuizen et al. 2002; Chang et al. 2003; Zeldis 2004), and it is most likely the denitrification sink which accounts for this. Smaller N sinks are via PON burial and harvest of mussels (note that the estimate of N discharge by farmed fish accounts for the removal of fish in harvests (Appendix 2), such their harvest is not an N sink with respect to the system). The absolute sizes of some of these net fluxes are given below and in Table 1.

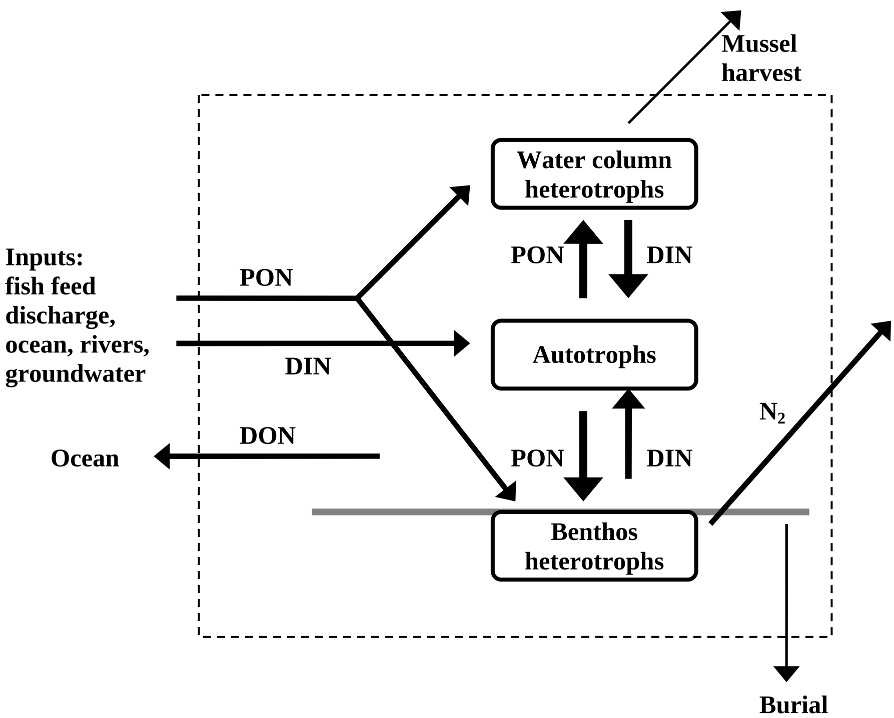

Figure 3: Nitrogen net fluxes and internal cycling in the Firth of Thames system. Dashed lines are system boundaries. Increasing arrow thicknesses denote small, medium and large flows. ‘Autotrophs’ are all primary producers and ‘Heterotrophs’ are all secondary producers.

Table 1. **Results of nutrient budget (revised from Zeldis 2005) showing Firth of Thames net N fluxes (t y^{-1}) of dissolved inorganic N (DIN), particulate organic N (PON), dissolved organic N (DON) and total N from rivers and the ocean boundary (ref. Fig. 1). Positive values indicate N inflows, and negative values outflows, with respect to the Firth. Also shown is the harvest of N in mussels from the Coromandel region for the 2006 calendar year (21,000 t GW) and the loss via denitrification. Ocean PON is estimated by difference with respect to denitrification (not including mussel harvest).**

River DIN	River DON	River PON	River total N	Ocean DIN	Ocean DON	Ocean PON	Ocean total N	Mussel harvest N	Denitrification
3200	800	3000	7000	1,400	-2,300	4500	3600	-126	-10,600

3.2. Quantifying the nutrient budget and primary production

Important results from the nutrient budget and primary production analyses were:

- On average, riverine loading of inorganic and organic N (Table 1) dominated that due to mixing across the ocean boundary (Figure 1). In Zeldis (2008) and this work, river nutrient inputs to the Firth described previously (Zeldis 2005) were updated using Sparrow output (NIWA 2004) and unpublished data (S. Elliott NIWA pers. comm. January 2008) for terminal river reaches, and showed that rivers contributed between approximately 50 and 72 % of Firth DIN flux under plausible shelf upwelling and downwelling scenarios, respectively. To this may be added the substantial riverine DON and PON contributions (Table 1).

- The Firth was a strong net sink for DIN and a relatively weak source for DON. Overall, deviations between observed and expected fluxes of total dissolved N in the Firth (Zeldis 2005) indicated that it denitrifies large amounts of nitrogen gas to the atmosphere on a net basis, according to equation 1 (Appendix 1: about 1.9 mmol m^{-2} d^{-1} or 10,600 t N y^{-1}: Table 1).

- About 7000 t N y^{-1} was added to the Firth by riverine DIN, PON and DON flux, and about 2300 t N of this was lost through hydrographic export of DON to the Hauraki Gulf. The riverine input of N to the Firth was about 60% of the N_2 lost to denitrification (Table 1). To balance this, the amount of oceanic PON required was about 4500 t PON y^{-1} as a net import to the Firth from the Hauraki Gulf.

- The mean planktonic primary production value was 460 mg carbon m^{-2} d^{-1} or about 28,000 t N y^{-1}, incorporated into organic material (Zeldis 2005).

Denitrification was about 0.37 × primary production, which suggests that N, once introduced into the Firth by net N import, cycles about three times through the production-decomposition cycle on average, before being lost to denitrification. This demonstrates how recycling generates the large amount of primary production found within the Firth, by 'amplifying' the imported new N.

- The present mussel harvest extracts insignificant amounts of N, relative to other Firth N sources and sinks.

- The production of one tonne of fish will require about 94 kg N, of which 60 kg N is discharged to the marine environment at FCR = 1.3 (Appendix 2). About 85% of this discharge will be in DIN, and the rest will be in particulate form.

- The coefficient of variation (CV) of ΣPP (Eqn. 2) was estimated as 0.28 (Appendix 4). CV on river gauging of nutrient concentrations was considered about 9% and CV on budgeted denitrification was estimated as 24%. Estimates of accuracy and precision of feed N discharged are unavailable, but a reasonable assumption could be that they are known with a CV of 30% or less.

3.3. Assessing influence of finfish aquaculture

Here, results on Firth system annual primary production, denitrification, and nutrient fluxes from riverine and oceanic end-members are combined with the data on total (dissolved + particulate) discharged N (TN) from fish farming per annum, to draw conclusions about the importance of finfish aquaculture within the Firth ecosystem (Table 2).

Table 2: **Finfish farm total discharged N (dissolved plus solid wastes) as percentage of various Firth system N fluxes, for (a) FCR = 1.3 and (b) FCR = 1.5, and four annual kingfish production sizes. TN is total N (inorganic plus organic, dissolved and particulate). Mussel harvest is the 2006 (calendar year) Coromandel region harvest (MIC 2008) of 21 000 t. Ocean fluxes are under non-upwelling conditions.**

	Fish Production (t y^{-1})				
	1000	***2000***	***3000***	***5000***	***10000***
(a) ***FCR = 1.3***					
Farm N discharged:Firth N primary production	0.2%	0.4%	0.6%	1.1%	2.1%
Farm N discharged:Firth denitrification	0.6%	1.1%	1.7%	2.8%	5.6%
Farm N discharged:Firth river TN loading	0.9%	1.7%	2.6%	4.3%	8.6%
Farm N discharged:Firth river DIN loading	1.9%	3.8%	5.6%	9.4%	18.8%
Farm N discharged:ocean DIN loading	4.7%	9.3%	14.0%	23.4%	46.7%
Farm N discharged:river+ocean DIN loading	1.3%	2.7%	4.0%	6.7%	13.4%
Farm N discharged:river+ocean TN loading	0.6%	1.1%	1.7%	2.9%	5.7%
Farm N discharged:mussel harvest	48%	96%	143%	239%	478%
(b) ***FCR = 1.5***					
Farm N discharged:Firth N primary production	0.3%	0.5%	0.8%	1.3%	2.7%
Farm N discharged:Firth denitrification	0.7%	1.4%	2.1%	3.5%	6.9%
Farm N discharged:Firth river TN loading	1.1%	2.1%	3.2%	5.3%	10.7%
Farm N discharged:Firth river DIN loading	2.3%	4.7%	7.0%	11.7%	23.3%
Farm N discharged:ocean DIN loading	5.8%	11.6%	17.4%	29.0%	57.9%
Farm N discharged:river+ocean DIN loading	1.7%	3.3%	5.0%	8.3%	16.6%
Farm N discharged:river+ocean TN loading	0.7%	1.4%	2.1%	3.6%	7.1%
Farm N discharged:mussel harvest harvest	59%	118%	178%	296%	592%

At a FCR of 1.3 and production size 2,000 t, discharged N is about 0.4% of the Firth system N primary production, and about 1.1% of its denitrification rate. In interpreting this, it should be remembered that the absolute level of primary production is about 3 times that of the source and sink terms because of recycling (section 3.2). At 2000 t production and FCR 1.3, discharged TN is about 1.7% of the loading of TN from rivers, and is about 3.8% of loading of DIN, which is the most bio-available form of N for primary production. Discharged N is a considerably larger proportion of ocean loading than it is of river loading, because of the dominance of river loading in this system (about 70% of loading is riverine under non-upwelling conditions, Zeldis 2008), though it should be noted that ocean loading can be expected to increase under plausible upwelling conditions, and in that case total N loading, is underestimated by this analysis. Discharged N is about 2.7% of total loading of DIN from all sources under this fish production scenario. This N discharge would be about equal to the N extracted by the

Coromandel region 2006 mussel harvest. The percentages increase with increasing production sizes and by about 25% with FCR = 1.5 (Table 2a and 2b). The estimated precision of the components of these proportions is ≅30% (coefficient of variation: Appendix 4).

These calculations give perspectives on the sizes of N discharges by finfish farming, relative to sources and sinks of N for the Firth which sustain its present ecosystem functions. They do not consider any functional affects N loading from fish farming may have on the rates themselves (discussed further below).

3.4. Nitrogen removal through mussel harvest

One tonne green weight (GW) of harvested Green Shell mussels was estimated to contain 5.9 kg N (Appendix 3), whilst production of one tonne of kingfish discharges 60.2 kg N at FCR = 1.3 and 74.6 kg N at FCR = 1.5 (Appendix 2). These values were used to calculate the N discharged by potential fish farms between 1000 and 10,000 t and to estimate the amount of N removed by mussel harvests relative to these discharges (Table 3). The current (June 2008) annual mussel harvest biomass (GW) from Area A at Wilson Bay (with 72% of mussel lines developed) is approximately 13,000 t. The pre-existing mussel lines adjacent to Area A add about 1000 t to this giving a WBMFZ total of 14,000 t. The harvested mussel biomass from the Coromandel region as a whole was about 21,000 t in calendar year 2006 (Mussel Industry Council (2008), of which 95% is within the boundary of the Firth as defined by the mass-balance model (Fig. 1).

Table 3. Nitrogen discharged (t y^{-1}) to the environment by fish farming and the tonnages of harvested mussels with N removal equivalent to the discharge (after rounding) for (a) FCR = 1.3 and (b) FCR = 1.5 and four annual kingfish production sizes.

	Fish Production (y^{-1})				
	1000	***2000***	***3000***	***5000***	***10000***
(a) *FCR = 1.3*					
Fish N discharge (t N y^{-1})	60	120	181	301	602
Mussels (t GW y^{-1}) to remove N equiv.	10,200	20,400	30,600	51,000	102,000
(b) *FCR = 1.5*					
Fish N discharge (t N y^{-1})	75	149	224	373	746
Mussels (t GW y^{-1}) to remove N equiv.	12,600	25,300	37,900	63,200	126,400

About 10 t of mussel harvest will remove the N equivalent of N discharged by one t of fish production at FCR = 1.3. The main reasons for this inefficiency are the low weight-specific N content of mussels (high water content of GW product, large proportion of GW in the shell and low weight-specific N content of the shell), combined with the inefficiency of N retention by finfish farming (about 64% of fed N is discharged at FCR = 1.3, and about 69% at FCR = 1.5).

As per Table 2, Table 3 b shows that the 2006 Coromandel region mussel harvest (21,000 t) will remove slightly more N than that discharged by about 2000 t fish production at FCR = 1.3. At the current development status of the WBMFZ (14,000 t GW harvested y^{-1}) annual mussel harvest from that region will remove N equivalent to that discharged by about 1300 t of fish production. Removals by future scenarios of mussel farm development in the Firth are considered in the Discussion.

4. Discussion

4.1. Significance of fish farm N discharge in the context of the Firth ecosystem

The ratios of Table 2 suggest that N discharged from fish farms varying from 1000 t to 10,000 t production[2] would exert influence which spans a qualitative range from ‘insignificant’ to ‘significant’, relative to extant Firth-wide N ecosystem processes. This differs from mussel farms in the Firth (Zeldis 2005) where effects on N dynamics were found to be insignificant at the Firth-wide scale, even for large farm harvest sizes (e.g., 21,000 t mussel harvest). While the hypothesised direction of effects for mussel farms is opposite that projected for fish farms (N depletion vs. N enrichment, respectively), the major reason for the contrast in severity of effects is that cultured mussels are not fed, whereas cultured finfish are. The trophic inefficiency of N assimilation by mussels allows N in their food (which is natural, particulate organic matter) to recycle back to the ecosystem via the fluxes described in Fig. 3, while the same trophic inefficiency of finfish (operating on added feed), causes the potentially significant discharges associated with their farming, which continuously discharges added N during the production cycle.

Approximately 85% of total farm N discharge is DIN (i.e., dissolved ammonium and urea N), which will be more bio-available to phytoplankton over short time-scales than the particulate fraction of the discharge. However, it is likely that most of the particulate N will ultimately dissolve to DIN, to add to the phytoplankton nutrient pool (although some

[2] Depending on farm layout, stocking density, and site factors, 1,000 t y^{-1} would require a total consented area of 5 to 10 ha, 3,000 t $^{-1}$ would require a total consented area of 20 to 30 ha, and 10,000 t y^{-1} would require a total consented area of 70 to 100 ha.

of this may be denitrified because of its proximity to sediments). Also, much of the riverine PON and DON will mineralise in the Firth (it must do, to sustain the Firth denitrification), so whilst being less immediately bio-available, ultimately it will become so. It is therefore meaningful to consider the total riverine N loading (i.e., riverine TN), relative to farm TN discharge.

The riverine discharges to the Firth are high by New Zealand standards. The Waikato catchment is today almost entirely cleared of native forest and invested in agriculture, causing its high nutrient effluxes in flow-volume-specific terms (i.e., 10-fold those of adjacent native-forested catchments: Close and Davies-Colley 1990, Zeldis 2005) and absolute terms (NIWA 2004, Zeldis 2005). Thus, catchment-side delivery now dominates Firth total N loading (mainly by the Waihou and Piako Rivers (Zeldis 2005; 2008). This finding, combined with the fact that oceanic source waters for the Firth (i.e. the Hauraki Gulf) are not high in DIN, means were the Firth not enriched with anthropogenic nutrients it would be quite oligotrophic among New Zealand coastal systems. Thus, present-day water quality of the Firth is significantly enriched, and its productivity is probably substantially higher than pre-historically. This has implications for why the Firth is today an area of high mussel and zooplankton (including larval fish) production (Zeldis and Francis 1998, Zeldis et al. 2005). It also raises the issue of the acceptability of further loading from finfish farming, albeit relatively small in Firth-wide terms (Table 2), in the face of current efforts to reduce catchment-side loading (e.g.,. Environment Waikato 2004).

4.2. Protection of ecosystem services: Firth vs local scales

At the Firth-wide scale, discharged N for a 2,000 t fish farm at FCR = 1.3 was about 1.1% of Firth-wide denitrification and about 2.7% of river+ocean DIN loading. Considering that the area of the Firth is about 1100 km^2, at a more local scale around the WBMFZ discharged N as percentages of these quantities will be much higher (Sowles 2005). For example, in principle, the proportions could be 10-fold higher over an area $1/10^{th}$ the Firth area, (i.e., 1100 $km^2/10$ = 110 km^2) surrounding the WBMFZ. The actual degree of this focussing of effects will depend on fish farming intensity and hydrodynamic dispersal of discharged N, and also on any functional effects that discharged N may have on the ecological rates themselves.

This conclusion is supported by the conservative tracer modelling of Area A by Oldman and Senior (2000; see also Zeldis et al. 2006), which shows the hydrodynamic dispersal of materials from a point source at Wilson Bay, and illustrates their potential area of influence. This work showed a steep, Gaussian-like increase of the concentration of modelled tracer released within the WBMFZ, as tracer measurements approached the release point (i.e., a farm). If proportional relationships between loading and chlorophyll increases are assumed (e.g. Monbet 1992), it is evident that if N additions remain local to the WBMFZ for sufficient time, there is potential for significant increases in phytoplankton.

Healthy coastal ecosystems provide extremely valuable ecosystem services by assimilating catchment runoff and by denitrifying much of this N load which otherwise can cause eutrophication (National Research Council 2000). An example where this service was stressed by excessive organic loading leading to hypoxia at the sediment surface is Chesapeake Bay. About 25% of the N entering the Chesapeake system was estimated to be denitrified (Boynton et al. 1995). In the summary of Seitzinger (1988) closer to 50% of input N was denitrified in a number of estuarine systems where hypoxia was not an important feature. The mechanism underlying this inefficiency in Chesapeake is that a good portion of annual estuarine denitrification is based on "coupled denitrification" wherein nitrification in oxic sediments provides the NO_3^- needed for denitrification. If sediments of the estuary become hypoxic from organic loading, coupled denitrification is depressed and a positive feedback on eutrophication ensues, as more N is available for recycling leading to more primary production. These conditions have led to enlarged and more extreme hypoxic zones within Chesapeake Bay (Testa et al. 2008).

In the Firth, the nutrient budget has shown that denitrification removes nearly all the new N loaded to the system, and so is a crucial ecosystem component. This observation is consistent with other findings (Zeldis unpubl. data and Giles et al. 2007) that Firth bottom waters (> 4.5 mg O_2 L^{-1}) are well oxygenated suggesting they support a healthy coupled denitrification environment. However, by the scaling argument made above, discharge of new N from fish farming could potentially rival or exceed the areal N loading local to the WBMFZ. At this local scale, if new N loading translates to increased organic supply (from new phytoplankton and from feed solids and faeces directly) sub-oxic conditions could form. This could suppress nitrification at the local scale, and thereby trigger negative feedback on denitrification (in addition to having direct adverse sub-oxic effects on the farmed fish and nearby mussel farms). On the other hand, if the scale of these effects is small relative to hydrodynamic dispersal, such feedback may not occur. Another consideration is that the natural N loading to the Firth would increase if upwelling is active over the northeast Hauraki shelf: the total flux (oceanic plus riverine minus residual) could increase by about 55% under conditions of strong upwelling (re-calculated from Zeldis 2005 in Zeldis 2007). This could bring the system closer to eutrophy and exacerbate the effects of farm loading at the local scale.

Given the uncertainties on fluxes at local scales, such possibilities need to be examined more closely. This is a strong reason to support better-resolved dynamic bio-physical modelling of the local area (see below), including oxygen dynamics and coupling with sedimentary processes. This will, in turn, require better field data on water column and benthic processes. NIWA hold considerable data on oxygen, nutrients, phytoplankton and other variables collected over a number of years near Area A and elsewhere in the Firth, which will be useful for validating such modelling.

4.3. Implications for co-culture

The considerations above indicate potential for significant increases in N local to the WBMFZ, depending on fish farm production sizes and hydrodynamic dispersal. It is therefore important to consider how such increases could be remediated. One way could be through extraction of N from the Firth by mussel harvest. The N discharged by fish production operating at FCR 1.3 and 2,000 t is about equal to that removed in the current mussel harvest (21,000 t GW; Table 3; Appendices 2 and 3). The future Firth-wide mussel harvest is uncertain but could ultimately approach 30,000 t y^{-1} (i.e., at completion of WBMFZ development (Areas A and B: about 21,000 t y^{-1} plus existing farms in Coromandel Harbour and western Firth). It appears unlikely that mussel farm development in the Firth will expand beyond this size. The N extracted in the harvest of these mussels would equal the discharge of N by about 2900 t fish production. The discharge from 5,000 t fish production equals that removed by over 55,000 t mussel harvest, which is well beyond foreseeable mussel farm development in the Firth.

There is an important point to consider with respect to the focussing of N discharge at the fish farms and the efficacy of mussel harvest in its bio-remediation. Because of the focussing, the ecological effects of fish N discharge will happen predominately at the local spatial scale (whatever scale that actually turns out to be) and only mussels growing within that perimeter will be relevant in remediation. The extent to which they are relevant will depend on their positions with respect to the actual effects (e.g., zones of excess growth phytoplankton, deposition of faeces). Again, biophysical modelling of the farm environment is required to reduce the associated uncertainties.

Considering the findings of this study that there is potential for impact on the dissolved and particulate nutrient environment local to the WBMFZ associated with commercial-scale fish farming, in addition to the mussel harvest there should be consideration of co-culture of algae and benthic deposit feeders in the Area to act in bio-remediation. Overseas, macroalgal and macrofaunal co-culture has been implemented in combination with finfish culture to capitalise on N subsidies added by finfish farming (e.g. Ahlgren 1998; Neori et al. 1996; Michio et al. 2003; Yang et al. 2005).

4.4. Conclusion

This study indicates that fish farms operating at relatively small production rates (e.g. 1000-3000 t y^{-1}) will generate N discharges that are small percentages of Firth-wide processes. However, the percentages will increase steeply at local farm scales. The extent to which this can cause deleterious effects on ecosystem services and the degree to which they are effectively offset by mussel harvest N uptake needs to be assessed. Dynamic biophysical modelling is required for this. The modelling would inject fish farm N into the local turbulent regime around the WBMFZ, while suffusing it into phytoplankton, to accurately assess its local impacts (e.g., on phytoplankton growth and oxygen dynamics) over relevant spatial scales. This modelling would include the uptake by mussels of phytoplankton production generated by N discharged by the fish and of faecal production. Other studies will need to consider the intensity and spatial extent of local-scale impacts on the benthic environment, which will inform the modelling of the water column effects.

Ultimately, to manage environmental performance of finfish farming at Wilson Bay, we should work toward forming defensible, locally applicable 'limits of acceptable change' to use in adaptive management of farm development (e.g., Turner and Felsing 2005, Zeldis et al. 2005). This should be informed by the modelling just described and by meta-analyses of known fish farm effects from other studies (e.g., Giles 2007).

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7. Appendices

7.1. Appendix 1: Stoichiometry of N fluxes and calculation of primary production

Nitrogen has major flux pathways involving denitrification and its back-reaction, N fixation:

$$(CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 94.4HNO_3 \leftrightarrow$$
$$106CO_2 + 177.2H_2O + H_3PO_4 + 55.2N_2 \quad (1)$$

Because there is no gas phase for P, it may be used to predict N fluxes, by using the Redfield relationship between N and P; that is, the non-conservative flux of dissolved inorganic P (DIP) can be considered an approximation of net N metabolism, at the scale of the ecosystem. This enables the *expected* flux of N to be predicted from DIP flux, by using the N:P composition ratios of reactive organic particles as shown in Equation 1. The deviation of the *observed* (i.e., budgeted) flux of dissolved inorganic N (DIN) from that *expected* (based on DIP flux) provides an estimate of net denitrification. In the current application the commonly found Redfield molar ratios for C:N:P of 106:16:1 were used, on the assumption that most organic matter metabolised in the system is of recycled, marine planktonic origin (Zeldis 2005; See references in main body text).

Depth-integrated primary productivity of Firth of Thames waters was determined using a depth-integrated model approach of Behrenfeld and Falkowski (1997):

$$\sum PP = P^b{}_{opt} \times f[E_0] \times DL \times C_{avg} \times Z_{eu}, \quad (2)$$

where the optimum chlorophyll-specific C fixation rate of the productivity profile, $P^b{}_{opt}$ (mg C mg chl^{-1} h^{-1}), is combined with a non-linear irradiance dependent function ($f[E_0]$, dimensionless), daylength (DL, h), average water column chl-*a* (C_{avg}) and euphotic zone depth (Z_{eu}) to calculate integrated production (ΣPP, mg C m^{-2} day^{-1}). In the present application, $P^b{}_{opt}$ data were obtained from photosynthesis-irradiance determinations (Gall et al. 1999) made on board ship during primary production experiments over 6 C-SEX voyages from spring 1999 to summer 2000 at the Firth of Thames mooring site (Fig. 1; Gall et al. 2002). The $P^b{}_{opt}$ results from spring 1999 and 2000 were averaged, as were those from summer 1999 and 2000, and these means were then averaged with the autumn and winter 2000 values, to produce an annual mean. The parameter $f[E_0]$ was taken from Behrenfeld and Falkowski (1997). C_{avg} was water-column average chl-*a* determined over water column profiles (n = 10 to 17 profiles per voyage; each profile with 2 to 6 chl-*a* values, depending on bottom depth), sampled over a grid pattern from inner to outer Firth waters in summer 2002, and autumn, winter, spring and summer 2003, as part of the C-SEX project (Broekhuizen and Zeldis 2006). Z_{eu} was the depth of penetration of light in the water column to 1% of its surface value, determined using a log-linear fitting routine to the attenuation of photosynthetically active radiation from CTD profiles (Broekhuizen and Zeldis 2006). The mean ΣPP value from the two summer voyages was averaged with the other seasonal values to calculate the annual mean ΣPP.

7.2. Appendix 2: Estimating nitrogen derived from yellowtail kingfish aquaculture

The objective here is to obtain estimates of total kingfish nitrogen (N) discharges during a commercial production cycle in Firth of Thames. This information was acquired from A. Forsythe, NIWA, by pers. comm. May 2008.

Yellowtail kingfish (*Seriola lalandi*), culture is now established in Southern Australia. Information on feed formulation and feed conversion rates have been provided by Clean Seas Tuna Ltd., Ridley Agriproducts Pty Ltd and Skretting Australia.

Protein content is determined using the Kjeldahl procedure which estimates protein by multiplying the nitrogen content by 6.25. Consequently the nitrogen content of feedstuffs with published protein contents can be accurately expressed by dividing protein by 6.25. Standard production diets for yellowtail kingfish contain 42 - 45% protein and 20% lipid. Kingfish feed therefore contains approximately 72 kg N per tonne (1000*0.45*0.16).

Current best practice (as applied to yellowtail kingfish in South Australia) results in feed conversion rate (FCR) of 1 (one kg dry feed producing one kg wet weight of fish) for animals up to one kg. A recognised technical gap in winter diet formulation and feed management results in seasonally reduced feed use efficiency. Using current feed formulas and management regimes FCR's for overwintering fish from 1 – 3 kg are approximately 1.5:1. (M. Thomson, pers. com. 2008). Using a standard salmon feed in tanks, Moran et al (in progress) conducting initial feed trials at NIWA's Bream Bay Aquaculture Park have demonstrated an FCR of 1.3 for the weight interval 0.55 – 1.2 kg.

Applying current best practices and based on a mean harvest weight of 3 kg an FCR of 1.3 is forecast, but scenarios using FCR = 1.5 are also used in the present study because it lies within the range of FCR experienced. Further improvements as noted in other species such as Atlantic salmon can be anticipated. Gillibrand et al. (2002) reported that mean FCR for salmon in Scotland was 1.17. Subsequent advances have been reported by commercial producers.

Nitrogen content of of *Seriola lalandi* is estimated from data for the Japanese yellowtail *Seriola quinqueradiata* (Ramseyer 2002): 3 kg fish had N content of 3.34%. Using a Kingfish farm production model (A. Forsythe, NIWA, pers.comm. June 2008) with FCR = 1.3, feed N level of 7.2% and fish N content of 3.34%, 60.2 kg N (dissolved + particulate) will be discharged to the marine environment per tonne of fish produced. The value for FCR = 1.5 is 74.6 kg N t^{-1}.

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7.3. Appendix 3: Estimating the N content of mussels

The objective here was to obtain a best estimate of the nitrogen (N) content of whole freshly harvested mussels (i.e., green weight: GW), to enable comparison of kingfish farm N discharges with N removals through mussel harvests. This information was acquired largely from J. Ren and A. Forsythe, NIWA, by pers. comm. April-May 2008.

This parameter was estimated using two semi-independent methods.

Ren/Zeldis method

Mussel meat N:GW was estimated as the proportions: meat N to meat C (0.21 w:w) and C to meat DW (0.40 w:w) (Smaal and Vonck 1997). Meat DW to GW (0.057: Key 2001) was then used to estimate meat N as a proportion of GW (0.0048). The proportion N in the shell (0.0021 w:w) was calculated using data for N to carbon ratio for the horse mussel *Atrina novaezelandica* (M.Gibbs NIWA pers comm. May 2005), and using shell weight:GW proportions from analyses by Ren, Hayden and James (Zeldis 2005). This was added to the proportion for meat N:GW to estimate proportion of total N in mussel GW.

Forsythe method

Mussel meat N:GW was estimated as the proportions cooked meat weight to cooked half-shell product weight (0.55: Food Service Fact Sheet 1). This was scaled to account for the other valve to yield cooked meat yield to whole cooked mussel (0.38). N in protein (0.16 w:w:) literature value), and protein to cooked meat weight (0.12: Food Service Fact Sheet 3) were then applied to yield N per unit cooked whole-shell weight (0.0073). This was scaled using a Sealord Shellfisheries-acquired dataset (J. Wilson, Sealord pers comm. April 2006 to J. Zeldis) which allows conversion of whole-shell cooked weight to GW (0.67). The proportion N in the shell (estimated in the Ren/Zeldis method) is added, to estimate proportion of total N in mussel GW.

These two methods produced identical estimates: 5.9 kg N per tonne GW of harvested mussels.

References:

Food Service Fact Sheet No 1 *[14/02/2006]* NZ Greenshell fact sheets (IQF half shell focus) http://www.nzmic.co.nz/Assets/Content/Publications/nzmic%20nz%20factsheeno1.pdf

Food Service Fact Sheet No 3 *[14/02/2006]* NZ Greenshell fact sheets (IQF half shell focus) http://www.nzmic.co.nz/Assets/Content/Publications/us%20factsheetno3.pdf

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http://www.ew.govt.nz/publications/technicalreports/tr0530.htm

7.4. Appendix 4: Accuracy and precision

The annually averaged primary productivity value (p = 168 g C m^{-2} y^{-1}) assessed from the seasonal surveys across the Firth of Thames is well within a range of typical productivity values for temperate estuaries (Boynton et al. 1982; see references in main body text). To estimate precision, Zeldis (2005) employed a bootstrapping approach to propagate errors of terms in the primary production estimate used in this report. The coefficient of variation (CV) of ΣPP (Eqn. 2) was estimated as 0.28.

For the elements of the LOICZ budget, it is noted that gross Firth respiration (r: 48 mmol C m^{-2} d^{-1}) was within the range for a number of European estuaries documented by Frankignoulle et al. (1998), while net metabolism (p-r = -11 mmol C m^{-2} d^{-1}) was near the mean of heterotrophic cases within the distribution of 70 LOICZ metabolic estimates obtained from budgets made around the world (compiled by Buddemeier et al. 2002). The denitrification estimate (1.9 mmol N m^{-2} d^{-1}) was also near the mean of estimates from the 70 budgets tabulated by Buddemeier et al. (2002) and the mean of the summary of Seitzinger (1988) for 12 shelf and estuarine studies (1.8 mmol m^{-2} d^{-1}), as well as the modelled estimate of Firth denitrification made by Giles (2001), predicted using organic loading data from Firth benthic biogeochemical field surveys of Nodder et al. (2000; note, however, that no field experimental estimates of denitrification have been obtained for the Firth, to date). The precision of budgetary estimates was estimated using a similar ‘bootstrap’ approach as used above (see Zeldis 2005). CV on river gauging of nutrient concentrations was considered about 9% and CV on budgeted denitrification was estimated as 24%.

Overall, the production and denitrification values obtained appear reasonable in context of similar estimates made elsewhere (both with and without the same methods), while the error rate on the estimates appears to be about 30% or less. Estimates of accuracy and precision of feed N discharged are unavailable, but a reasonable assumption could be that they are known with a CV of 30% or less.