FRDC Project 97/212

Quantifying and Predicting the Impact of Prawn Effluent on the Assimilative Capacity of Coastal Waterways

and

Aquaculture CRC Ltd Project E1

Pond and Effluent Management

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FRDC Objectives

1. Quantify the assimilative capacity of the receiving environment for the major nutrients and sediments in prawn farm effluent by describing the dynamics of C, N, O, P pathways in the substrate and water column of discharge creeks, and thereby determine the environmental impact of prawn farm effluent.
2. Refine and extend existing hydrodynamic models of the Hinchinbrook and Port Douglas estuaries in order to predict the behaviour of prawn farm effluent entering coastal waterways, thus enabling simulation modelling of the carrying capacity of the environment for prawn farming.

Aquaculture CRC Objective:

3. Determine the fate and nutrient processing of effluent in receiving environments.

Outcomes Achieved

The results of this project have improved our understanding and predictive capacity regarding the dilution and flushing of prawn farm effluent in mangrove tidal creeks (hydrodynamic models). This should benefit both industry and regulatory planning when considering alterations to existing farms and assessing new farm proposals. Our estimates of the nutrient budgets (nutrient pathways) and the capacity of tidal mangrove creeks to assimilate prawn farm effluent (assimilative capacity) provide benchmark levels for use in the sustainable development of the industry.
We demonstrated that biological processes within the water column of mangrove creeks provide mechanisms for the "repackaging" of farm derived particulate material into live zooplankton between the farm discharge and the coastal waters. Once repackaged as zooplankton, a wide range of larger grazers, including fish, can incorporate material in prawn farm effluent. Our work demonstrates some of the rates and pathways whereby farm effluent can be incorporated into the complex coastal food webs which support multi-million dollar commercial and recreational fisheries.

1. Hydrodynamic models

Field data improved and extended our knowledge about the behaviour of water in tidally influenced mangrove creeks. Computer predictions (models) were generated on

the fate of prawn farm effluent in these creeks. Video simulations show creek flushing characteristics under a variety of scenarios of tide, pond loading and discharge volume. These models suggest that more nutrients and sediments move downstream during spring tides or periods of high discharge during harvesting of the ponds. Excess nutrients and sediment not assimilated in the upper reaches of some creeks are transported to the lower reaches or coastal ocean. The assimilative capacity of the creek was exceeded in Muddy Creek during the later stages of the prawn farming cycle, when farm discharges of nutrients and sediments were highest. No excess nutrients or sediments moved beyond the upper reaches of Muddy Creek during the early stages of the prawn farm cycle, when farm discharges were small or zero.

2. Nutrient pathways

(a) Sediment and water column processes

Nutrients in prawn farm effluent were found to be predominantly in particulate form (80-90% for nitrogen (N), 60-80% for phosphorus (P), 50-70% for carbon (C). Through biological and physical interactions, these particulate nutrients had high settling velocities that allowed significant quantities to settle out during periods of low currents (neap tides and slack water). We investigated the effects of this particulate material on the flux of C and N between the water column and the sediments of discharge and non-discharge creeks, during wet and dry seasons. There was limited capacity for nitrogen loss to the atmosphere through denitrification, high benthic respiration rates, very low photosynthesis, and low uptake of dissolved organic carbon in the creeks. At the landward end of the discharge creek, the bulk of the pond derived material either accumulates on the creek bottom or is transported seawards, with little material being assimilated *via* sediment nutrient processes. There was evidence that sediments accumulated during low current periods were resuspended during stronger flows and subsequently transported further downstream.

(b) Pelagic processes

Primary production and bacterial growth rates were very high in discharge creeks during discharge periods. Zooplankton grazing rates were much higher during discharge periods; these high rates declined seawards. Potentially all daily primary production (algal growth) may be consumed within the creek by zooplankton, while up to one half the standing stocks of algae and bacteria could be consumed each day. These rates indicate a large capacity for consumption of the algae and bacteria discharged by the prawn farm or stimulated by extra nutrients in the creek waters. The removal rate (grazing) of this extra production within the upper reaches of some creeks appears to exceed the rate of supply from the prawn farm. However, further downstream, grazing and production are in balance. The zooplankton are potential food items for a wide variety of juvenile fish that were detected in large numbers in the discharge creek. Nutrients are therefore likely to be transferred through the food chain via primary production, bacterial growth, grazing by zooplankton, and possibly by juvenile fish. Preliminary work revealed that during discharge periods in Muddy Creek,

there were highly abundant juvenile fish populations, including groups adapted for feeding on zooplankton. This estuarine food chain provides a possible mechanism for farm derived nutrients to enter, and move through the coastal environment.

3. Assimilative capacity

Preliminary estimates of the assimilative ability of a mangrove lined creeks to accommodate prawn farm discharge were based on field measurements of nutrient processes within the upstream waters (water column, pelagic communities and sediments). All rates of removal of C and N from the system by benthic and water column nutrient processes were exceeded by the rate of supply from the prawn farm. High sedimentation rates combined with rapid burial to prevent the release of C from the system. Supply exceeded turnover in most steps of the C budget in Muddy Creek as indicated by the following:

- most of the C input from the farm is buried in creek sediments rather than mineralised
- this rate of C supply exceeds sediment respiration rates
- primary production is much higher in discharge creeks
- high primary production rates are exceeded by even higher rates of respiration,
- despite these high respiration rates, only a small percentage of the C supply from the farm is respired
- C supply from the farm greatly exceeds the removal rate via photosynthesis
- C moves out of the upper section into the middle reaches of Muddy Creek.

The rates of N transformation processes also represent a small fraction of the rate of the farm supply. The oversupply of N was highlighted by:

- primary production which consumes less than 10% of the farm supply of N
- loss of N to the atmosphere by denitrification accounts for less than 10% of the farm supply
- N moves out of the upper section into the middle reaches of Muddy Creek.

Despite the assimilative capacity of the upper reaches of the discharge creeks being exceeded during harvesting periods, farm effluent did not appear to result in eutrophication due to a variety of mechanisms. These are a combination of physical and biological processes operating within the creek waters and include:

- rapid settling of nutrient rich particulates within the forest and creeks,
- effective flushing and scouring of sediments during spring tides and/or wet season run-off,
- grazing of excess primary production by zooplankton,
- consumption of particulates and zooplankton by mobile fish populations,
- intermittent, seasonal discharges which allow "fallowing" of the estuary.

Introduction

Background

Prawn farming in Australia currently produces around 2,000 tonnes of product with a farm gate value around $AUS 32 million (Lobegeiger 1999). It remains one of the fastest growing sectors of all Australian aquaculture products and has been projected to become second in value at $150 million by 2004-05 (ABARE data). One of the major impediments to current operations and indeed, the future growth of the industry, is a poor environmental image and the inconsistent and costly monitoring requirements required by relevant state and federal licensing authorities (Australian Prawn Farmers' Association (APFA) 1996 Environmental Workshop, July 1996).

Concerns have been raised regarding the impacts of the overseas prawn farming industry that has experienced a rapid expansion in recent years. Conflicts over resource use such as declining traditional fisheries, mangrove destruction, groundwater use, and salinisation of agricultural soils have contributed to issues of social conflict in many prawn farming nations (Primavera 1998). Eutrophication of coastal waters, alteration of tidal dynamics and acid sulphate soil runoff have also been experienced where poor coastal planning and regulation exist. These problems are often inferred as applying to the Australian industry. Environmental issues were rated as the top priority for funding in the Australian Pawn Farming Industry Research and Development Plan (Macarthur Consulting Pty Ltd 1995). Although this environmental priority has since given way to increased concerns over security of larval supply and disease prevention (National Prawn Farming Environmental Management Workshop, 24-25 May, 2000, Brisbane), satisfying public and governmental concerns over environmental impacts remains a major issue. A notable lack of knowledge of the impacts of Australian prawn farming practices on Australian environments was a constant theme in the discussions at workshops and conferences mentioned above.

One project which addressed the issue of documenting local farming impacts on local environments was the collaborative project between Mossman Central Mill Co Ltd, Sea Ranch Pty Ltd and AIMS carried out at Port Douglas, north Queensland (November 1993 - November 1996). This project compiled a unique data set on the behaviour of prawn farm effluent in tropical Australian waterways and adjacent mangrove forests (Trott and Alongi 1999, 2000). The ability to extend that research into investigations on the assimilative capacity of discharge creeks was made possible by joint funding from the Aquaculture Cooperative Research Centre Ltd (CRC), the Fisheries Research and Development Corporation (FRDC) and an environmental research levy paid by the Australian Prawn Farmers' Association (APFA). The project was co-ordinated through an existing Aquaculture CRC project "Pond and Effluent Management" (Preston *et al.* 2001a) which capitalised on the expertise of staff from the Commonwealth Scientific

and Industrial Research Organisation (CSIRO) and the University of Queensland (UQ). These research partners focused on both established and novel bio-indicators of prawn farm effluent in coastal biota. The research covered three main areas: pond management, effluent management, and impacts of effluent on coastal waters. The pond management component is described in the CRC for Aquaculture Final Report (Preston et al. 2001a), effluent management is described in the FRDC Project 95/162 Final Report (Preston et al. 2001b). The impacts on coastal waters is described in this report (AIMS component) and the UQ component is in the CRC for Aquaculture Final Report (Preston et al. 2001a). The research addressed in this coordinated study is unprecedented in the range of techniques focussed on the issue of the I impact of prawn farm management techniques and effluent on receiving waters.

Through the Aquaculture CRC, the research partners consulted widely with stakeholders via the Aquaculture CRC Discussion Paper "The environmental impacts of waste waters discharged from prawn farms, a coordinated program" which was formulated through extensive discussions with industry, researchers, and government regulators. This joint approach provided access to the expertise and resources of the major research groups (AIMS, CSIRO, UQ) working towards a sustainable future for the prawn farming industry.

The fate, processing and assimilation of prawn farm effluent by the water column and substrate in the upper ends of tidal creeks are critical environmental functions with strong potential for use as indicators of the impact of water borne nutrients. Results from the Sea Ranch project (1993-1996) showed that these mangrove environments are capable of assimilating a substantial load of prawn farm nutrients and sediment, but the capacity of these systems to remove or assimilate effluent for the longer term was unclear. The Sea Ranch results (Trott and Alongi 2000) noted that these mangrove forest floors were flooded for less than 15% of the monthly tidal cycle, and in the first 2 years of discharge were unaffected by prawn farm effluent. The prawn farm discharge and incoming tidal waters are contained within the creek profile during all other phases of tides. Therefore, we concentrated our research on the assimilative nutrient processes within the creeks and not within the forests. These assimilative nutrient processes are common to large areas of the tropics and temperate regions, not only where prawn farms are located. Therefore, increased understanding of the mechanisms involved in assimilating nutrient and sediment rich effluent should improve our ability to detect, and hopefully ameliorate, other forms of coastal impacts.

This report describes AIMS research on three areas of potential impact of prawn farm effluent in tidal, mangrove lined creeks in north Queensland.

1. In hydrodynamic studies we focussed on tidal flushing and mixing of prawn farm discharge water with incoming tidal waters. Full tidal cycles were studied where net movement of water, sediment and dissolved and particulate nutrients were measured in and out of these tidally influenced creeks. These processes have been incorporated in a proven mathematical model established at AIMS for use in

modelling and visualising complex circulation patterns in mangrove and coral reef areas. Computer visualisation has the advantage of enabling interaction between oceanographers, biologists and coastal resource managers through simulation exercises with graphical displays, while manipulating parameters such as farm size, water exchange rates and nutrient loads.

2. In studies on nutrient pathways in the water column and sediment we investigated the ability of these assimilative processes to consume, recycle or release prawn farm effluent. Prawn farm effluent nutrients are predominantly in particulate form with high settling velocities that allow the particulate C, N and P to settle out during periods of low water velocity (slack water and neap tides). We investigated the effects of this material on the fluxes of dissolved inorganic and organic nitrogen (NH_4^+, NO_2^-, NO_3^-, DON), dissolved inorganic and organic carbon, (DOC, alkalinity, O_2 consumption), dissolved inorganic and organic phosphorus (PO_4^{3-}, DOP), primary production/respiration (O_2 production/consumption) and denitrification (N_2 loss). The assimilative capacity of the creeks were estimated by calculating the total annual inputs and outputs of sediments and nutrients in the study areas and constructing a nutrient budget for C and N.

3. In pelagic studies we focused on the trophodynamics of the mangrove lined creeks adjacent to prawn farms. There is some understanding of the nutrient composition, bacterial and primary production and standing stocks of prawn ponds (Moriarty 1986, Alongi 1992, Burford 1997), however, the behaviour of this nutrient rich, thriving microbial soup after it enters receiving waters is less well understood (O'Donohue and Dennison 1997, Trott and Alongi 2000). Our goal was to document the microbial and zooplankton populations and their capacity to consume and transform the prawn farm wastes within the mangrove creeks.

This research has great potential in the protection of mangrove and other coastal ecosystems that are significant areas of Australian fish and shellfish habitats (Robertson and Blaber 1992). There is also potential for this type of research to quantify the impact of other activities which have nutrient and sediment inputs to the coastal zone (eg agriculture, urban development) which are currently of great concern to the wider Australian community. It is hoped that the scientific information and recommendations arising from this project are incorporated into the debate on the impacts of aquaculture by the fledgling Australian prawn farming industry, the environmental regulators, and the concerned public.

Need

Our research proposal responded to the recommendations of several industry and government meetings on environmental issues in prawn farming, and the canvassing for environmental impact research proposals from the APFA in their "Call for Research 1997". The need for the research described in this proposal was also identified in two major

reports instigated by the FRDC, ie The Macarthur Report (1995), and The Queensland Fisheries Research and Development Strategy (1995-2005). These documents identified that:

a) "The industry and the key researchers do not yet fully know the effect of nutrient and suspended solids on specific coastal ecosystems and hence are unable to estimate sustainable loads." and
b) recommended a strategy to "Assess the relative impacts of different Aquaculture methods on the environment." and "Provide a scientific basis for the objective evaluation of sustainable fisheries and Aquaculture management options."

The collaborative studies already completed (Aquaculture CRC E.1 Project and FRDC Project 95/162: *Prawn farm effluent: composition, origin and treatment* by N. Preston, C. Jackson, P. Thompson, M. Austin and M. Burford) provide a strong link between the quantity and quality of effluent produced under different farming methods. The research carried out by AIMS contributes information required to estimate sustainable loads of nutrients and suspended sediments in coastal ecosystems, provides a scientific basis for the evaluation of aquaculture management options, and assists in the development of sustainability indicators for aquaculture. As the Western Australian and Northern Territory prawn farming industries are expected to expand, this research will also provide useful information to industry and government agencies in those states. This research contributes to the sustainability of not just the prawn farming industry, but also the highly valuable commercial and recreational fisheries resources within in Queensland, currently valued at above $200 million annually, as well as the health of the coastal water resources, upon which they all depend.

Objectives

FRDC Objectives

Quantify the assimilative capacity of the receiving environment for the major nutrients and sediments in prawn farm effluent by describing the dynamics of C, N, O, and P pathways in the substrate and water column of discharge channels and creeks, and thereby determine the environmental impact of prawn farm effluent.

Refine and extend existing hydrodynamic models of the Hinchinbrook Channel and Port Douglas estuaries in order to predict the behaviour of prawn farm effluent entering coastal waterways, thus enabling simulation modelling of the carrying capacity of the environment for prawn farming.

Aquaculture CRC Objectives

Determine the fate and nutrient processing of effluent in receiving environments.

Study Area

The two study areas in north Queensland, Australia, are characterised by tidally-dominated mangrove creeks (Table 1, Figures 1 and 2) that receive lower freshwater input in the dry season extending from May to November (260 mm average) than in the monsoonal wet seasons from December to April (1,370 mm average) (Figure 3). The main study area at Sea Ranch (Figure 1), near Port Douglas, consists of a narrow catchment (2-4km wide), 40 km coastal strip, fringed by mangroves on the northern side, a steep, 300 m high forested range to the South, and by the Daintree River to the West. Between the towns of Port Douglas and Daintree, the coastal strip has been extensively cleared for agriculture, predominantly sugar cane production. Packers Creek and Muddy Creek are the largest creeks in the region, while significant areas of mangrove forest are also drained by Sandfly Creek and Control Creek (Figure 1). Muddy Creek is 6 km long and receives the discharge from 13.5 ha. of ponds from an adjacent shrimp farm. Sandfly Creek does not receive any effluent because, due to an area of salt flats at the inland upper reaches, it is not directly connected to the catchment of the coastal strip. Both creeks are shallow, seldom deeper than 1-2 m in depth at low tide. Previous hydrological surveys in the region indicate that the lower reaches of the major creeks are flushed efficiently by tidal action, but significant water trapping occurs in the upper reaches of some creeks (Wolanski *et al.* 1992). During the wet season, less saline water is trapped in the upper reaches for 10-40 days. During the dry season, water may reside in the upper reaches of creeks for between 5-15 days.

The Sea Ranch study region has extensive high-intertidal saltpan, salt marshes, and mangrove forests. There are two major types of mangrove forest in the area; mixed *Rhizophora-Bruguiera* forests in the mid-intertidal zone and *Ceriops* forests in the high-intertidal areas. Stranded beach ridges occur throughout the region supporting mainly *Acacia-Melaleuca* woodlands. The study area is within a 3 km x 4 km section of mangrove forest immediately to the West of Port Douglas. (Figure 1). Semi-diurnal tides prevail with a 2.6 m. mean higher high water (MHHW) and 0.6 m. mean lower low water (MLLW) with a 1.6 m. mean sea level (MSL).

Table 1. Physical descriptions of Muddy Creek and Pig Creek

MUDDY CREEK		PIG CREEK	
Length	6,904m	Length	2,228 m
M1-M2	1,308 m	Pig 2-Pig 4	966 m
Surface Area	100,000 m^2	Surface Area	34,050 m^2
M1-M2	9,930 m^2	Pig 2-Pig 4	12,996 m^2
Tidal exchange	10^7 $m^3.yr^{-1}$	Tidal exchange	10^7 $m^3.yr^{-1}$
Tidal range	0.0-3.0 m	Tidal Range	0.1-3.5 m

Figure 1. Sea Ranch ponds and sampling location map.

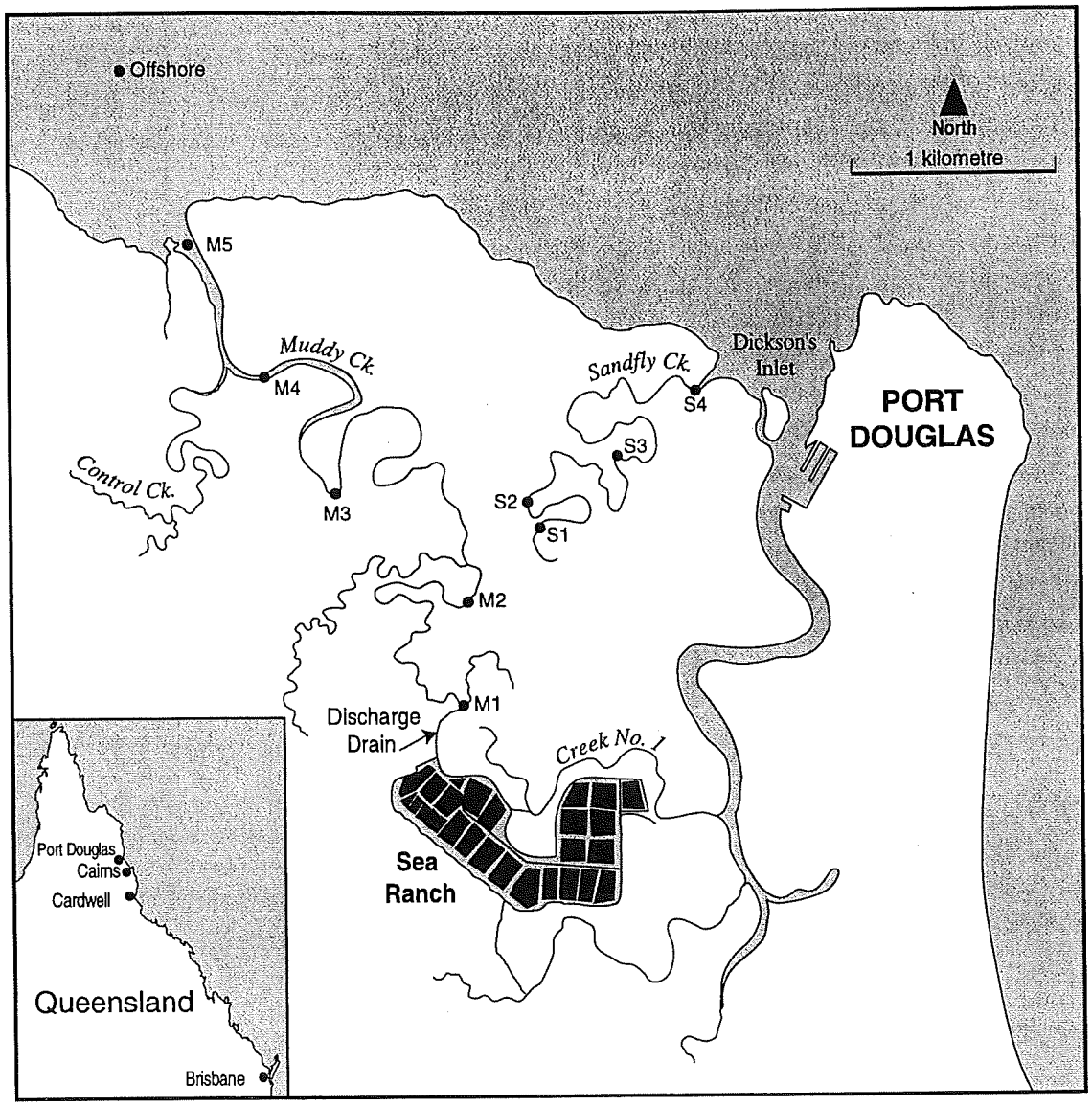
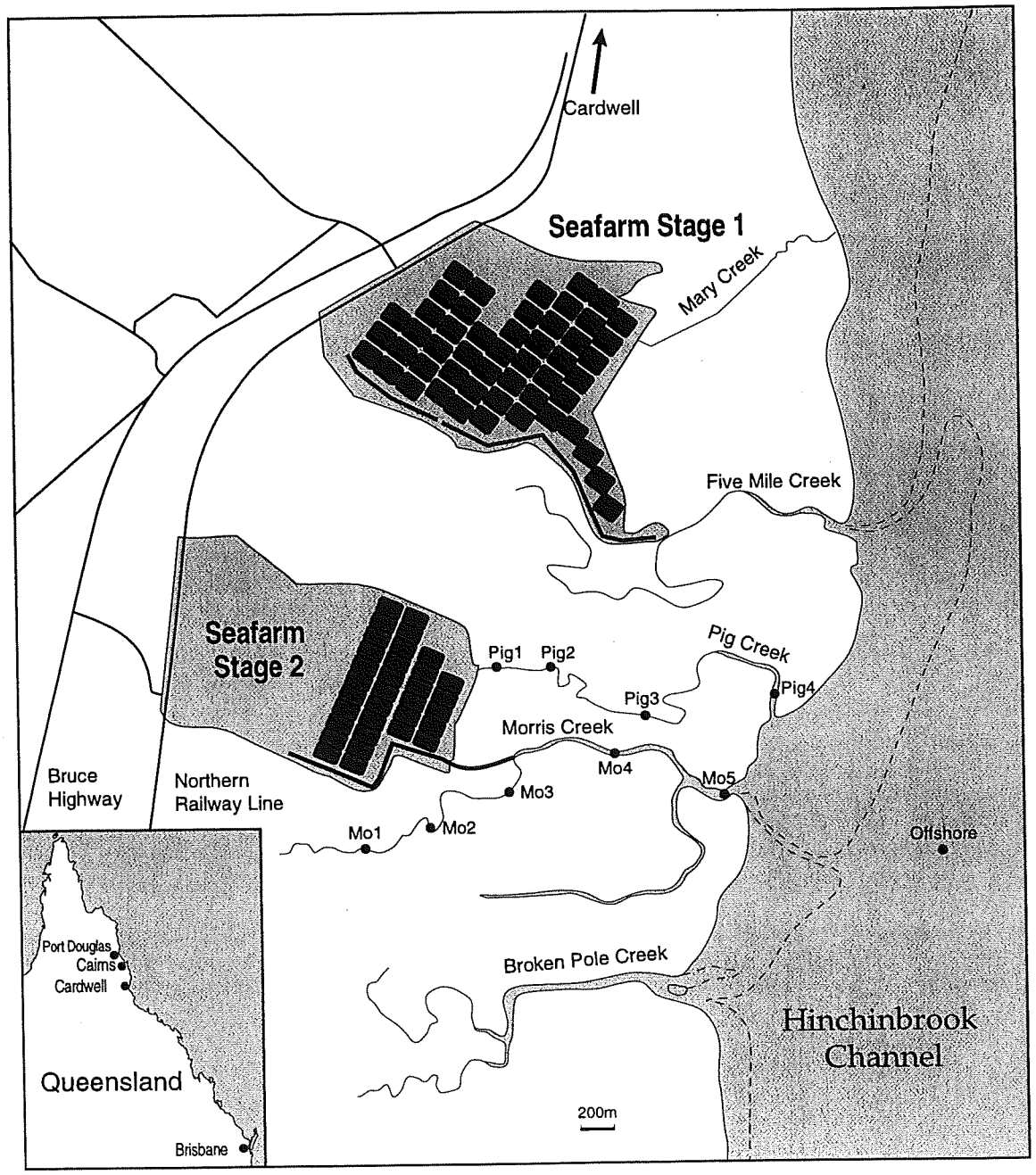


Figure 2. Seafarm ponds and sampling location map.



Farm Operations

Sea Ranch Pty Ltd is the only prawn farm within the catchment area. This 28.8 ha farm currently discharges effluent from a portion (13.5 ha) of the semi-intensive shrimp ponds into the adjacent Muddy Creek. This creek also receives occasional run-off from sugar cane farms in the catchment (Figure 1). Pond stocking densities of *Penaeus monodon* averaged 25-35/m^2 in 1-1.5 ha ponds, 1.5-2.0 crops/year were achieved delivering around 5 t/ha from a food conversion ratio (FCR) of 1.5-1.8 during successful cropping cycles, but delivering an overall average of 2.3.

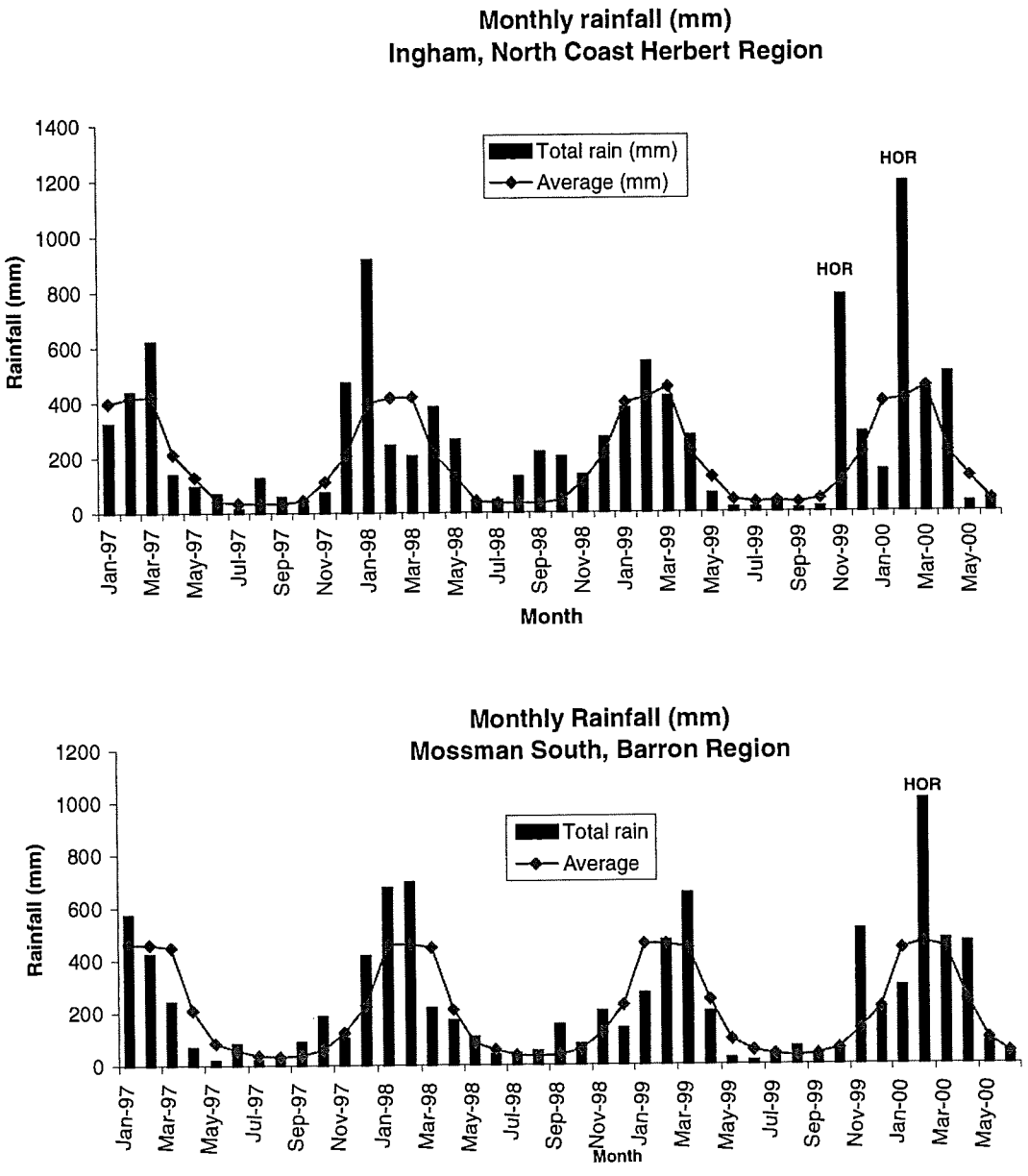
Commercially available pelleted feed for *P. monodon* (Australian and imported) was used throughout the period of this study. Protein content of the feeds ranged from 30-42% (moist weight). Water exchanges from ponds varied according to the stage of the cropping cycle ranging from 0% in the first month up to 30% volume per week during the final growth stages and harvesting. The peak discharge volume at Sea Ranch (729,000 m^3 per month) was reached during December1997.

The climate in the Port Douglas area has a winter dry season (average rainfall = 260 mm), and a summer wet season (average = 1,370 mm), with an average annual rainfall of 2,223 mm (Bureau of Meteorology)(Figure 3).

Seafarm Pty Ltd is currently one of the largest prawn farms in Australia. Seafarm is run on similar principles and stocking densities to Sea Ranch. Approximately 70 ha of ponds are in Stage 1 and 30 ha of ponds are in Stage 2. Stage 1 and Stage 2 have separate intake and discharge creeks. A component of this project was carried out in Stage 2 intake creek (Morris Creek) and discharge creek (Pig Creek). The farm is located 5 km South of Cardwell, adjacent to the Hinchinbrook Channel (Figure 2). The Channel separates the mainland from Hinchinbrook Island by less than 1 km for over half its length. Hinchinbrook Channel is a 44 km long tidal channel dominated by extensive mangrove forests and tidal mud flats. Tides in the channel are semi-diurnal with a range of 2 m.

The climate in the Cardwell area is similar to that of Port Douglas with a winter dry season (average rainfall = 153 mm), and a summer wet season (average = 954 mm), with an average annual rainfall of 1,969 mm (Bureau of Meteorology) (Figure 3).

Figure 3. Observed and long-term average monthly rainfall (mm) at stations near Sea Ranch and Seafarm. HOR = Highest rainfall on record for that month.



Hydrodynamics and tidal fluxes

Methods

MATHEMATICAL MODEL

Field and model studies were carried out on the flushing and processing of shrimp pond effluent in Muddy Creek, a mangrove-fringed tidal creek near Port Douglas, and Pig Creek near Cardwell, Australia. This report will focus on the results from Muddy Creek at Sea Ranch.

Flushing is slow in Muddy Creek, a 6 km long mangrove creek, with a residence time varying between 4 days at spring tides and 10-15 days at neap tides. Since spring and neap tides alternate at 7 days intervals, the system is never at equilibrium. A quantitative estimate of the physical and biological processes of nutrients and suspended sediments in the creek was made possible by comparing their discharge from the farm (Station M1, Figure1) with their net, tidal-averaged discharge in the creek at a point 1.3 km downstream (Station M2, Figure1). Intensive field studies were carried out over entire tidal cycles on (See Table 2).

Table 2. Trip codes, dates of field trips and associated information for field trips where tidal cycles of nutrients were investigated.

Trip Code	Date	Tide	Season	Discharge
SEA RANCH				
CA	August '97	spring	dry	yes
CC	December '97	neap	wet	yes
CD	March '98	spring	wet	no
CF	July '98	neap	dry	yes
CG	November '99	spring	wet	yes
SEAFARM				
CB	October '97	spring	dry	yes
CH	September '98	spring	dry	yes
CI	October '98	spring	dry	yes

These periods were selected because there was no diurnal asymmetry in the tides, ie the two successive high tide elevations were the same. Sampling was carried out at sites M2 at hourly intervals and occasionally at M1, starting at slack high tide and finishing at slack high tide. During these intensive field studies the creek was sampled for dissolved inorganic and organic N and P (NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, DON, DOP), dissolved organic C (DOC), particulate C (PC), N (PN) and P (PP), chlorophyll a (Chl *a*) and total suspended sediment (TSS) concentrations. These parameters were also sampled along a channel transect during ebb tide intervals of these tidal cycles. These

parameters were also sampled along a channel transect in neighbouring non-discharge creeks at both Sea Ranch and Seafarm.

Bathymetric data. Muddy Creek was surveyed for bed elevation and width of twelve cross-sections of the tidal channel. A number of spot measurements of elevation of the substrate in the swamp including mangroves and salt flats were also made.

Hydrodynamic data. Water velocity data was obtained at 10 minute intervals using an InterOcean S4 current meter and a Unitech current meter deployed at mid-depth (mean depth ≈ 2 m) at Stations M2 and M1 respectively. Data collection was carried out over an entire tidal cycle of approximately 13 hours duration

Hydrodynamic model. The creek-mangrove swamp hydrodynamic model of Wolanski *et al.* (1980) was used for Muddy Creek. The model solves the two-dimensional, depth-averaged momentum and continuity equations around a lattice of cells. The model is forced by the sea level (the tides) at the mouth and by the farm water discharge upstream, there being no other freshwater discharge in the system in the dry season. Bottom friction is parameterised using a Manning friction parameter.

Using the bed level data obtained from the bathymetric surveys the tidal creek – mangrove swamp system of Muddy Creek was divided into 104 cells. These cells have arbitrary shapes and sizes and are chosen to fit the contour of the terrain. The only independent parameter, the bottom friction coefficient, was selected to ensure a good fit between observed and predicted tidal heights and currents at Stations M1 and M2 respectively. The results from the hydrodynamic model were then visualised using OpenDX [formerly Data Explorer] (Galloway *et al.* 1995).

Tidally-averaged fluxes. The calibrated hydrodynamic model was used to calculate the net, tidally-averaged fluxes in Muddy Creek at Stations M1 (the shrimp farm outflow canal) and M2 (1.3 km downstream from M1). This allowed a mass balance calculation for this 1.3 km stretch of mangrove creek. The model predictions were used to calculate the flow rate ($m^3 s^{-1}$) at 10 minute intervals at Station M2. This was necessary because the velocity (< 0.05 m s^{-1}) was often too small to be accurately measured by the current meter. Therefore, the flow rate at Station M2 was determined by the model in calculations of the net flux of water.

The flow rate data was combined with the nutrient and suspended solid concentration data, interpolated at 10 minute intervals, and used to calculate the fluxes of components at 10 mine intervals at Station M2. The tidally-averaged flux, ie the net flux from slack high tide to slack high tide, was then calculated as the time integral of the fluxes at 10 minute intervals. Because successive high tide elevations were the same during the field study, there was no net change in the volume of water in the creek. The load of nutrients and suspended solids entering the creek at Station M1

(discharge from the shrimp farm) was calculated from the product of the shrimp pond discharge and the concentration of each component as measured at Station M1.

WATER QUALITY

We measured temperature and salinity using a Seabird CTD, dissolved oxygen concentration using a YSI O_2 meter and a Hydrolab Datasonde 3 datalogger , and pH using a Metrohm or Hanna pH meter. Total suspended solids were estimated using a calibrated nephelometer attached to the CTD and with 2 self-logging nephelometers immersed at Stations M1 and M2 (Figure 1) which were calibrated in-situ. At Stations M1 and M2, three replicate samples were taken and analysed for dissolved inorganic and organic nitrogen and phosphorus (Ryle *et al.* 1981, Ryle and Wellington 1982), dissolved organic carbon (Robertson *et al.* 1998), total suspended solids (modified version AS 3550.4-1990), chlorophyll *a* (Strickland and Parsons 1972), particulate phosphorus (Thompson and Walsh 1989) and nitrogen (Robertson *et al.* 1998). Briefly, the methods used for nutrient and sediment analysis were as follows. Two sets of triplicate samples were collected from sub-surface creek waters (0.3 m below surface) using sterile plastic syringes: one set for dissolved inorganic (NH_4^+, NO_2^- + NO_3^-, PO_4^{3-}) and the other set for dissolved organic nitrogen and phosphorus. Samples were filtered (0.45 um cellulose acetate filters) with acid-washed 50 ml disposable syringes into acid-washed test tubes and maintained on ice for up to 6 hr before being frozen. Dissolved inorganic nutrient concentrations were determined using standard automated techniques as described in Ryle *et al.* (1981) and Ryle and Wellington (1982). DON and DOP concentrations were determined on the other set of samples following 16 hr digestion in a LaJolla UV photo-oxidation apparatus. Pre-digested N concentrations were subtracted from the post-digested NO_3^- levels to derive the DON concentrations. Similarly, DOP concentrations were determined by difference between pre- and post-oxidized PO_4^{3-} concentrations. Analytical precision was 1% for P and 1.5 % for N values.

Triplicate samples for chlorophyll a analysis were collected from sub-surface waters using distilled water washed 500 ml polypropylene bottles, and stored on ice in the dark for a maximum of 6 hrs before filtering. 50 ml of sample was filtered through a 25 mm Whatman GF/F filter on a vacuum manifold or with a 50 ml disposable syringe. Filters were stored frozen in foil until analysis. Filters were added to a 90% acetone/double distilled water mixture and were processed by homogenising in a motorised teflon and glass mortar and pestle. The pigment extract was analysed for chlorophyll *a* on a Turner Instruments AU100 fluorometer.

Estimates of TSS were obtained by filtering 150-300 ml of sub-surface waters through pre-dried, weighed 0.45 µm cellulose acetate filters. Filters plus solids were dried to constant weight at 60°C, and the dry weight of solids obtained by subtraction (modified version of Australian Standard 1990). These filters were subsequently analysed for particulate phosphorus on a Varian Liberty 220 ICP-AES (Thompson and Walsh

1989). Microphotographs of the suspended solids were also obtained *in situ*, and these were digitised for estimation of the 2 dimensional surface areas using the technique of Wolanski and Gibbs (1995). The results from the study of flocculation of suspended solids were reported in Wolanski *et al.* (2000).

Estimates of particulate carbon and nitrogen were made from filtering 150-300 ml of sub-surface waters through pre-combusted and weighed Whatman GF/C glass fibre filters. The filters were dried to a constant weight at 60°C, and the dry weight of solids obtained by subtraction. These filters were subsequently analysed for C and N content on an Antek analyser.

Results and Discussion

MODEL VISUALISATION AND PREDICTIONS

Field data was incorporated into models of water circulation in Pig Creek at Seafarm, and Muddy Creek at Sea Ranch. A single frame from a computer visualisation of spring tide water flow in Muddy Creek is shown in Figures 4a and 4b. The black arrows indicate direction and velocity of the water flow, while the colour contours (depicted in the legend) represent the depth of water. The farm discharge is located at the bottom left of the frame. At the top right of each frame is the creek mouth where water flows in from the ocean. This appears as a blue line in Figure 4a, where an ebb tide has already left the mouth of the creek and tidal elevations are low (represented by blue). The tidal water has still to drain from the upper reaches of the creek where tidal heights are higher (represented by yellow). The tide has receded from the upper creek forest floor in Figure 4b and is contained in the creek bed, however the tide has turned at lower reaches of the creek and the flood tide is entering the forest floor. The water circulation in the tidal creek-mangrove swamp system was controlled mainly by the tides. Spring tides inundate the swamp for a small period of the tidal cycle, however during neap tides, the water remains within the confines of the creek bed. The largest currents occurred in the creek near the mouth where they peaked at about 0.5 m s^{-1}. The currents in the swamp were sluggish seldom exceeding 0.05 m s^{-1}. At neap and intermediate tides, the bulk of the water remains in the mangrove creek where the currents are sluggish seldom exceeding 0.1 m s^{-1} anywhere. The differences between the extent of flooding in the forest during spring and neap tide can be readily viewed using this model.

Figures 5a and 5b display single frames of suspended solids concentrations in Muddy Creek with the concentration legend on the right hand scale. The ocean is at the top right, the farm discharge is at the bottom left of the frame. The higher suspended solids concentration from the farm discharge can be seen moving down the creek, the cleaner oceanic water comes in from the creek mouth. The frames depict a spring tide under existing loads of and TSS discharged into Muddy Creek, as measured in field studies.

Muddy Creek

Fig 4a

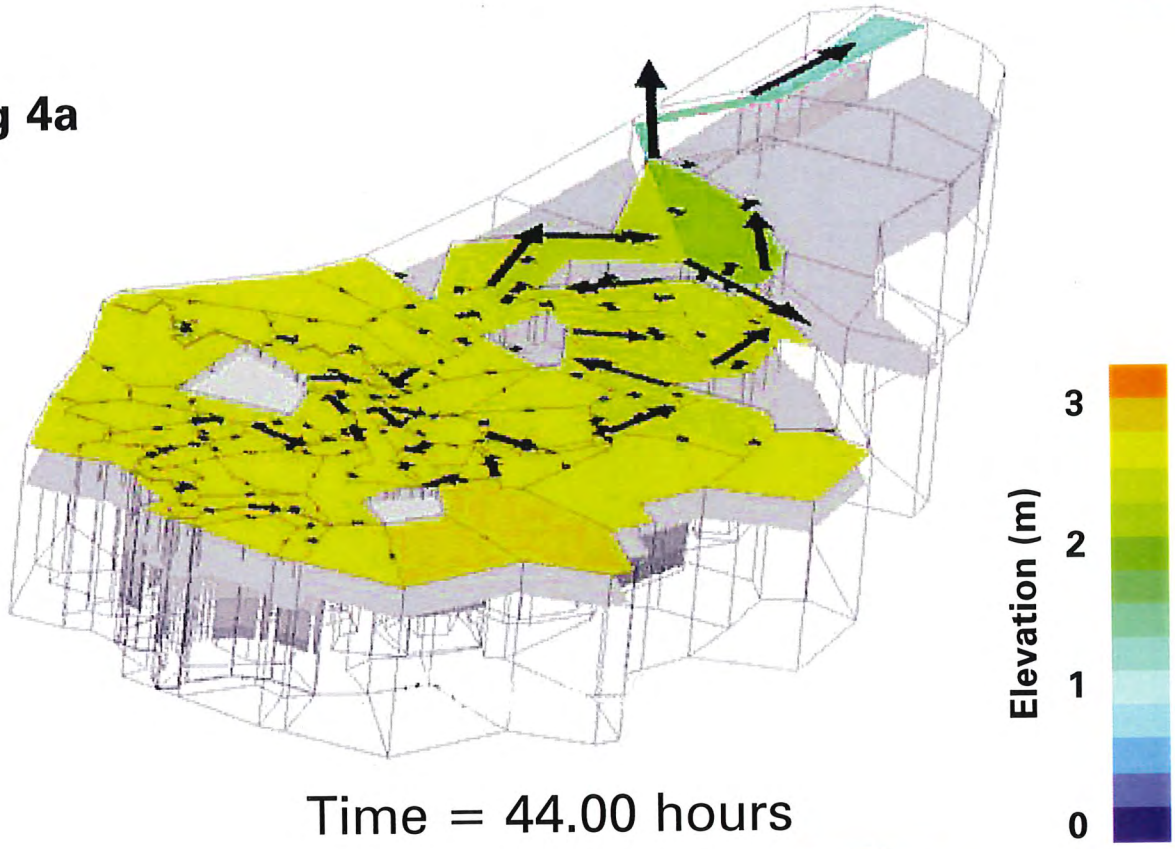


Fig 4b

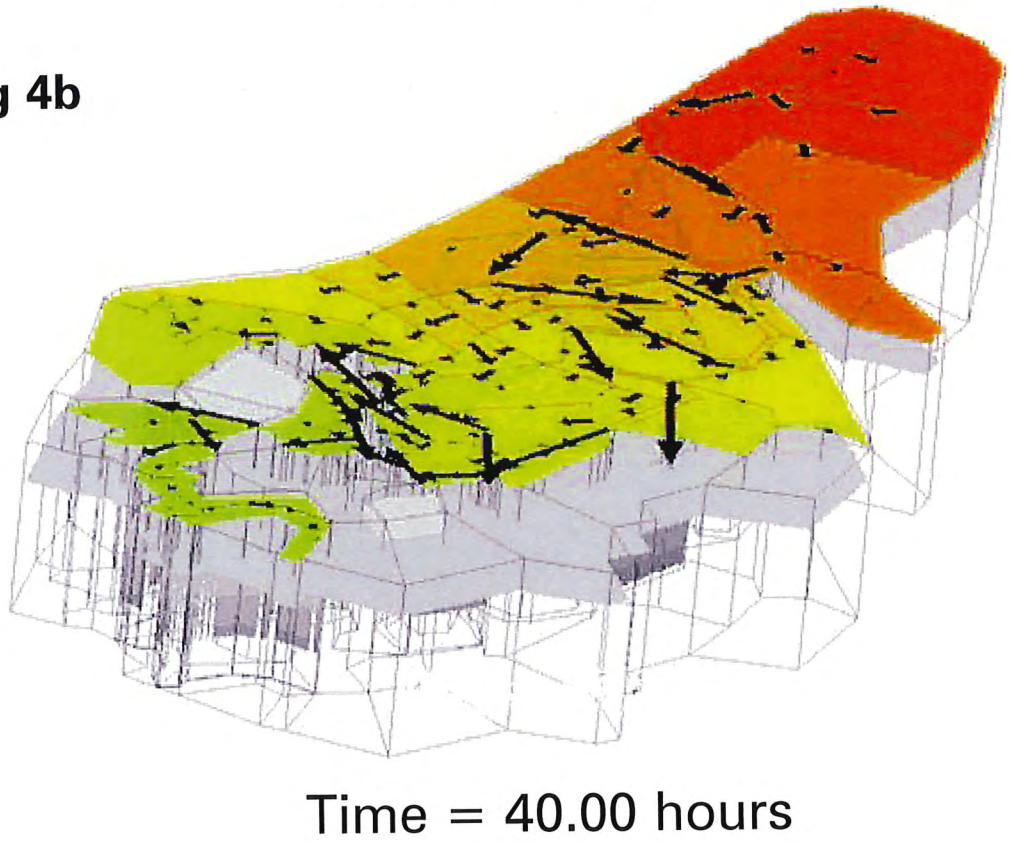


Figure 4a,b. Single frames from a computer visualisation of water flow in Muddy Creek during a spring tide.

Muddy Creek

Fig 5a

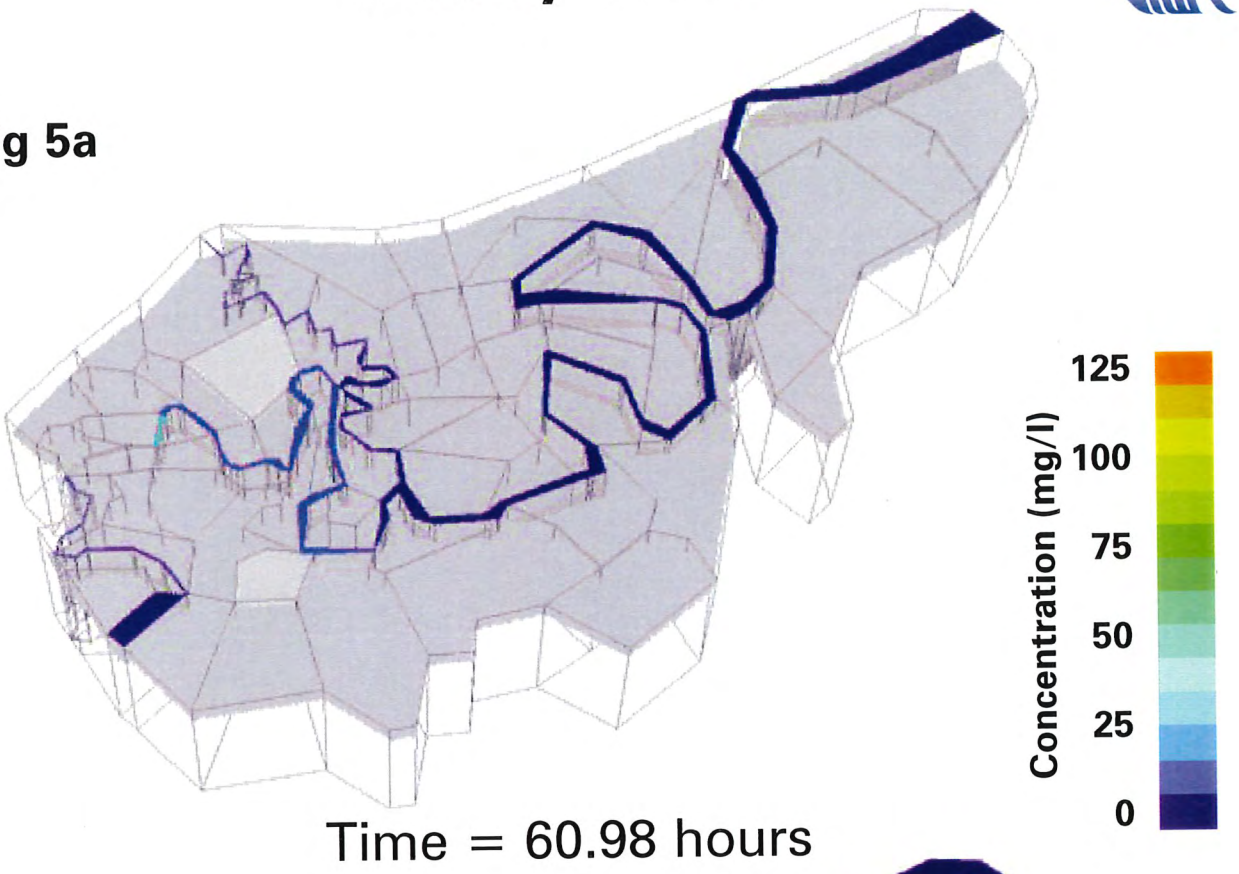


Fig 5b

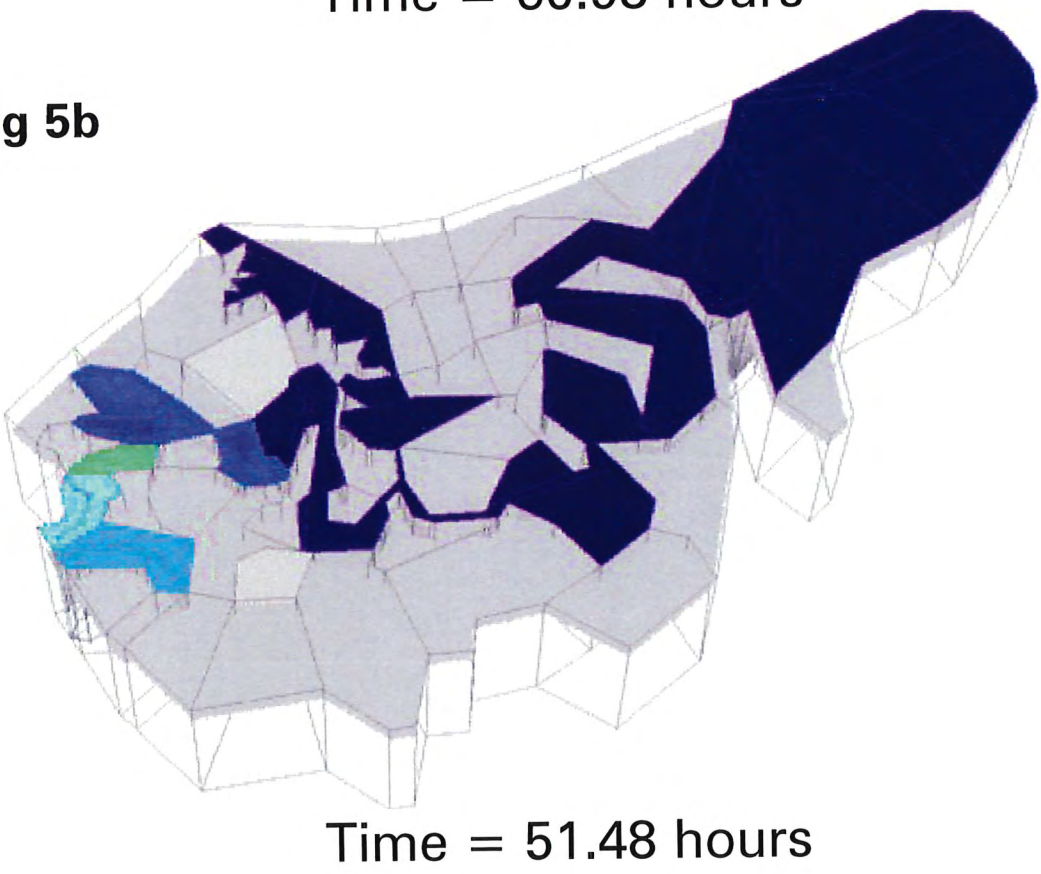


Figure 5a,b. Single frames from a computer visualisation of suspended sediment concentration in Muddy Creek during a spring tide.

Muddy Creek

Fig 6a

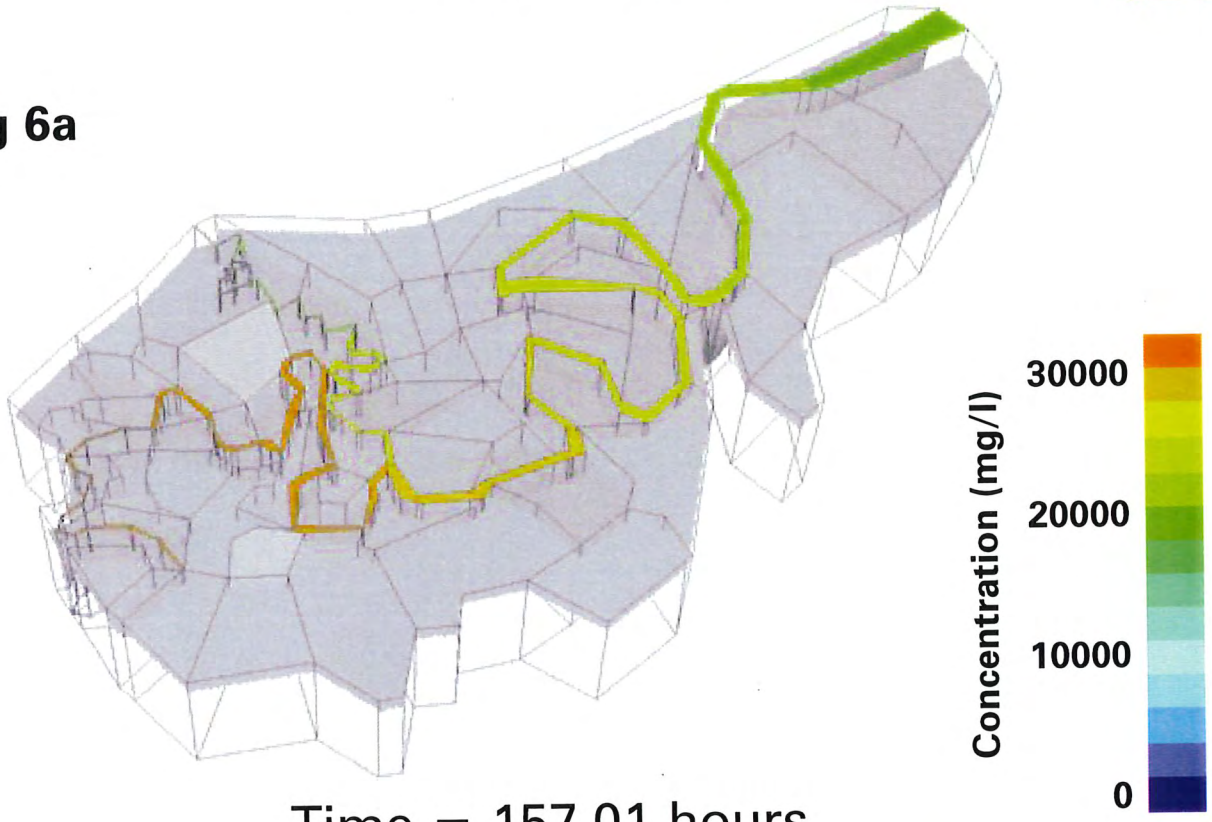


Fig 6b

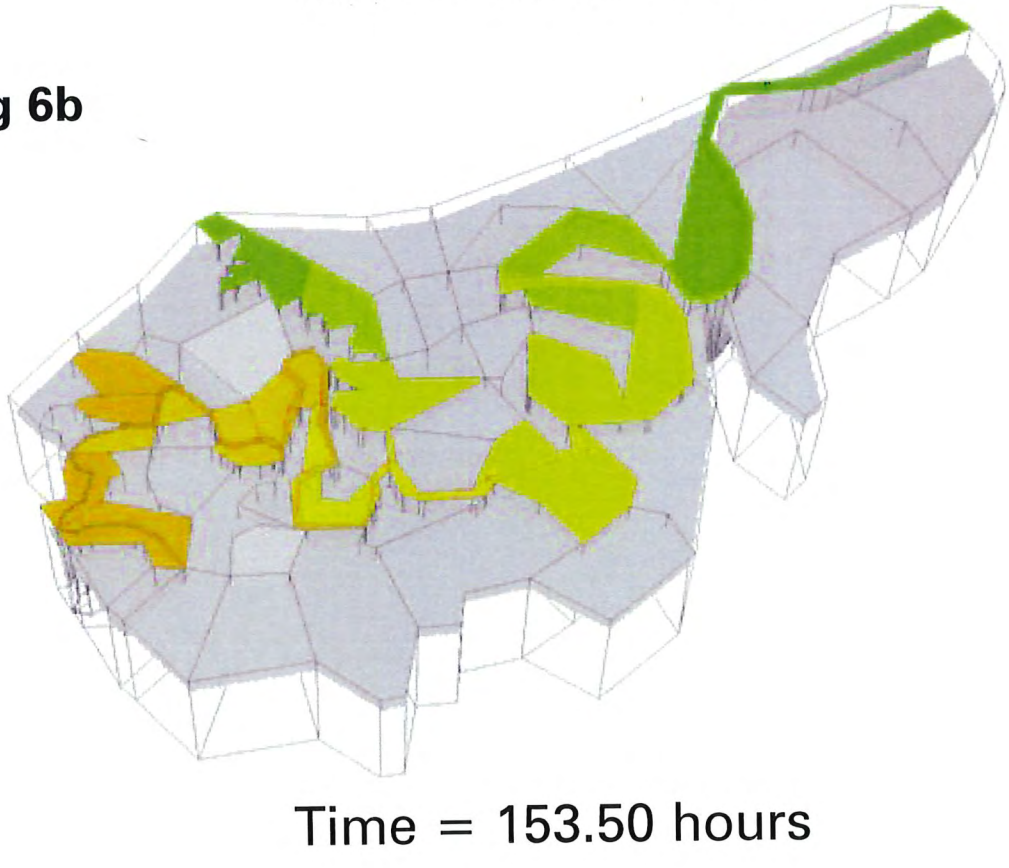


Figure 6a,b. Single frames from a computer visualisation of a ten fold increase (10x) in suspended sediment concentration in Muddy Creek during a neap tide.

Muddy Creek

Fig 7a

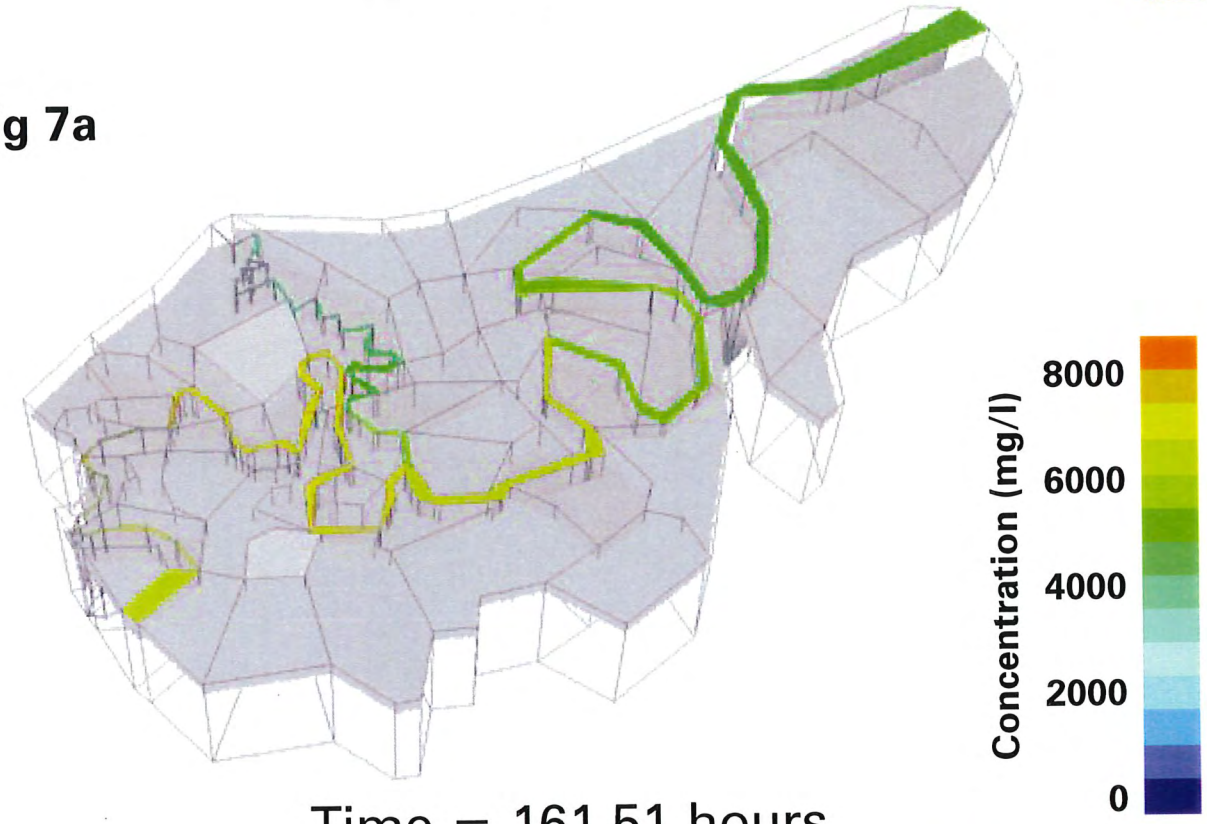


Fig 7b

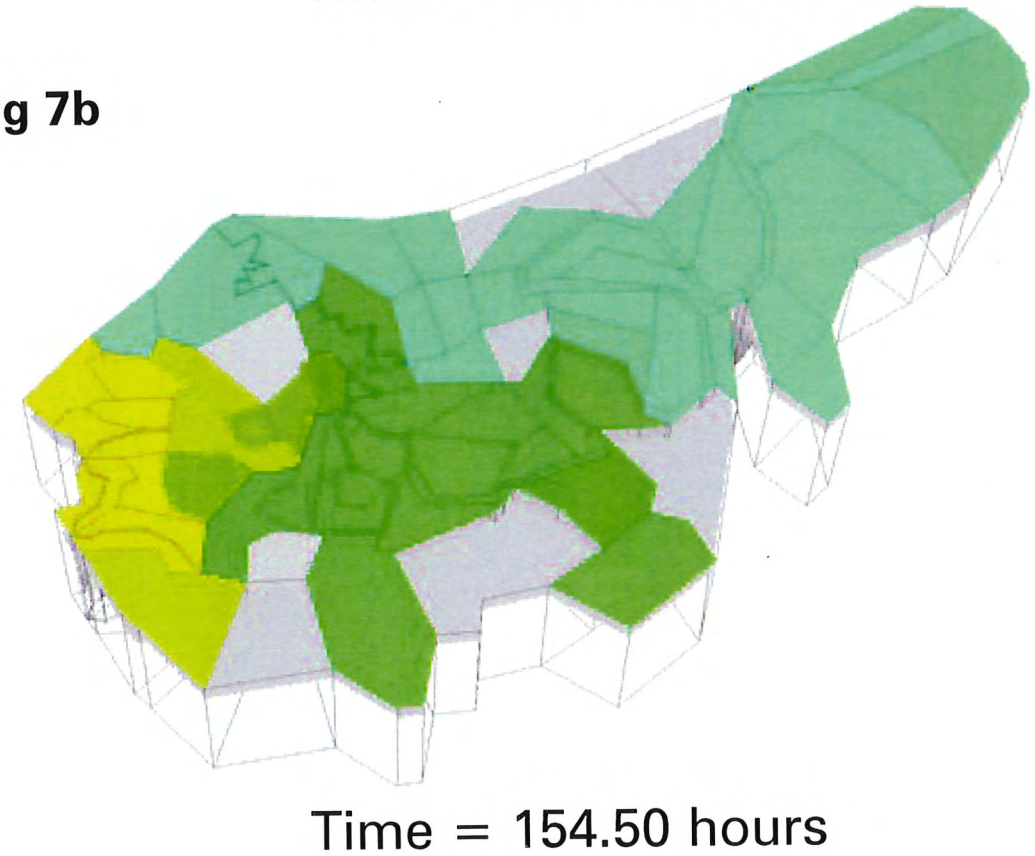


Figure 7a,b. Single frames from a computer visualisation of a ten fold increase (10x) in suspended sediment concentration in Muddy Creek during a spring tide.

Figures 6a and 6b show the predicted behaviour of suspended sediments during a neap tide in the same creek. Under this scenario the sediment discharged from the farm of has been manipulated to be 10 times the actual concentration. Under neap tide conditions, this higher sediment load can be seen moving further down the creek and remaining trapped within the creek profile. The water and sediment do not spread into the forest, and all components of the farm discharge are retained within the creek profile. During neap tides, all assimilative processes are restricted to the creek bed and water column.

Figures 7a and 7b also show a 10-fold concentration of sediment being released from the farm at the lower left under spring tide conditions. Under spring tides a passive contaminant (suspended sediments) discharged at Station M1 reaches Station M2 within one tidal cycle. The sediments are trapped in the creek at low tide and spread laterally in the swamp near high tide. The contaminant discharged at Station M1 does not reach the sea in one tidal cycle; flushing is thus largely due to tidal mixing and diffusion. This flushing is enhanced by lateral trapping in the swamp near high tide. As a result, when the contaminant is discharged continuously, equilibrium concentrations are reached in the system within 4 days at spring tides. The increased sediment is carried into the forest floor by the increased tidal height, and rapid settlement of flocculated particles occurs here (Wolanski *et al.* 1980). However, at neap tides the flows are very sluggish and the contaminant disperses seaward only very slowly (Figures 6a and 6b). Equilibrium is reached after no less than 10-15 days. Since the transition from a spring to neap tide cycle takes two weeks, the mangrove creek-mangrove system is essentially never under equilibrium conditions. The water body changes continuously from a relatively well-flushed system at spring tides to a system that is effectively impounded at neap tides.

The stronger ebb tide currents can scour the creek beds of other particulate material and move this material further downstream. Large flocs, typically >400 μm in diameter were present in the discharge creek, and were formed by aggregations around plankton and other biological detritus (probably originating from the shrimp ponds). These large flocs were not found in non-discharge creeks (Wolanski 1995, Wolanski *et al.* 2000) where the flocs are small with a diameter typically <100 μm. The large flocs have a high settling velocity, which was measured directly in a settling tube and found to be within 0.1-0.2 cm s^{-1}. This implies that the suspended solids can readily settle out during the 1-2 hour of low current velocities (>0.05 $m.s^{-1}$). These large flocs provide a mechanism for particulate matter to settle out in the creek during the short periods of slack tide. As well as settling in the mangrove forests, some fraction of the particulate nutrients may also have deposited within the creeks and some may possibly have been incorporated higher up the food chain (eg into zooplankton and/or juvenile fish).

The computer visualisations presented here explore the differences in behaviour of the effluent using a theoretical ten-fold (10x) increase in concentration of suspended

sediments. These visualisations can be used to predict prawn farm effluent behaviour under other theoretical scenarios, such as: different tidal regimes, altered composition and volume of discharge, different locations of discharge pipe, or timing of discharge during the tidal cycle. This capacity can be extremely useful during planning exercises by the industry and regulators when examining the optimum timing, location, and composition of discharge.

TIDAL CYCLE STUDIES

Data for the tidal flux estimates was obtained from hourly measurements at fixed sampling stations (Stations M1 or M2 at Sea Ranch and P1 or P2 at Seafarm) during 12-24 hour tidal cycles. Graphs of time series for entire tidal cycles of the mean concentrations (+/- 1SD) of dissolved and particulate nutrient concentrations, water depth, current speed, and C, N, P ratios have been prepared. The data was obtained during 3 partial tidal cycles at Seafarm and 5 complete tidal cycles at Sea Ranch. Incomplete tidal cycles at Seafarm resulted from extreme flooding events and difficulty in creek access at low tides. Trip codes and dates of field trips for tidal cycle sampling events are presented in Table 2.

The following plots of time series for the following parameters are available from the authors upon request.

Sea Ranch tidal cycle plots

1. Tidal height (m)
2. Tidal currents (m/s)
3. Salinity
4. pH
5. DO (% saturation)
6. TSS (mg/L)
7. Chl *a* (µg/L)
8. NH4 (µM)
9. DIN (µM)
10. DON (µM)
11. TDN (µM)
12. TDP (µM)
13. DOC (mg/L)
14. PC (µg/L)
15. PN (µg/L)
16. PP (µg/L)

Seafarm tidal cycle plots.

17. Salinity
18. pH
19. DO (% saturation)
20. TSS (mg/L)
21. Chl *a* (µg/L)
22. NH_4^+ (µM)
23. DIN (µM)
24. DON (µM)
25. TDN (µM)
26. DOP (µM)
27. TDP (µM)
28. DOC (mg/L)
29. PC (µg/L)
30. PN (µg/L)
31. PP (µg/L)

During spring tides there was a trend in some parameters to increase in concentration late in the ebb tide cycle at Muddy Creek (Station M2) and in Pig Creek (Station P1, see Figure 2). The peak in concentration of most of these parameters is experienced near low tide and decline with the incoming tide. This trend is more pronounced in sediments and particulate nutrients (especially PC, PN and PP). This phenomenon is probably due to a combination of resuspension and scouring of exposed mud banks as well as the creek volume being reduced and containing a higher proportion of farm effluent. Concentrations of most parameters decrease with the incoming flood tide due to dilution with cleaner incoming coastal water. Tidal flushing of Muddy Creek and similar estuaries has been attributed to asymmetric tidal flows caused by damping of the tidal cycle by mangrove forests, whereby ebb tide currents within creeks can be 20-50% stronger than flood tide currents (Wolanski *et al.* 1980). These faster ebb currents scour the channels and drains and resuspend lighter sediments. The increase in concentration of several nutrients, observed here during ebb tides, probably reflects this scouring action, especially during spring tides.

Some parameters plotted in the tidal cycle graphs display fluctuations that may be due to incomplete mixing of creek and farm discharge water. Fluctuations in concentrations of these parameters within a tidal cycle (ie within 6 hours) pose a challenge to the determination of an "average" or representative measure of concentration based water quality programmes in tidally influenced creeks. For example during one sampling event at Station M2 at Sea Ranch the PN concentration ranged from 250 - 1250 µg/L, the PP concentration varied from 30 -110 µg/L and the chl *a* concentration varied from 25 – 100 µg/L, all within the same 4 hour period. Regulatory authorities and the prawn farming industry need to be aware of the limitations of single point, single time monitoring of any water quality parameter in tidally influenced discharge drains and creeks. Temporal variability of water quality parameters in prawn ponds and effluent drains has also been raised in previous studies (Burford *et al.* 1998, Preston *et al.* FRDC Project 95/162).

TIDAL FLUX STUDIES

Figure 8 shows the net movement (downstream or upstream) of the various forms of particulate and dissolved nutrients. These plots are derived from field measurements and show the stage of farm production when tidal cycles were carried out plotted against the net movement or flux at Station M2 (in kg/tide). For each of the parameters the positive bars indicate a net downstream movement beyond the study area ie downstream of Station M2 and into the middle reaches of Muddy Creek. Bars extending below the 0 on the y axis, indicate net import of the parameter. A positive flux implies that either effluent discharge is beyond the assimilative capacity of this section of the creek and/or that there could be other sources of nutrients into the water column (eg re-suspension of deposited sediments and/or a supply from surface or ground water inputs from agriculture such as the adjacent cane farms). Negative flux of nutrients and sediments could occur when there is an import into the creek, which implies a nutrient assimilation and/or storage capacity. The graphs show that the net export of both nutrients and sediment into the mid section of Muddy Creek increase with the later stages of the prawn cropping cycle. Export of all particulate components (chlorophyll *a*, TSS, PC, PP, and PN) is displayed in Figure 8, while the dissolved components of C, N and P are shown in Figures 9 and 10. The series of graphs in Figures 9 and 10 show the net fluxes of dissolved forms of the nutrients in kg/tide, also plotted during the various stages of farm production. The only exception to increased net fluxes during later cropping stages is seen in PO_4^{3-} concentrations that occasionally show net imports into the upper reaches of the creek. As expected, greater exports occur during later cropping and harvesting periods, which coincide with greater farm discharges. No net exports were detected during the empty phase, when no discharge was occurring. The quantities of particulate material such as chlorophyll *a*, TSS and particulate nutrients are elevated in prawn farm discharge in the later stages of the cropping cycle. The box insert in Figure 11 shows the average % of components of N exported at M2 and demonstrates that PN is still the dominant form of N in the water column at this point in the creek. DON is only occasionally a significant component. Figure 11 also shows that PN is the major form of exported N during mid to late cropping stages with DON becoming the dominant form of exported N in the non-discharge or early periods of cropping. During the empty phase of the cropping cycle (zero discharge), an import of PN is seen, while DON and DIN each comprise about half of the exported N. PC is the only parameter in the same order of magnitude as TSS. Figure 12 shows the tidally averaged fluxes (moles/tide) of total C, N and P, which demonstrates the dominance of C over the other nutrients exported at M2.

Figure 8. Net flux (kg/tide) of chlorophyll *a*, TSS, PC, PP and PN in the upper reaches of Muddy Creek.

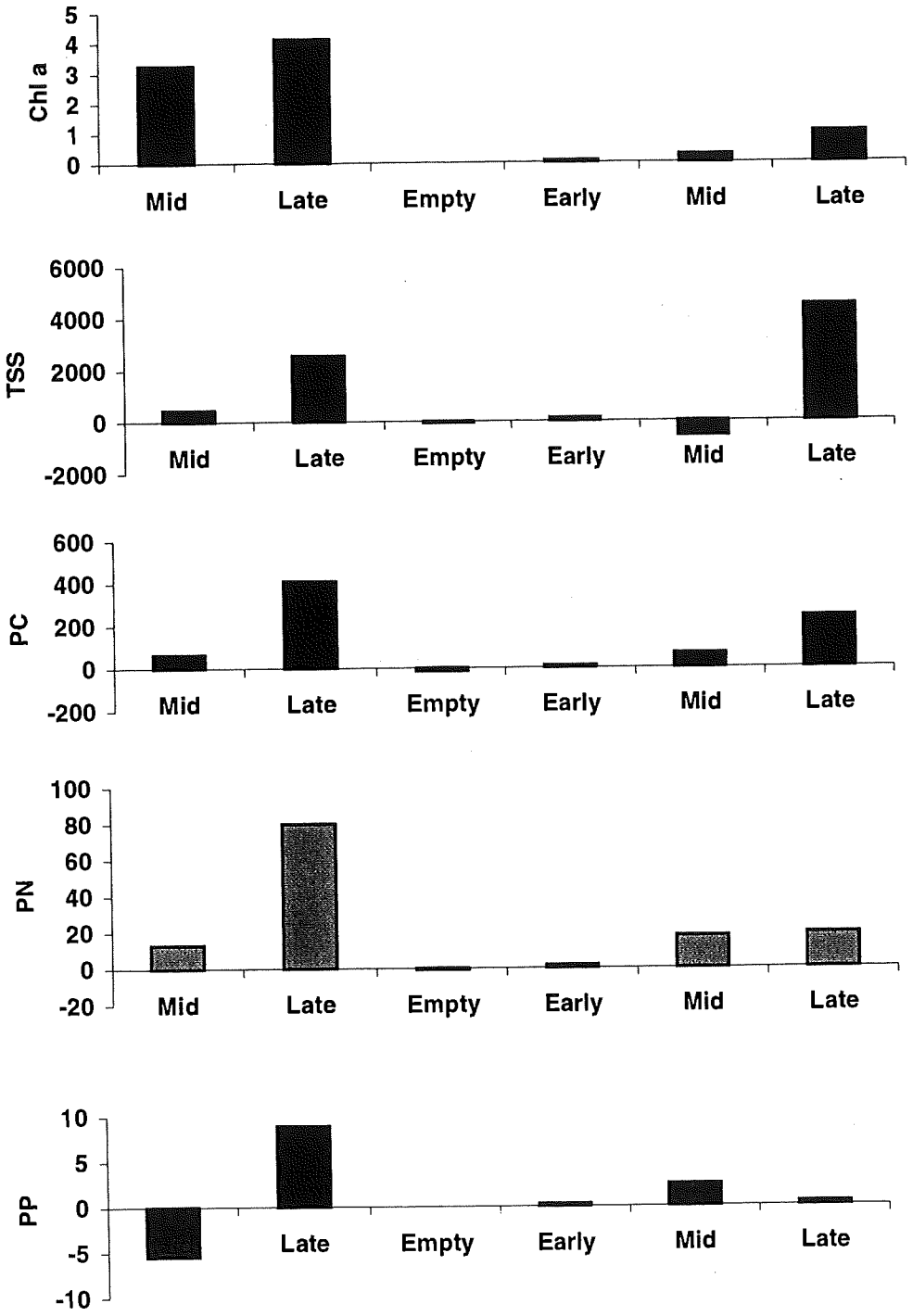


Figure 9. Net flux (kg/tide) of dissolved inorganic C, N and P in the upper reaches of Muddy Creek.

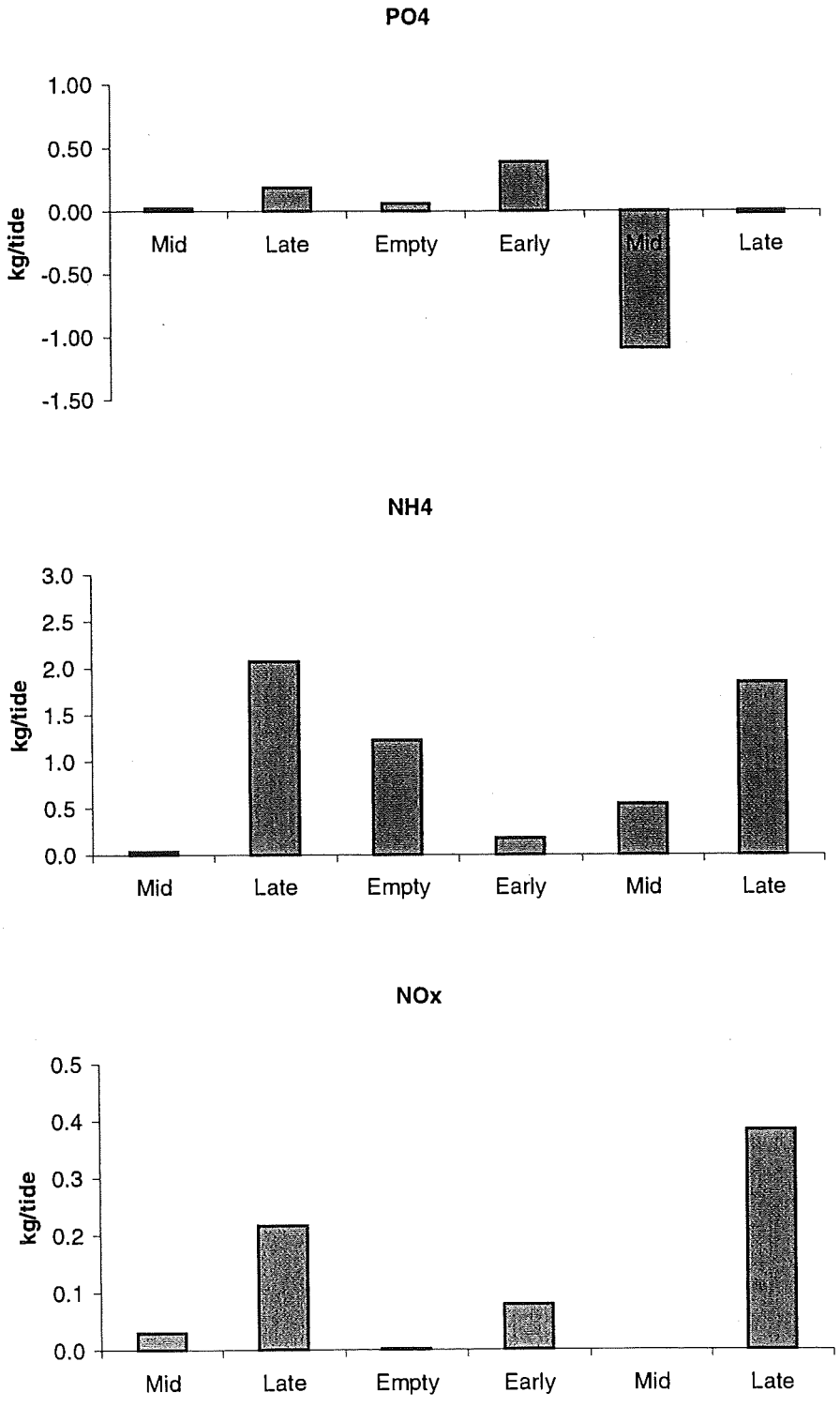


Figure 10. Net flux (kg/tide) of dissolved organic C, N and P in the upper reaches of Muddy Creek.

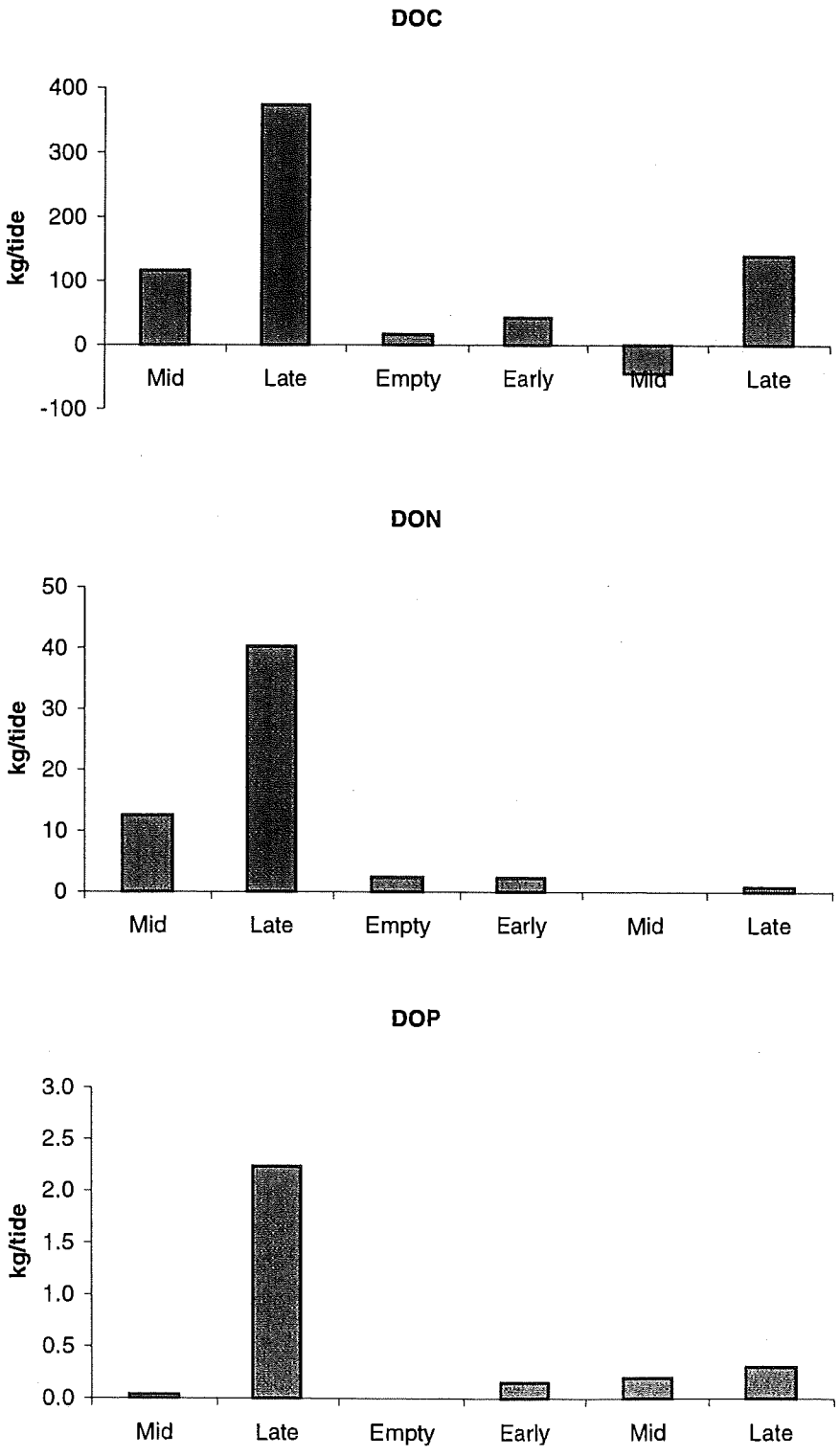


Figure 11. Net flux of PN, DON, and DIN (kg/tide) at Station M2 showing the dominance of PN during different cropping stages at Sea Ranch.

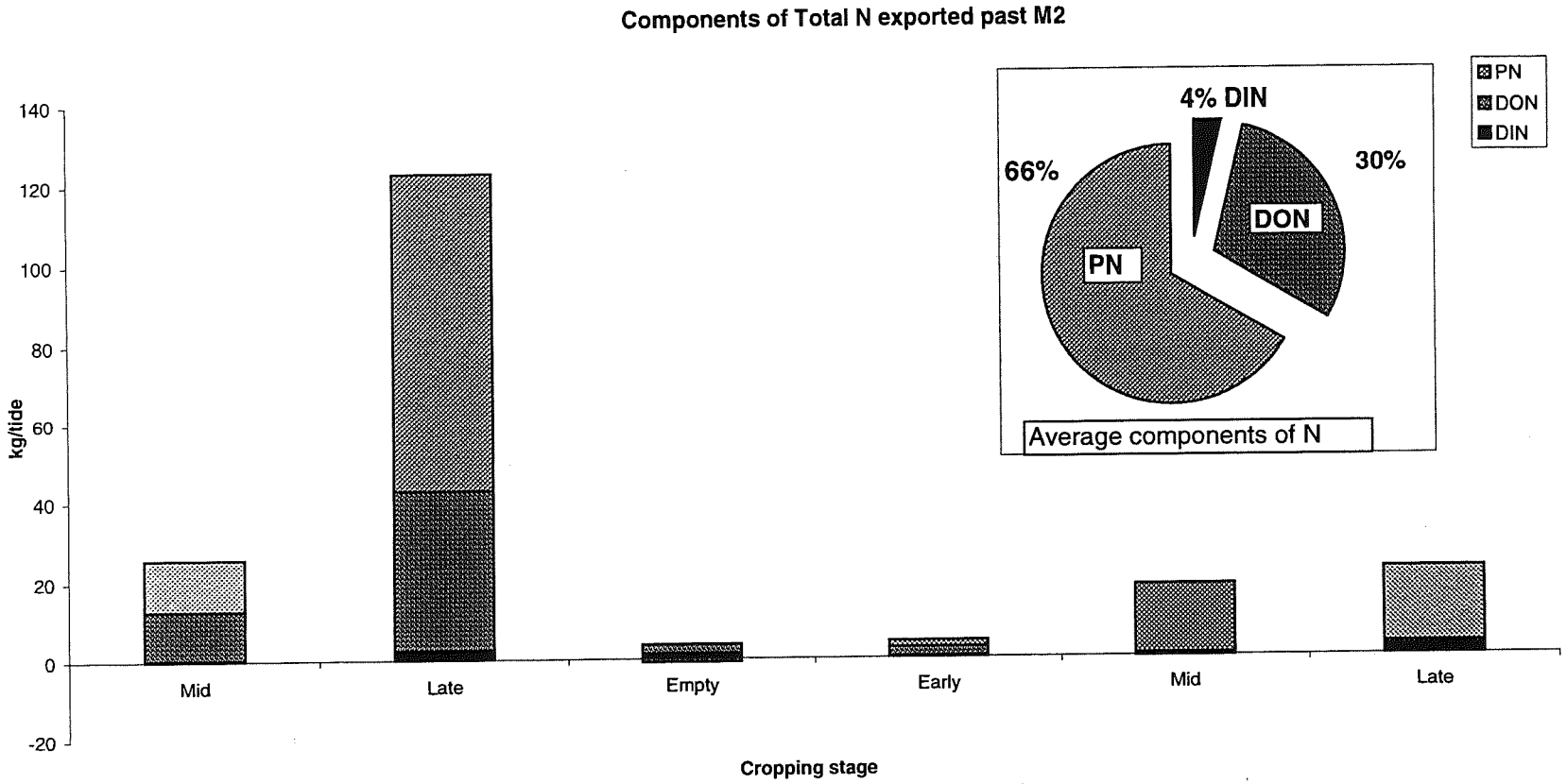
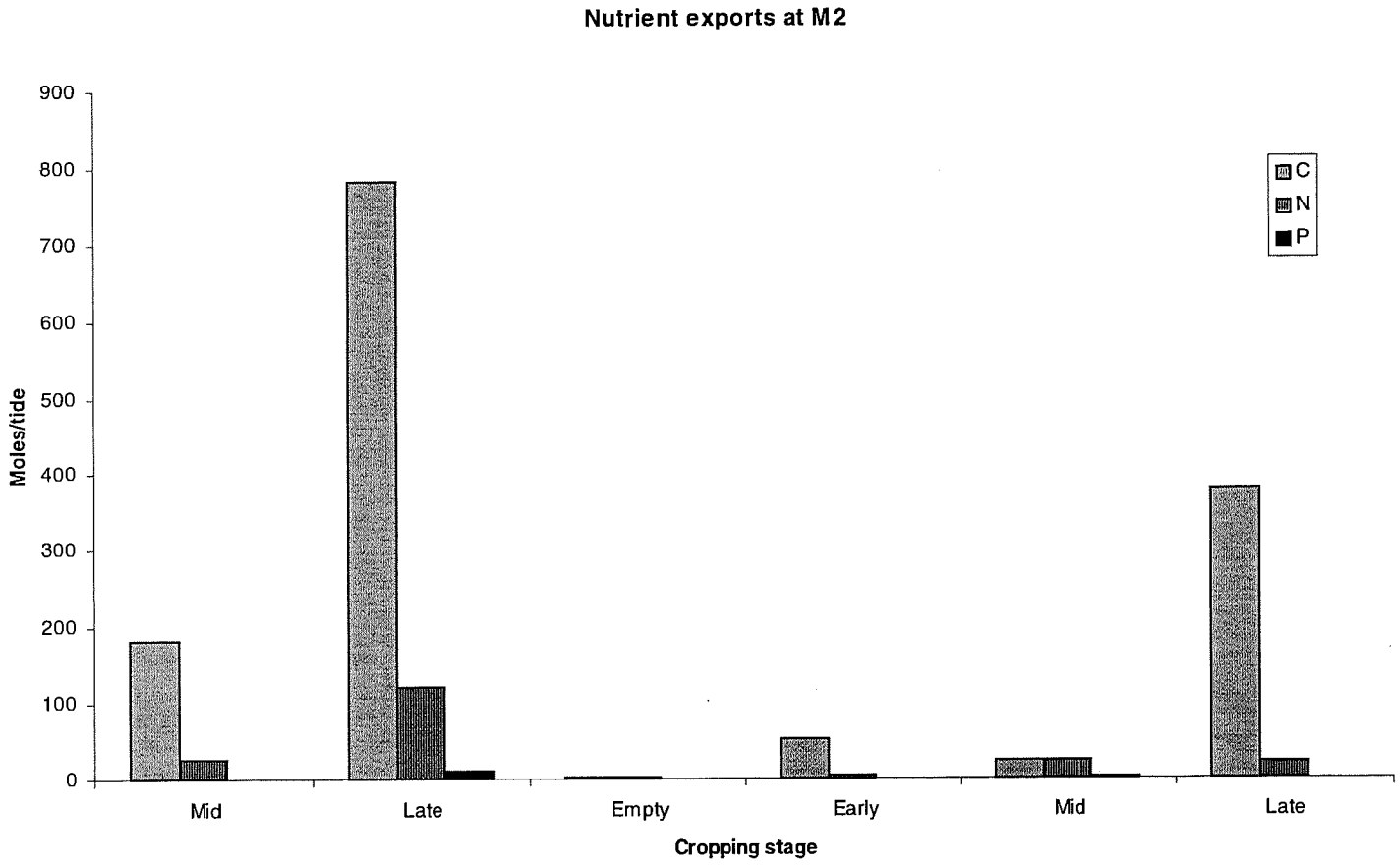


Figure 12. Net flux of C, N and P (moles/tide) at Station M2 during different cropping stages at Sea Ranch.



Sediment and water column nutrient processes

Methods

BENTHIC SOLUTE FLUXES

Fluxes of NH_4^+, NO_2^- + NO_3^-, DON, PO_4^{3-}, DOP, DOC, and O_2 across the sediment-water interface were made from three clear and three dark glass chambers (surface area = 0.007 m^2) inserted into boxcorer samples and incubated in a shaded water bath at ambient temperature (Alongi *et al.* 1999). Each boxcorer liner was inserted into the creek sediments at each site to a depth of 25 cm and removed with minimal disturbance. Each chamber had a propeller-electric motor unit and two sampling ports, one port for an oxygen electrode and one port for the dissolved nutrient sampling. Samples for dissolved N, P and C were taken at 45-min intervals for 3 h., filtered (using a sterile plastic syringe and 0.45 µm Minisart filters for N and P, or 0.4 µm Nucleopore filters for DOC,) and analysed by standard automated techniques (Ryle *et al.* 1981, Ryle and Wellington 1982). Samples were stored frozen (for dissolved N and P), or on ice (for alkalinity and ΣCO_2). DOC was determined by high temperature catalytic oxidation on a Shimadzu TOC-5000 Analyser (Hedges *et al.* 1993). Blanks using Milli-Q water were run for DOC concurrently with the samples. O_2 concentration in the overlying water of each chamber was logged at 10 minute intervals on a TPS WP-82 DO/Temperature Meter with a Clark oxygen electrode. Combined rates of benthic and water column respiration were obtained from linear regressions of the O_2 data.

DENITRIFICATION

Denitrification was measured from replicate cores taken in November 1998, February 1999, June 1999 and March 2000 from Stations M1, M2, S1 and S2, using the N_2 gas flux technique of Nowicki (1994). Sediment cores (volume range 230 to 385 cm^3, (sediment depth range 6 to 10cm) were taken by pushing open-ended plastic bottles into the sediment surface and removing the core with minimal disturbance by sliding a hand underneath to prevent slumping of the core. Each core was placed in a gas-tight glass chamber (height 23.5 cm, i.d. 7.6 cm). Sediments in each chamber were covered with ~500 to 800 ml seawater collected from the same estuary. Each chamber was sparged with either an 80% He/ 20% O_2 mixture (4 experimental chambers per site, see below) or 100% He (1 control chamber per site, see below) to remove N_2 and, in the case of the experimental cores, to maintain dissolved O_2 concentrations. The overlying water in each sealed chamber was stirred continuously. All chambers were incubated for 9 days at ambient temperatures to mimic field conditions.

In the experimental chambers, the gas phase was flushed repeatedly with an 80% He/ 20% O_2 mixture after the overlying water had been periodically replaced with low N_2

seawater. The water exchanges maintained oxygen conditions and an adequate nitrate supply. The control chambers were incubated under anaerobic conditions (100% He gas and de-oxygenated water exchanges) in order to block nitrification and denitrification (Nowicki 1994). Water exchanges were made on all chambers on Day 4. On Days 1, 2, 3 and after the water exchange on Day 4 the gas headspace was flushed three times per day for 2 minutes with an 80% He/ 20% O_2 mixture in the experimental chambers and 100% He in the control chambers. From Day 5 to Day 9 the accumulated N_2 gas was measured in the headspace of each chamber. A regression (µm N_2. m^{-2}. day-1) was calculated from the daily accumulated N_2 gas in the headspace from each chamber.

Despite denitrification being blocked in the control cores, there can be significant de-gassing of N_2 from the sediment pore water that diffuses into the overlying water and gas. This background flux of N_2 (F_{dg}) measured in the control chambers was subtracted from the total flux (F_t) measured in the experimental chambers to derive the rate of N_2 flux due to denitrification (F_{dn}), where $F_{dn} = F_t - F_{dg}$ (Nowicki 1994). Denitrification rates (µmol $N_2.m^{-2}.d^{-1}$) were calculated as the average rate of four replicate cores from each site over the 5 day incubation period following the water exchange on Day 4.

Measurements of N_2 and O_2 concentrations in the overlying gas phase in each chamber were made by withdrawing samples through the chamber sampling ports using a He flushed syringe. The gas sample was analysed for N_2 and O_2 using an MTI Analytical Instruments P200 gas chromatograph under conditions specified by Nowicki (1994). Calibration standards were run with each set of samples using a gas mixture (2.0% N_2, 20.0% O_2 and 78.0% He) certified by BOC Gases Australia Ltd (Townsville, Australia).

TRANSECT WATER QUALITY

Discharge and non-discharge creeks were sampled for surface water quality (dissolved and particulate nutrients C, N and P, TSS, chlorophyll *a*, pH, salinity, and D.O.) at fixed positions along a transect covering the upper 1 km of Muddy Creek (Stations between M1 and M2, Figure 1) and Sandfly Creek (stations between S1 and S2, Figure 1) at Sea Ranch. Transect locations at Seafarm (Stations Pig1, Pig2, Pig3 and Pig4 in Pig Creek, and Stations Mo1, Mo2, Mo3, Mo4 and Mo5 in Morris Creek, Figure 2) were sampled. Sampling commenced usually no later than 1 hour after slack tide. All transect samples were completed and stored on ice within 1 hour of taking the first sample. All samples were analysed as described previously in Hydrodynamics – Water quality section. The discharge creeks were Muddy Creek at Sea Ranch and Pig Creek at Seafarm, while the non discharge creeks were Sandfly Creek at Sea Ranch and Morris Creek at Seafarm.

Results and Discussion

BENTHIC SOLUTE FLUXES

Fluxes of all solutes (dissolved N, C, O and P) showed high variability between and within replicate chambers from the same site, creek and season. The replicate mud cores for these benthic incubations were in close proximity, therefore, these variable results indicate a highly variable microbial status within sediments over short distances. This variability prevented us from identifying statistically significant differences between creeks or seasons, however, some general observations are given below.

Mean fluxes of NH_4^+ out of the sediments were more than twice as high in Muddy Creek (2,074.9 $\mu M.m^{-2}.d^{-1}$) than Sandfly Creek (900.4 $\mu M.m^{-2}.d^{-1}$) indicating slightly more anaerobic conditions in Muddy Creek. Fluxes of inorganic oxidised N (NO_2^- + NO_3^-) were into the sediments in both Muddy Creek (68.4 $\mu M.m^{-2}.d^{-1}$) and Sandfly Creek (18.4 $\mu M.m^{-2}.d^{-1}$). DON was taken up by Muddy Creek sediments (298.7 $\mu M.m^{-2}.d^{-1}$) but released by Sandfly Creek sediments (650.7 $\mu M.m^{-2}.d^{-1}$). Organic (DOP) and inorganic P (PO_4^{3-},) were taken up by both creek sediments. DOC was taken up by Muddy Creek sediments (41.95 $\mu M.m^{-2}.d^{-1}$) at a faster rate than by Sandfly Creek sediments (15.35 $\mu M.m^{-2}.d^{-1}$). O_2 respiration rates were similar in sediments from both Muddy (25.1 $\mu M.m^{-2}.d^{-1}$) and Sandfly Creek (32.3 $\mu M.m^{-2}.d^{-1}$).

DENITRIFICATION

There was no significant difference in denitrification rate ($\mu m\ N_2.m^{-2}.hr^{-1}$) between Sandfly (mean +/- 1 SD = 67.26 +/- 123.10) and Muddy Creek (mean +/- 1 SD = 57.06 +/- 65.65). Once again, high variability in the results were observed in upstream and downstream sites, in both creeks, and across the four sampling events. The mean denitrification rates are at the lower end of the published range of 0-500 um $N_2.m^{-2}.hr^{-1}$ for similar mangrove environments (Rivera-Monroy and Twilley 1996).

TRANSECT WATER QUALITY

Plots of mean concentration (+/- SE) of water quality parameters along the Muddy Creek and Sandfly transect of approximately 1,000 m during ebb tides are shown in Figures 13 and 14. Figure 13 shows that TSS concentrations in Muddy Creek increase significantly in the first few hundred metres downstream of the Station M1. This increase is greater during spring tides than neap tides, and is present in both the wet and dry season. TSS concentrations along the transect did not increase during neap tides. During these same periods, a smaller increase occurred in the TSS concentrations along the Sandfly Creek transect during the wet season, whereas the dry season concentrations are consistently low (Figure 14). The most likely cause of the increase in TSS concentrations along the Muddy Ck transect is the resuspension of particulate material that has previously settled out of the water column during the preceding slack water period. In both Sandfly and Muddy Ck, the particulate material

can originate from the sides and bottom of the creek which have been eroded and resuspended in the water column and/or from the mangrove forests. In the case of Muddy Ck there is an additional source from the prawn farm. The lower C:N and higher N:P ratios shown in Figures 15 and 16 suggest that this particulate material is from the prawn farm. Resuspended sediments which had recently settled out of the water column would exhibit high proportions of N (low C:N ratios) because of the high nutrient content of prawn pond suspended particles. The combination of increased tidal speeds which occur during ebb spring tides and lower water levels would also aid in resuspending the recently settled sediments. Immediately below Station M1, the discharge channel widens and becomes quite shallow, with a mud bank exposed at tides below approximately 0.8 m. Resuspension of particulate sediments from this mud bank during ebb spring tides is proposed as the cause of the peak in several nutrient parameters at 200 m and 500 m locations in Muddy Ck (See Figures 13 and 17).

Chlorophyll *a* concentrations in Muddy Creek (Figure 13) do not change significantly along the transect, as shown under the combinations of tide, season and discharge. The low chlorophyll *a* concentrations (~3 µg/L) seen during wet season, non discharge, spring tide periods suggest that these sampling events occurred during periods when the creek was well flushed by heavy wet season rains and strong spring tide currents. The consistently low chlorophyll *a* concentrations seen in Sandfly Creek (Figure 14) are almost certainly due to the lack of prawn farm discharge and catchment run-off entering this creek, as demonstrated in Trott and Alongi (1999).

The mean ratio (+/- 1 SE) of C:N and N:P in suspended particulate material in the water column of Muddy Creek (Figure 15) and Sandfly Creek (Figure 16) both show a fall in the C:N ratio at the first downstream positions. The ratio drops from 8.5 to 7.0:1 in Muddy Creek and from 11.5 to 10.5:1 in Sandfly Creek. The lower C:N ratio from Muddy Creek indicates higher N content of these particulates, whereas, in other mangrove forests the C:N ratios are in the range 18-35:1 indicating more refractory mangrove derived material (Alongi *et al.* 1992). In Muddy Creek, the first sampling position is immediately downstream of a mud bank, suggesting that resuspension of N rich (low C:N ratio) farm derived particulates is occurring during ebb tides. The particulate N:P ratio in Muddy Creek shows no significant change along the transect (Figure 15) despite the appearance of a slight downward trend. These results indicate that the sediments in the mud banks of Muddy Creek, with a higher N content, are being resuspended. Nutrient poor, and presumably older creek sediments, may also be resuspended, but are not in sufficient quantity to mask the rich N signal in Muddy Creek. This observation has implications for benthic nutrient processes further downstream, where the N rich sediment eventually settles.

Figure 33 shows TSS and chlorophyll *a* from Sandfly Creek which does not receive prawn farm discharge. TSS and chlorophyll *a* concentrations are consistently lower in Sandfly Ck during the dry season. There is also less resuspension of particulate material along the Sandfly Ck transect. This observation is supported by the results as

shown in Figure 15, which shows a mean for C:N ratio of the particulates along the Muddy Creek transect to be in the range 7-9.5:1. The lowest value is seen at 200 m, where a mean of 7:1 was recorded, indicating a high ratio of particulate N to C in the water column. Part b of this graph shows the N:P ratio in the same locations. Here we see the highest ratio (mean 105:1) occurring also at the 200m location. Again, this indicates that there is a higher ratio of particulate N in the water column at this transect point. These results indicate that this material has not been assimilated by the biochemical pathways in the water column or mud.

Mean particulate nutrient concentrations (+/- 1 SE) along Muddy Creek (Figure 17) and Sandfly Creek (Figure 18) show PC, PN and PP in terms of concentration in the water column along the top row ($\mu g.L^{-1}$) and in terms of relative mass of suspended matter ($\mu g.g^{-1}$). These two different measures represent the following

a) the total concentration of the particulate nutrient suspended in the water column ($\mu g.L^{-1}$), and
b) the relative weight of each nutrient on the suspended material ($\mu g.g^{-1}$).

The top row in Figure 18 reveals a similar trend to the TSS trends where immediately downstream of the discharge in Muddy Creek there is an increase in the amount of each nutrient suspended in the water column, and this declines significantly as the water column moves downstream. The relative amount of nutrient within the suspended sediment for this same transect does not change significantly. This suggests that nutrient stripping of particulates is not occurring in the water column (because the amount of nutrient per g of sediment does not change) but the physical processes of resuspension and settling are the dominant processes in this section of Muddy Creek. Sandfly Creek (Figure 18) displays a completely different trend, where low levels of suspended PC, PN and PP remain as the water body moves downstream. The mean concentrations of PC, PN and PP in Sandfly Creek were significantly lower than in Muddy Creek. The concentration of each nutrient (C,N, P) in the Sandfly Creek transect does not change significantly from the top to the lower end, whereas in Muddy Creek the mean concentration of each of the nutrients decreases significantly (Figures 17 and 18).

Graphs for dissolved nutrients in Muddy Creek (Figure 19) and Sandfly Creek (Figure 20) show no significant trends for TDN, TDP, DON and DOP. Likewise, the dissolved organic C:N ratio and dissolved organic N:P ratio show no significant trend along the transects. There is a significantly higher concentration of DON throughout the Muddy Creek transect and a lower DOC:DON ratio in Muddy Creek (Figure 19) than Sandfly Creek (Figure 20), presumably due to the higher DON concentrations discharged from the farm.

Figure 13. Mean concentrations of TSS (mg.l^{-1}) and Chlorophyll *a* (µg.l^{-1}) along the Muddy Creek transect in relation to season, tide and discharge.

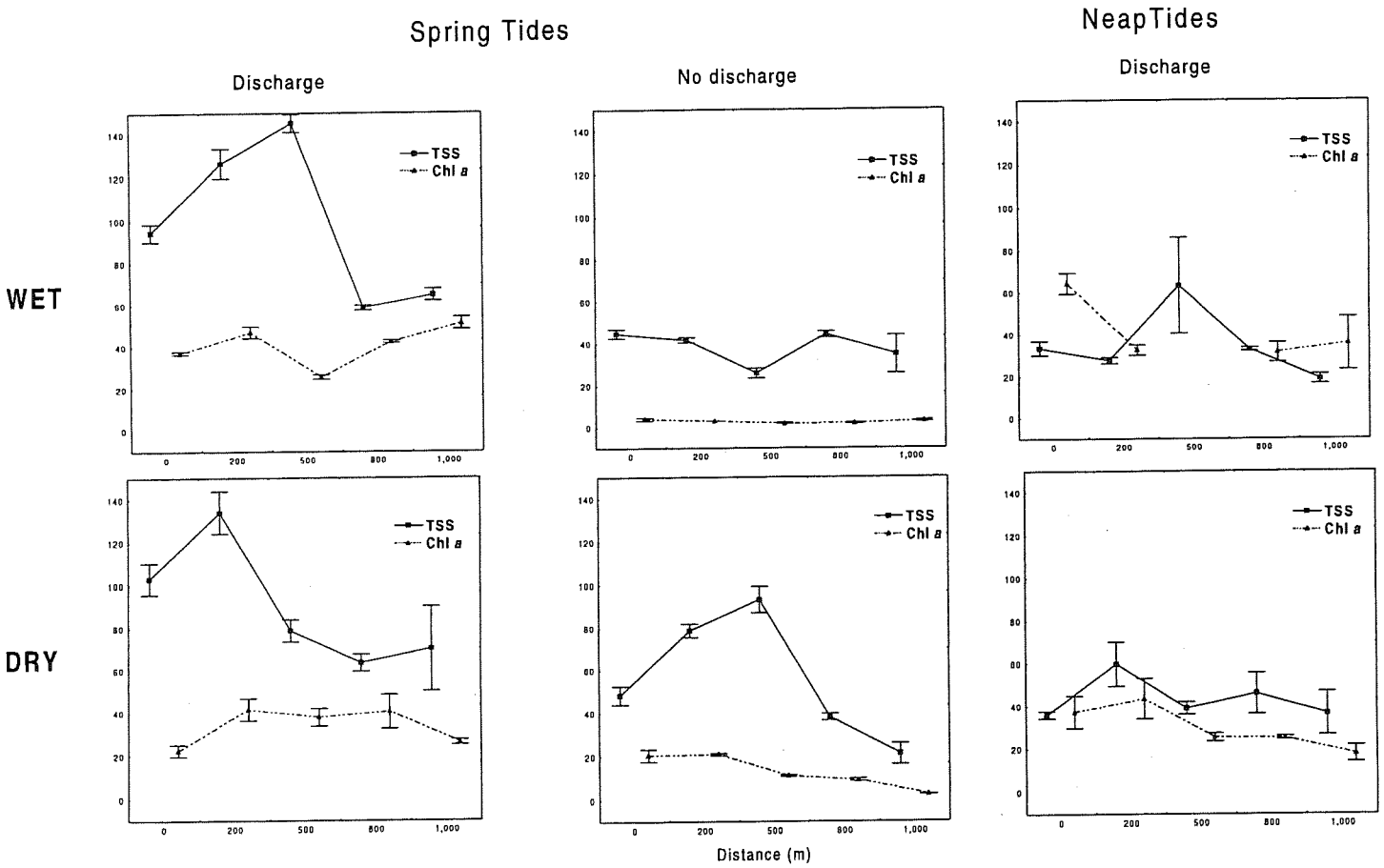


Figure 14. Mean concentrations of TSS (mg.l^{-1}) and Chlorophyll *a* (µg.l^{-1}) along the Sandfly Creek transect in relation to season, tide and discharge.

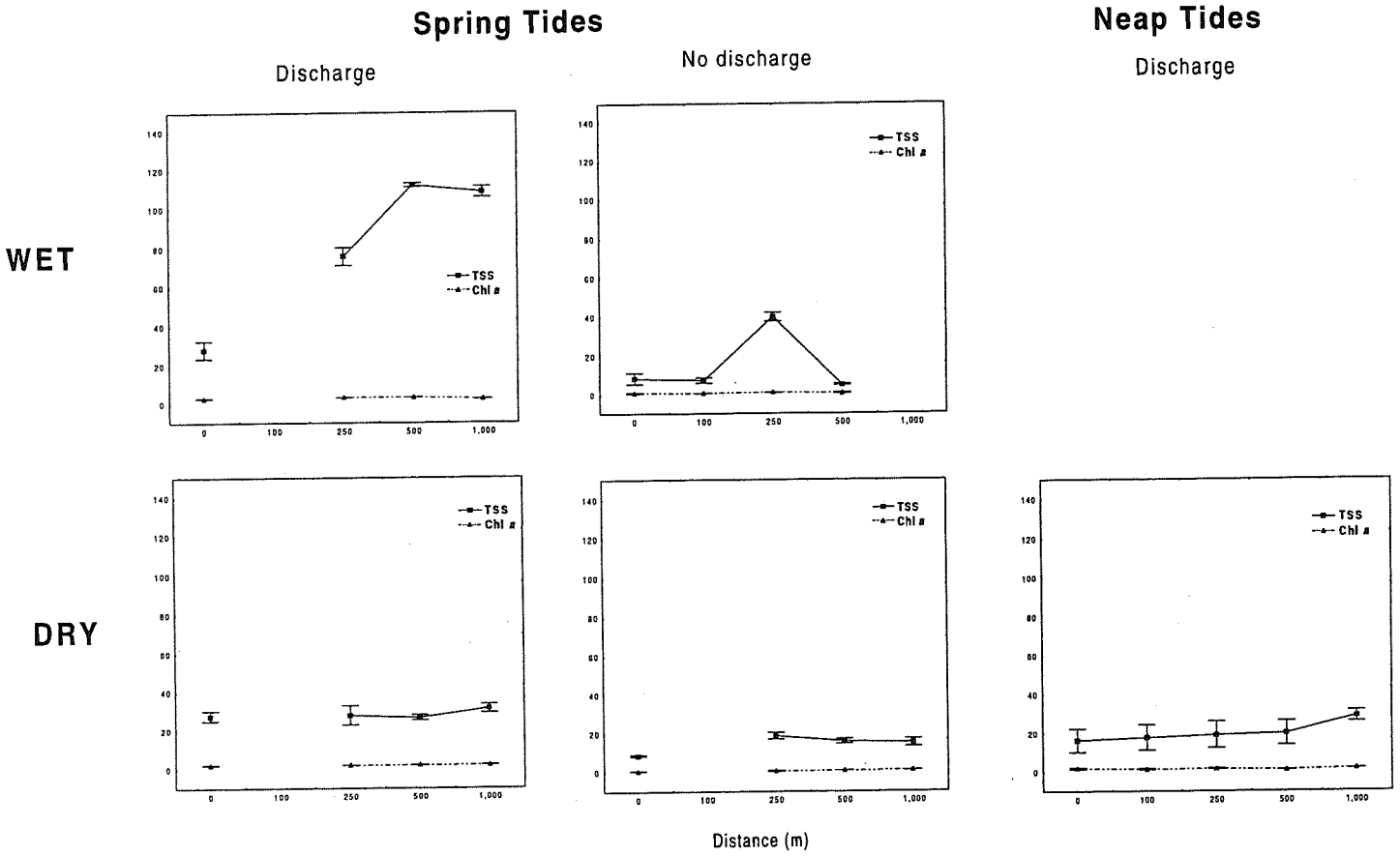
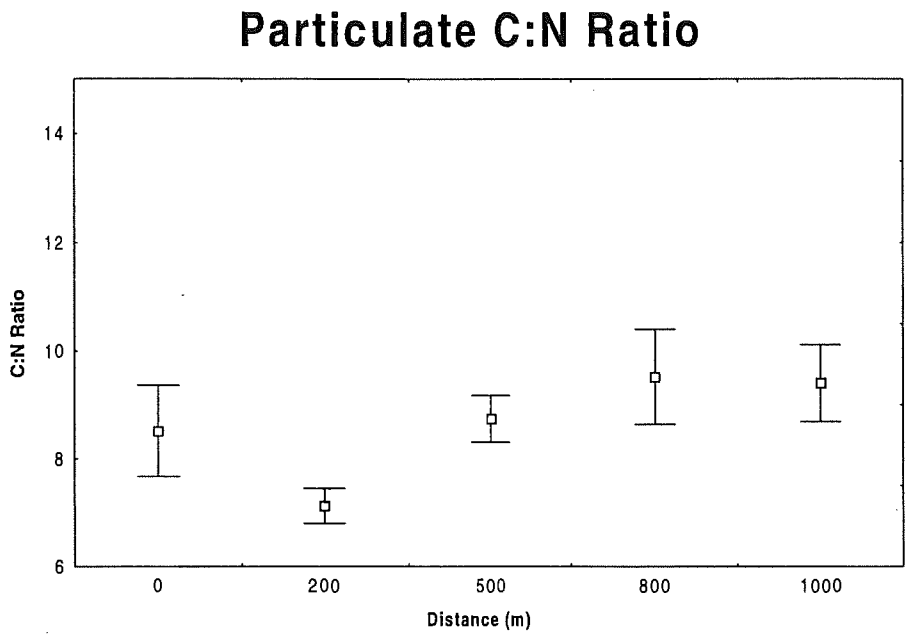


Figure 15. Mean C:N and N:P ratios along the Muddy Ck transect.



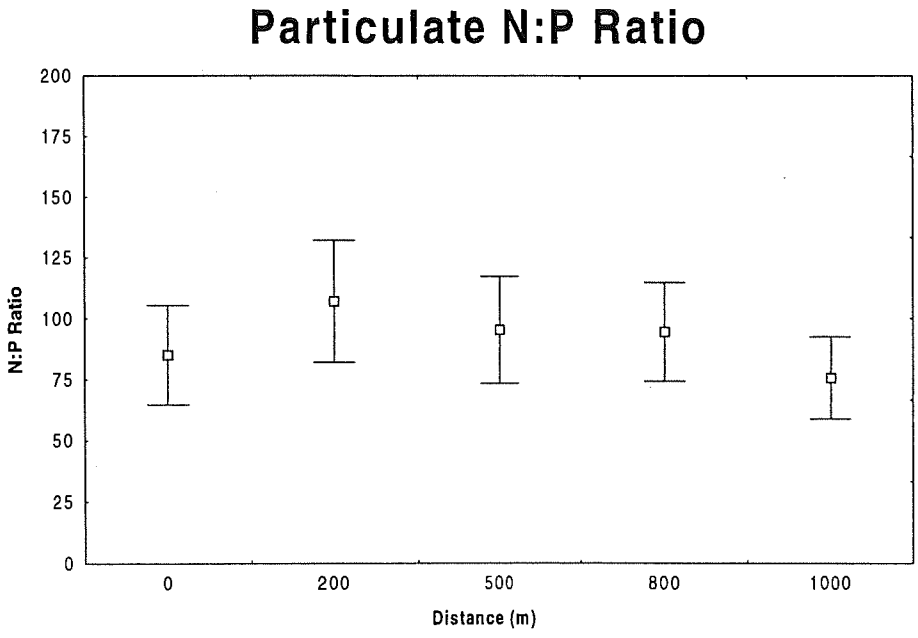


Figure 16. Mean C:N and N:P ratios along the Sandfly Creek transect.

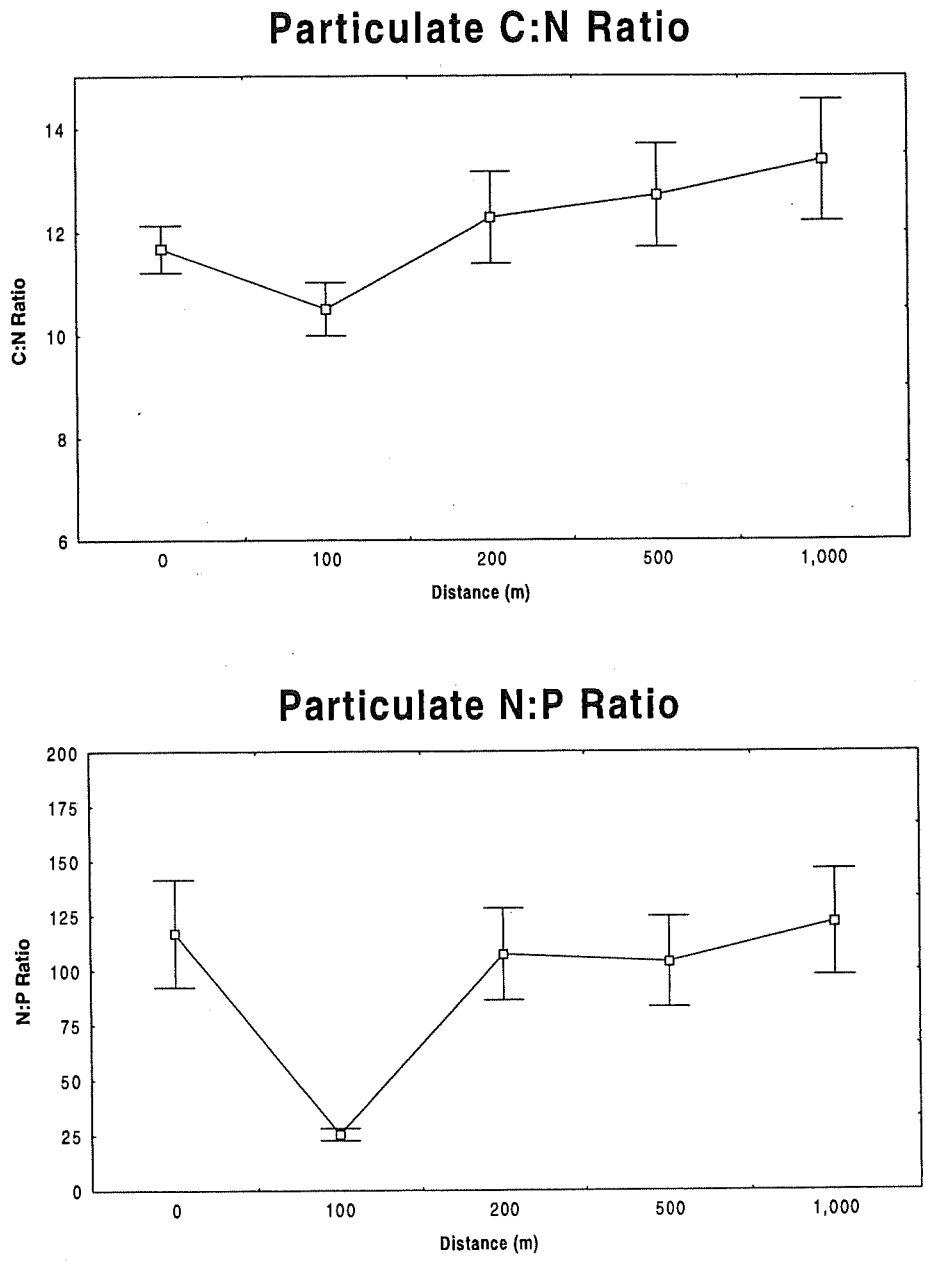


Figure 17. Mean particulate nutrient concentration (PC, PN, PP) along the Muddy Creek transect expressed on a volumetric (µg.L^{-1}) and gravimetric (µg.g^{-1}) basis.

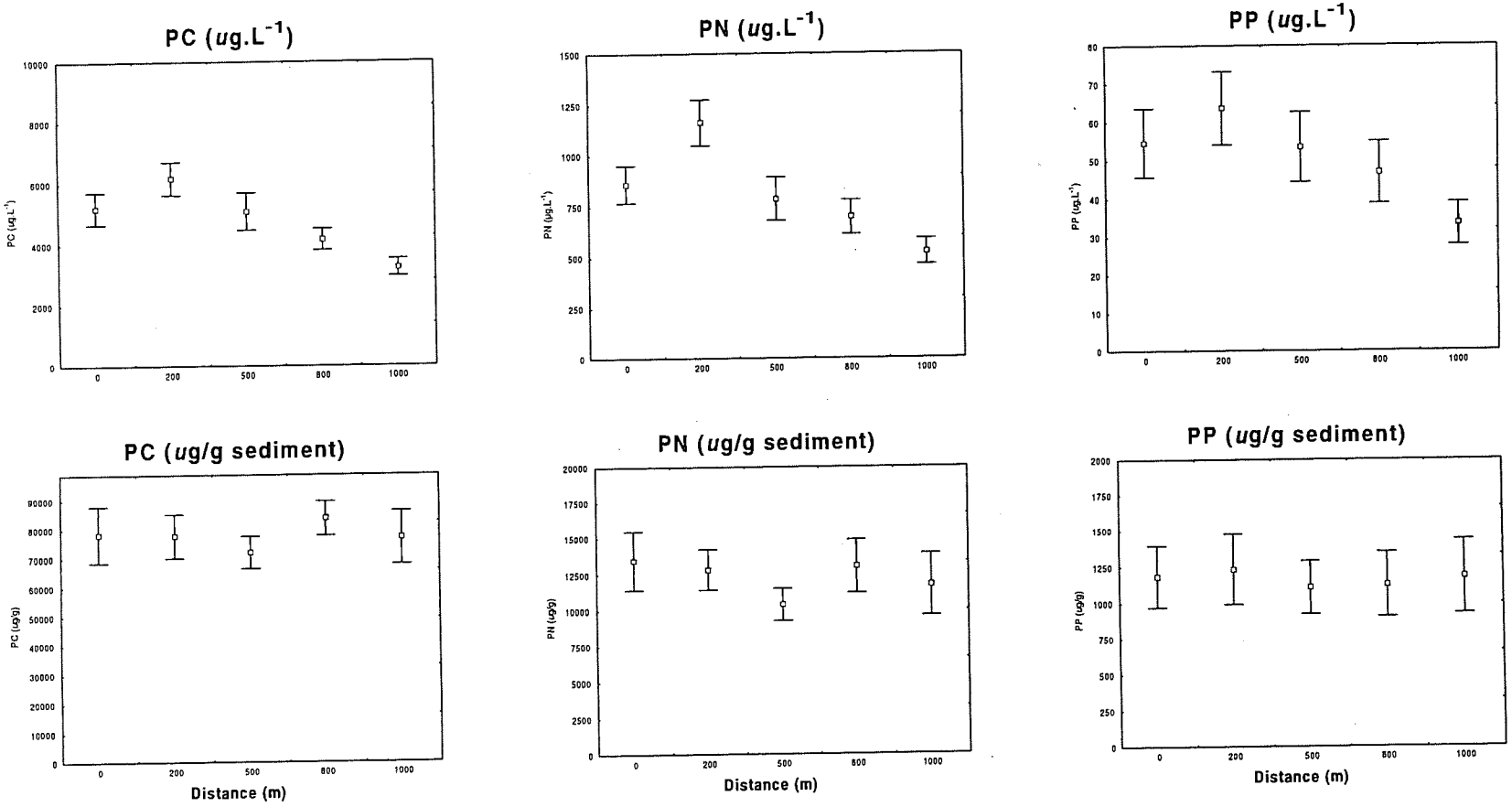


Figure 18. Mean particulate nutrient concentration (PC, PN, PP) along the Sandfly Creek transect expressed on a volumetric (µg.L^{-1}) and gravimetric (µg.g^{-1}) basis.

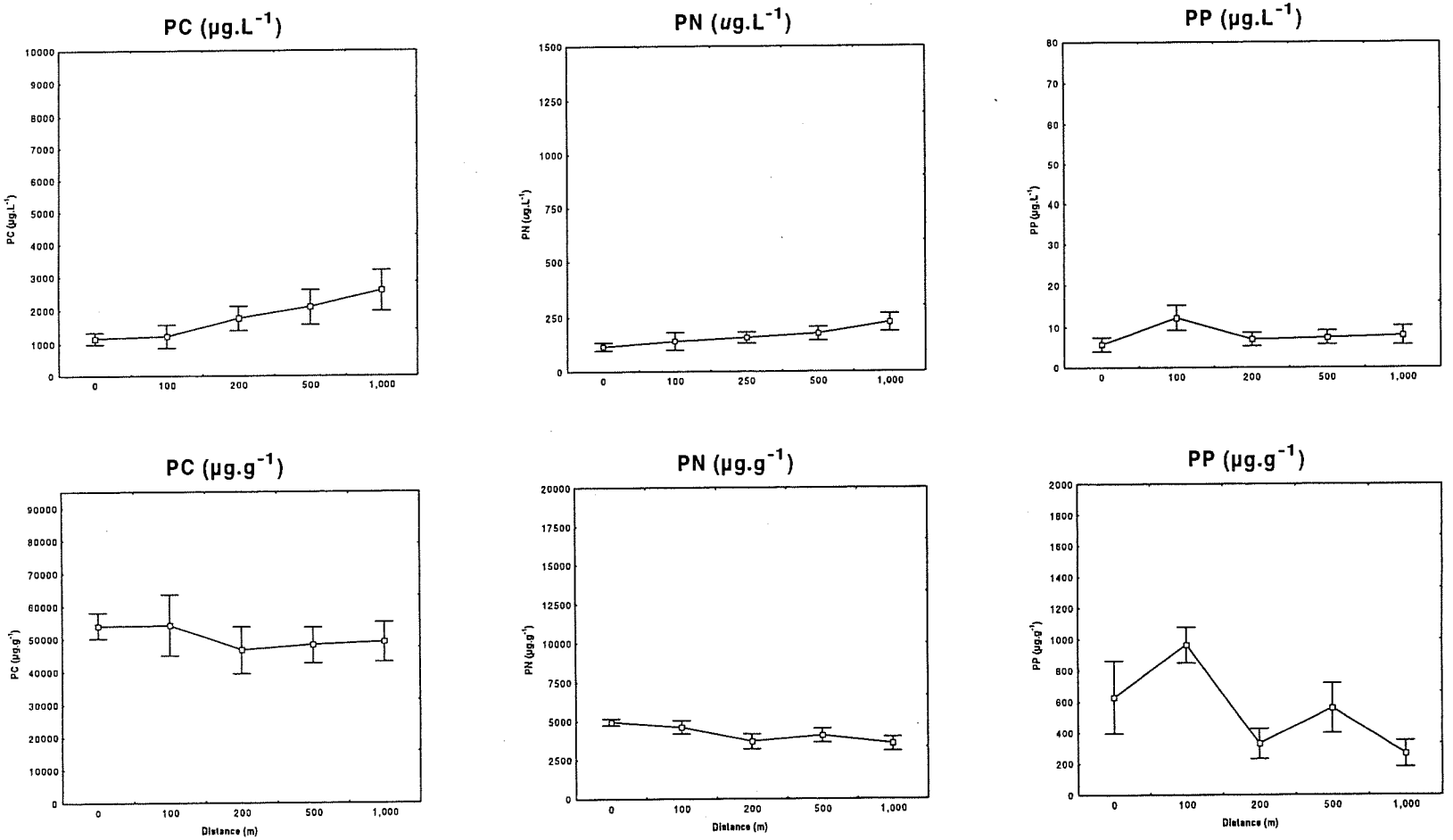


Figure 19. Mean dissolved concentration (TDN, DON, TDP, DOP) and ratios of DOC:DON and DON:DOP along the Muddy Creek transect.

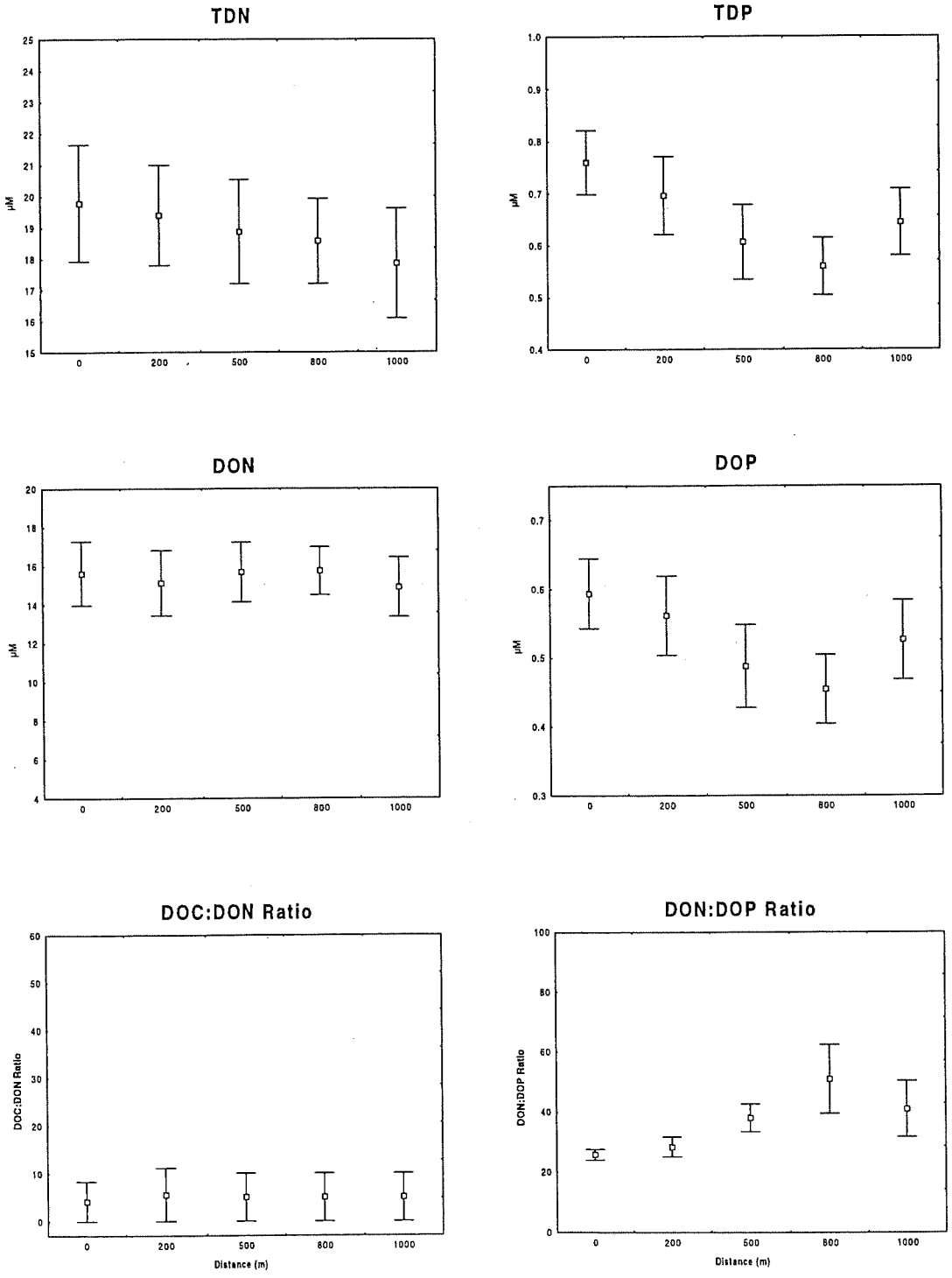
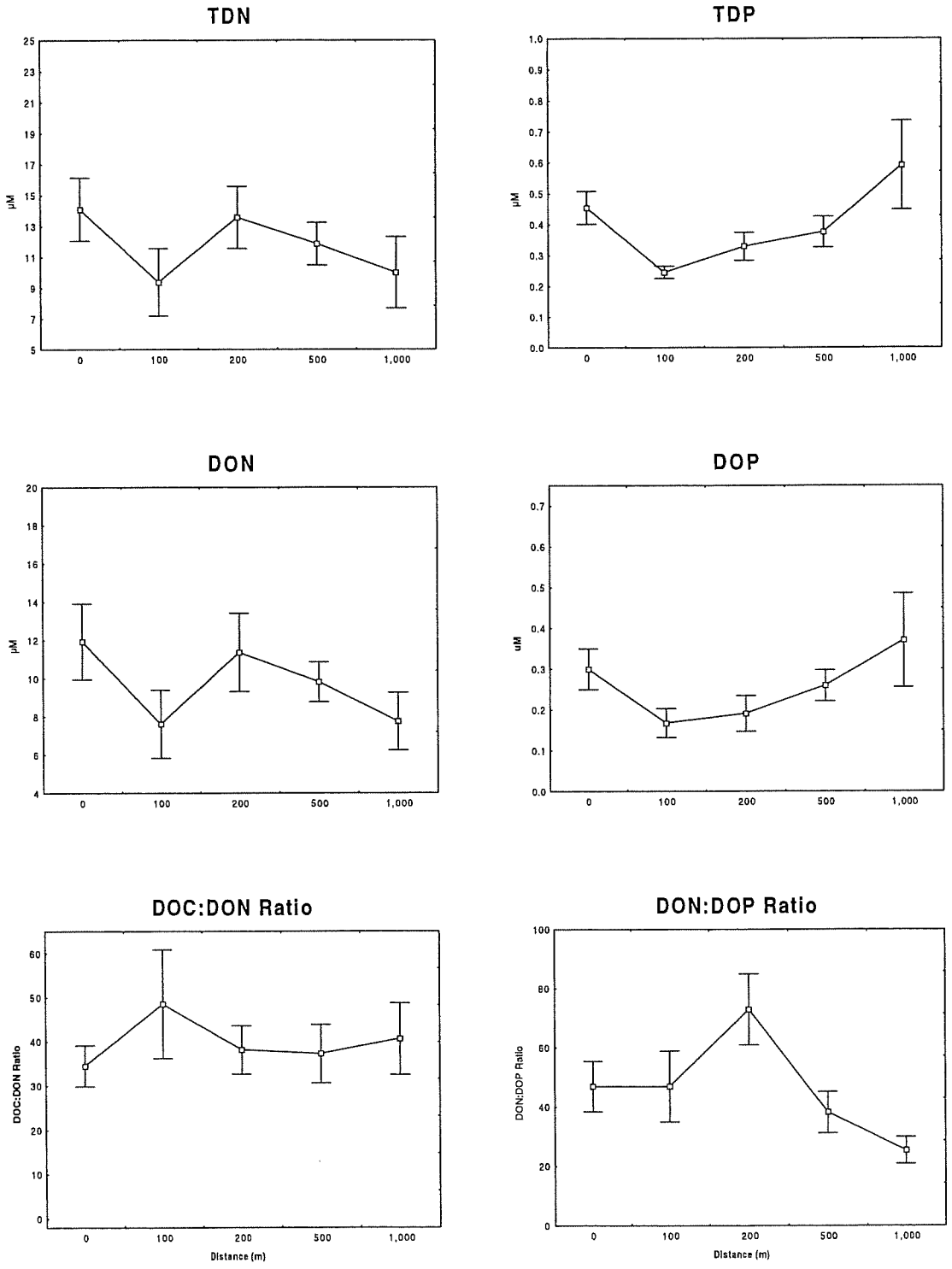


Figure 20. Mean dissolved concentration (TDN, DON, TDP, DOP) and ratios of DOC:DON and DON:DOP along the Sandfly Creek transect.



Carbon and Nitrogen budgets

Methods

Calculations of annual C and N budgets (Table 3) expressed as moles/year, were carried out for the upper end of Muddy Creek using the following assumptions and approximations.

Benthic chamber flux experiments and denitrification rates provided dissolved N, P and C fluxes into or out of the muddy sediments ($\mu m.m^{-2}.d^{-1}$) which were multiplied by the area of the creek bed and the number of days per year. The figures used were the mean rates from replicate upstream and downstream locations in the wet and dry season. Oxygen consumption rates by the benthos were converted to C (as CO_2 production). Sedimentation rates of PC, PN and PC were calculated from replicate samples taken from pond and discharge drain water. The water was allowed to settle for up to 12 hours in Imhoff cones during which time replicate cones were sacrificed to estimate the settling dynamics of the individual parameters. A 2 hour settling time was used to estimate the rates, as this time interval was observed during slack water in the upper ends of these tidal creeks neap to moderate tides. Rates obtained ($\mu g/l/day$) were multiplied by the estimated neap and spring tide volumes of water in the top ends of the creeks, extrapolated over one year to include oscillations between spring and neap tide volumes. Inputs to Muddy Creek from the prawn farm were calculated from data supplied by Sea Ranch Pty Ltd for operations on their farm. This data included pond stocking densities, feeding rates, fertiliser additions, harvest weights, discharge volumes, and food conversion ratios (FCR). N and P content of feeds was obtained from the manufacturer's feed labels, and estimated nutrient discharge from the ponds was estimated from published (Funge-Smith and Briggs 1998, Martin *et al.* 1998, Paez-Ozuna *et al.* 1999,Teichert-Coddington *et al.* 2000, Preston *et al.* 2001c). See Figure 21 for a diagram outlining the major steps in estimating the annual C budget in and Figure 22 for a diagram outlining the major steps in estimating the annual N budget. See Table 3 (below) for estimates of the mean annual fluxes of C and N in the creeks.

Denitrification in the inter-tidal creek area between M1 and M2 (estimated at 10,000 m^2) could reduce the NO_3^- load from the farm by:

10,000 m2 x 57.06 μm $N_2/m^2/hr$ x 24 hrs x 365 days

= 4.999 x 10^9 μm = 4.999 x 10^3 moles N_2

= 1.3996 x 105 gm or 139.96 kg N as N_2 gas/yr.

The maximum rates observed in Muddy Creek were approximately 10 times the mean rate, and therefore the maximum potential removal of N from the creek if the entire area operated at maximum rates would be approximately:

10 x 140 kg N_2 gas/yr = 1,400 kg N_2 gas/yr

We used a figure of 60% of added N discharged in the outflow water when estimating the annual N loading from the farm (published range = 11.2% in Paez-Osuna *et al.*

1999, 26.2% in Martin *et al.* 1998, 27% in Funge-Smith and Briggs, 1998, 57% in Preston *et al.*, 2001c, 80% in Martin *et al.*, 1998). Using the figure of 60% and data provided by the prawn farm (harvest weight and total food supplied), the following N discharges from Sea Ranch were estimated:

2,068 kg 97/98
1,500 kg 98/99
1,560 kg 99/00

Using these estimated N discharges, the mean and maximum denitrification rates could remove between 6.8% and 67.7% in 97/98 and between 9.0 to 90% in the following years. However, due to the heterogeneous nature of mangrove soils and their microbial activity, the maximum denitrification rates are highly unlikely to be experienced over the entire creek area, or for an entire year. Therefore, we used the mean rate of denitrification in our budget calculations (below).

Figure 21. Diagram outlining the major steps in the C budget constructed for Muddy Creek.

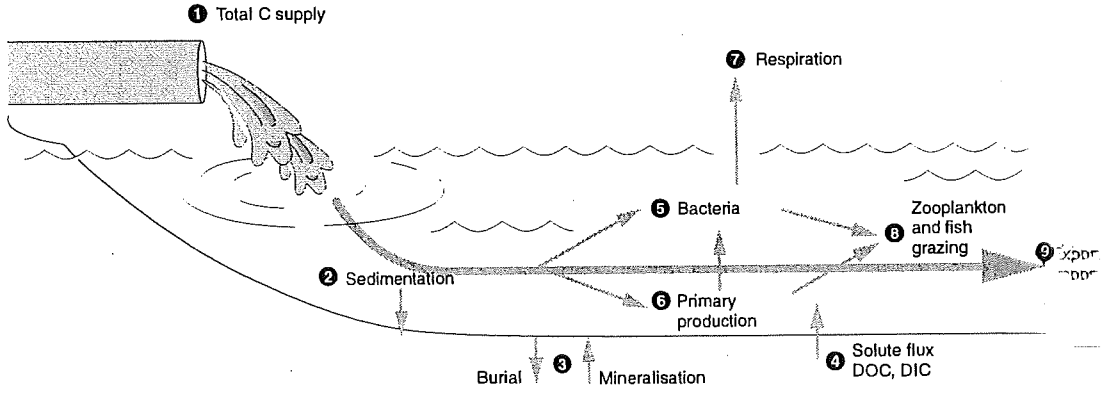


Figure 22. Diagram outlining the major steps in the N budget constructed for Muddy Creek.

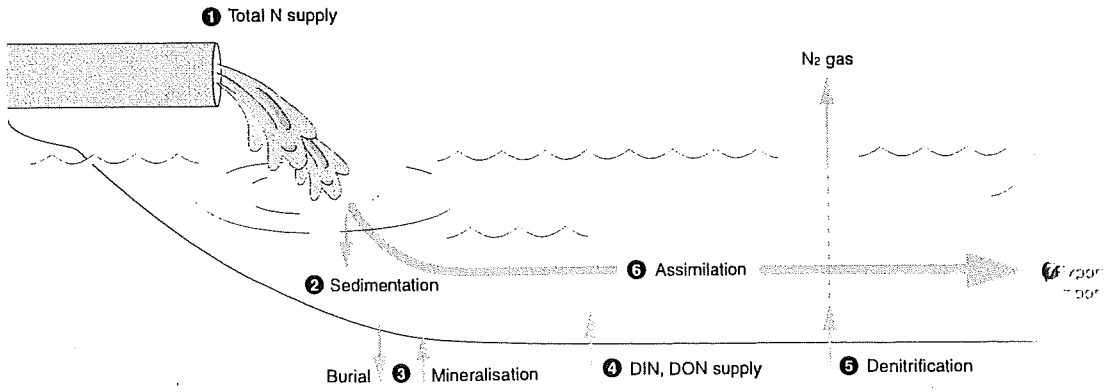


Table 3. Estimates of mean annual fluxes of C and N at the upper ends of Muddy Creek and Sandfly Creek (moles/yr).

Carbon			
		Muddy Creek	**Sandfly Creek**
1. Rate of farm supply	PC	2.04×10^5	None
	DOC	1.81×10^6	None
2. Sedimentation		3.66×10^5	3.61×10^4
3. Mineralisation (benthic respiration)		9.15×10^4	1.8×10^5
Burial		4.27×10^5	None
4. Solute flux	DOC	-1.53×10^5 (into mud)	-5.6×10^4 (into mud)
5. Incorporation into microbes		7.3×10^4	2.74×10^4
6. Primary production		1.15×10^5	3.07×10^4
7. Respiration (pelagic)		1.46×10^5	
8. Zooplankton and fish		????????	????????
9. Fluxes (export)		3.9×10^6 (= 46,800 kg)	

Nitrogen			
		Muddy Creek	**Sandfly Creek**
1. Rate of farm supply		1.71×10^5	None
2. Sedimentation		4.38×10^4	3.49×10^3
3. Mineralisation		5.72×10^3	7.38×10^3
Burial		3.81×10^4	None
4. Benthic DIN/DON supply		8.41×10^3	8.53×10^2
	NH_4^+	7.57×10^3	3.29×10^3
	NOx	-2.5×10^2 (into mud)	-6.71×10^1 (into mud)
	DON	1.09×10^3	-2.37×10^3 (into mud)
5. Denitrification		1.0×10^4	5.89×10^3
6. Assimilation into phyto N^{15}		2.7×10^4	
7. Fluxes (export)		4.6×10^5 (= 6,412 kg)	

TSS exports = 2.29×10^5 kg/yr
Chl *a* exports = 285 kg/yr

Results and Discussion

CARBON BUDGET

Sedimentation rates in Muddy were relatively high, as expected from a creek receiving prawn farm effluent. Additional material derived from the mangrove forests was not directly estimated, but is included in these budget estimates. The calculated rates of sedimentation may also include material deposited in previous slack water periods and resuspended in subsequent tides. Resuspension of sediments (See Transect Results) has been shown to be an important feature in the scouring of mangrove creeks (Wolanski *et al.* 1980). The scouring of mangrove creeks by stronger ebb tide currents can move settled particulate material downstream via resuspension and transport in currents. This action can contribute to the elevated sedimentation rates observed here.

Several steps in the turnover of C in Muddy Creek occur at higher rates than in Sandfly Creek. Firstly, the primary production and microbial uptake rates in Muddy Creek are significantly greater than in Sandfly Creek (Table 3), secondly the DOC flux into the mud is twice as high in Muddy Creek, whereas the benthic respiration rates for C loss are similar in both creeks. The rates of benthic and pelagic C processes within the Muddy Creek transect represent a small fraction of the supply rate from the prawn farm, suggesting accumulation of material is occurring here. Sandfly Ck was estimated to have slightly negative or zero burial of both N and C due mainly to the tenfold lower levels of sedimentation (Table 3.). This supports previous observations (Alongi *et al.* 1998) which showed that when high sedimentation rates are combined with rapid burial, release of C from the sediments is inhibited. The rate of 1.65×10^7 M $C_{org}.yr^{-1}.km^{-2}$ obtained by Alongi *et al.* (1998) for combined benthic and pelagic respiration rates in Hinchinbrook Channel are similar to the rates obtained here from upper Muddy Creek (2.1×10^7 M $C_{org}.yr^{-1}.km^{-2}$).

Supply exceeds turnover in many steps of the C budget in Muddy Creek, for example:

- 82% of the farm derived carbon input is buried rather than mineralised
- sediment respiration accounts for only 2.4% of the rate of C supply
- primary production in Muddy Creek is 3.7 times higher than in Sandfly Creek
- P/R ratio is 0.78 in Muddy Creek, revealing that the high primary production rates are exceeded by even higher rates of respiration
- only 4% of the C supply rate is lost from the system as CO_2, even though pelagic respiration rates are very high in Muddy Creek
- C supply from the farm is 33 times greater than the primary production rate of C incorporation
- net annual flux of C out of the upper section into the middle reaches of Muddy Creek is 3.90×10^6 moles (46,800 kg)
- lower sedimentation rates in Sandfly Ck, combined with reasonable mineralisation rates, result in no net C accumulation

The estimated annual fluxes of C and other nutrients, as reported in the Tidal Flux section, reinforce the conclusion that C in the prawn farm effluent is above the assimilative capacity of the upper reaches of Muddy Creek. Particulate organic carbon (POC) exports from similar mangrove forests in the region were estimated at 3,322 kg C $ha^{-1}.yr^{-1}$ (Robertson *et al.* 1992). In the present study, upper Muddy Creek (including prawn farm discharge) exports an estimated 46,800 kg/yr from a mangrove forested area of approximately 10 ha between M1 and M2. This provides a comparative figure of approximately 4,680 kg C $ha^{-1}.yr^{-1}$ exported from the upper end of Muddy Creek.

NITROGEN BUDGET

The rates of the various N transformation processes represent a small fraction of the rate of supply. The oversupply of N to the pelagic and benthic processes are highlighted by the following:

- uptake of N by primary production accounts for only 9% of the supply from the farm (estimated from a Redfield C:N ratio of 6:1 for actively growing phytoplankton (Valiela 1984)
- denitrification accounts for only 7% of the farm supply of N
- net annual flux of N out of the upper section into the middle reaches of Muddy Creek is 4.58×10^5 moles (6,412 kg)

The N^{15}-ammonium uptake rate by microbes in the water column were quite high (range 0.565-1.605 uM/hr) in the upper end of Muddy Creek. This range is similar to those measured in early growth season prawn ponds and in rivers in SE Queensland which are impacted by land based runoff (M. Burford, pers.comm.). Due to variability in the ammonium and PN concentrations, the ammonium uptake rates were likely to vary significantly over short time frames (M. Burford, pers. comm.). However, if we assume the following:

Average = 0.931 uM/hr
Av creek depth = 1.0 m
Creek surface area = 9,930 m^2
Day length = 8 hours (due to shading by turbid water and overhanging mangroves)
365 days/yr

This provides an estimate of 2.7×10^4 moles/yr of ammonium uptake through phytoplankton in the creek section M1-M2 of Muddy Creek (approx 1.3 km long). This is close to the estimated N uptake obtained by using the C:N ratio of 5.7 applied to C uptake by primary production in Step 6 in the C budget in Table 3 above (= 2.02×10^4 moles/yr). Taking Step 5 in this C budget (incorporation into microbes) and dividing by 5.7 (the C:N ratio), provides a N uptake of 1.28×10^4 moles/yr. By combining that figure with the estimated N uptake rates obtained from the N^{15}-ammonium results provides us with a total microbial N uptake in the M1-M2 section of 3.98×10^4 moles /yr.

This is from an estimated volume of 9,930 m^3 creek water. This equates to approximately 23% of the total N discharged from the farm (Step1 in N budget above). While this estimate appears to be high, it is entirely possible considering the high nutrient and mixing regimes of the creek.

Denitrification can potentially result in significant losses of N from estuaries (Rivera-Monroy and Twilley 1996) where adequate supplies of organic C, NO^{3-}, and a suitable low oxygen environment are available to denitrifying bacteria. However, lower rates observed in this study may be due to either a low supply of NO^{3-} from nitrification within the sediments, or low concentrations supplied from the overlying water. The low NO^{3-} concentrations in the farm discharge were discussed in the section on tidal cycles and tidal fluxes previously. While there were large amounts of particulate N and organic C in the farm discharge, there were consistently low concentrations of dissolved NO^{3-}. Low dissolved oxygen concentrations (DO) at the sediment surface can also cause reduced denitrification rates (Nowicki 1994). Datalogger monitoring of Muddy and Sandfly Creeks over several years (L.Trott, Final Report to Mossman Central Mill, 1998, unpublished) consistently shows that upstream DO levels can remain at around 30-40% saturation for several days during neap tides in these creeks. These levels of oxygen were identified in Dennison and Abal (1999) as being critical to the balance between the ability of muddy sediments to nitrify (NH_4^+ to NO^{3-}) or denitrify (NO^{3-} to N_2 gas). In that study, the denitrification efficiency was dramatically reduced when oxygen levels were reduced by 50%.

A net annual N flux of 10,234 kg $N.yr^{-1}$ was estimated from a much larger mangroves system (42.5 km^2) in Missionary Bay, Hinchinbrook Is. that does not receive prawn farm discharge (Alongi *et al.* 1992). In comparison, the Muddy Creek system of 10 ha (425 times smaller) exports approximately 6,412 kg $N.yr^{-1}$. The much higher N flux per unit area of mangrove from the Muddy Ck system is almost certainly the result of the demonstrated inputs from the prawn farm discharge.

Water column processes

Methods

SAMPLING SITES

We sampled at two points within the mangrove creek receiving effluent from prawn farm discharge, one immediately downstream of the point of discharge and another near the mouth of the creek. For comparative purposes equivalent stations were occupied in a nearby creek that did not receive effluent, and at a site approximately 500m offshore from the mouth of the discharge creek.

Seafarm (Stage 2) is a 30 hectare prawn farm located near Cardwell (Figure 1). Effluent is discharged into Pig Creek. Station Pig 1 (Pig 1) is located immediately downstream of the point of discharge, and Station Pig 4 (Pig 4) inside the mouth of Creek, some 2 km downstream. Similar positions were occupied in nearby Morris Creek.

Effluent from 13.5 hectare of prawn ponds at Sea Ranch, located near Mossman (Figure 2) is discharged into Muddy Creek. Station Muddy 1 (M1) is immediately downstream from the point of discharge, and Muddy 4 (M4) inside the creek mouth approximately 7 km downstream. In this case Sandfly Creek was the control creek.

SAMPLING REGIME

We sampled all sites between 0700 and 0900 on a full tide, to allow easy boat acce to each. At each site we measured O_2, pH, temperature and salinity using a Hydrol DataSonde 4 datalogger or by hand held instruments such as a refractometer (Bio-Marine Aquafauna, Inc), YSI O_2 meter and probe, and a Hanna pH meter. We took 500 ml water sample from beneath the surface for more accurate determination of salinity in the laboratory, and also for the determination of alkalinity. A 500ml water sample was taken and preserved with a final concentration of 10% Lugol's iodine fo the determination of microzooplankton, and a 20 ml sample preserved with 4% buffered formaldehyde for bacterioplankton abundance. We filled a 20L bucket with surface water and concentrated the mesozooplankton by pouring the contents of th bucket through a 37 µm mesh and backwashing it into a vial, to which we added formalin. Finally, a 2.5 litre acid-washed polycarbonate bottle was thoroughly rinsed with surface water, and gently filled with subsurface water, and maintained in the da at ambient temperature for transport back to shore. Light profiles through the water column at each station were measured with a Licor LI-1000 sensor in the middle of day, to better measure light extinction through the water column.

ESTIMATION OF STANDING STOCKS

Duplicate samples of appropriate volume (5 to 50ml) from the water collection at each station were filtered on 25 mm GF/F filters for the analysis of chlorophyll *a*. Filters were frozen and stored until subsequent extraction in 90% acetone and analysis of chlorophyll *a* by fluorometry (Strickland and Parsons 1972). A single 20mL water sample from each sample was fixed with 800 µL of formaldehyde for the later enumeration of bacterial abundance using the direct count method and the fluorochrome DAPI (4'6-diamidino-2-phenylindole) to stain bacterial cells (Porter and Feig 1980). Zooplankton abundance in the water column was calculated by counting either the entire 20-L water sample or appropriate subsamples taken with either a Stempel pipette or a Folsom Plankton Splitter. We identified copepodids to the level of suborder, and counted all copepod nauplii.

BACTERIAL PRODUCTION MEASUREMENTS

Bacterial production rates were estimated from the rate of incorporation of [^{3}H]thymidine into cold 5% trichloro-acetic acid (TCA) extracts of incubated water samples (Fuhrman and Azam 1982). Sets of 5 10-ml water samples from each station were incubated with 5nM [^{3}H-methyl]thymidine (Amersham, specific activity 3.03 TBq mmol^{-1}) for 60 minutes, extracted in ice-cold 5% TCA, filtered on to 0.2 µm Poretics membrane filters, rinsed with 1-2 ml of ice cold 3% TCA, and put into scintillation vials. An additional set of 5 water samples was killed with 2% formalin and incubated in the same way, to act as abiotic absorption controls. Radioactivity retained on the filters was asayed with a Wallac WinSpectral scintillation counter, which automatically compensates for quenching. Estimated rates of cell production were calculated by multiplying the rate of exogenous [^{3}H]thymidine incorporation into TCA-insoluble material (mol. thymidine litre^{-1} d^{-1}) by 1.7 * 10^{18} cells.mol $^{-1}$ thymidine incorporated (Fuhrman and Azam 1982, for coastal bacterioplankton). Estimated bacterial carbon production rates were calculated assuming 2 * 10^{-14} g C.cell^{-1}.

PRIMARY PRODUCTION MEASUREMENTS

Eighteen 35 ml polycarbonate tubes were rinsed and filled with unscreened incubation water collected from each site. The tubes were rigorously cleaned prior to each incubation. We divided the tubes into 6 sets of 3, and spiked each with 185 kBq of ^{14}C bicarbonate (Amersham). One of each set of 3 was wrapped with aluminium foil and used as a dark (control) tube. Five sets of tubes were incubated in neutral shadecloth bags corresponding to 70%, 50%, 30%, 20% and 8% of full irradiance in an incubator filled with ambient water. The sixth set was exposed to full ambient light. Flushing the incubator with water collected from the nearby creek controlled temperature, which was continuous logged with a temperature recorder. The experimental tubes were incubated between about 1000 and 1400 local solar time. At the conclusion of the incubation, the tubes were transferred to a cool dark box and each filtered on to Whatman GF/F glass fibre filters. We acidified the filters with 100 µl of 1N HCl, and later measured activity by liquid scintillation (Wallac Winspectral). Hourly carbon

uptake rates were calculated according to Parsons *et al.* (1984), and areal production calculated by trapezoidal integration of the vertical light profiles. Daily primary production was estimated by dividing the production measured over the 4 hour incubation period by the fraction of total daily irradiance during that interval. This approach does not include carbon losses incurred by phytoplankton populations during the night from grazing and respiration, giving a production estimate closer to gross production.

MICROZOOPLANKTON GRAZING

Inoculum water for experiments was collected from beneath the surface with acid-cleaned 20 litre carboys. After collection, the inoculum water was pooled into a clean polycarbonate carboy. Dilutant water was pre-filtered with a series of 10μm, 5μm and 1μm cartridge filters. All plasticware and tubing used for handling experimental water was acid soaked in 5% HCl, rinsed thoroughly with Super Q water and finally with seawater from the experimental site. Appropriate volumes of particle-free dilutant water were prepared by vacuum filtration through Millipore Sterivac filter cartridges (0.22 μm pore). A new cartridge was used for each experiment. Prior to filtering the dilutant water, several litres of Super-Q water were passed through the new cartridge to remove impurities from manufacture, wetting agents and storage preservatives, followed by sufficient seawater to fully flush out any Super-Q remaining. To set up the dilution experiments, we made up mixtures of 0%, 5%, 10%, 25%, 50%, 75% and 100% raw seawater: filtered seawater in 2-litre batches. From each dilution mixture, we filled three 500 ml polycarbonate bottles. The experimental bottles were fully filled to leave only a very small bubble when closed. After filling, the experimental bottles were initially stored in dark boxes and finally placed in a cage covered with neutral density shade cloth (30% of incident light) which we floated in a nearby prawn pond. Seawater temperatures during the incubation were monitored with a data logger.

Water remaining from the bulk dilution mixtures was sampled to determine starting (T_o) chlorophyll concentrations and bacterioplankton abundances at each dilution level. The same measurements were made on the contents of each individual experimental bottle at the end of the 24-hour incubation period. Duplicate aliquots of water were filtered through 25 mm Whatman GF/F filters for the chlorophyll determinations. The filters were folded, placed in foil envelopes and frozen until analysis. Chlorophyll *a* concentrations were determined by fluorometry after grinding in 90 percent acetone (Parsons *et al.* 1984).

Changes in chlorophyll *a* and bacterial cell concentrations identified at the beginning and end of each incubation were used to calculate specific growth (k) and grazing (g) rates. These was calculated according to the exponential model of Landry and Hassett (1982):

$$C_t = C_0 e^{(k-g)t}$$

where C_0 and C_t are prey or chlorophyll *a* concentrations at the beginning and at the end of the incubation, respectively. This equation can be linearized as:

$$1/t \ln C_t/C_0 = k\text{-}g(x)$$

where x is the dilution factor, and t is time. Estimates of k and g were obtained by Model 1 linear regression (SAS Institute Inc. 1989).

Potential production(P_p), realised production(P_r) and proportion of potential production grazed (P_g) were calculated according to (Verity *et al.* 1996):

$$P_p = C_0e^{k}\text{-}C_0$$
$$P_r = C_0e^{(k\text{-}g)}\text{-}C_0$$
$$P_g = 100(P_p - P_r)/P_p$$

Chlorophyll *a* concentration was converted to an estimate of carbon biomass by applying a C:Chl *a* ratio of 50 (Strickland 1965).

ZOOPLANKTON GRAZING

Abundance data from the counts of ciliates, copepod nauplii and copepodids were used to estimate the biomass of each group, assuming an average carbon content of 1.2 pg for a ciliate (Hansen *et al.* 1997), 23 pg for a copepod nauplius (Taniguchi 1977), and 0.24µg for a 64-200µm copepod (Roman *et al.* 2000). We assumed food to be non-limiting, and estimated the production of each group as the product of applied literature values of growth rate calculated from the field temperatures at the time of sampling and the previously calculated biomass. For the ciliates, we assumed a maximum growth rate of 0.06 hr^{-1} and applied a Q_{10} of 2.8 (Hansen *et al.*1997). For copepod nauplii and copepodids we applied the model of Hirst and Sheader (1997) to estimate growth rate. Ingestion rates were calculated assuming 40% gross growth efficiency for the ciliates (Jonsson 1986), and 30% gross growth efficiency for copepods (Checkley 1980, Kiørboe *et al.* 1985). Total ingestion by ciliates, nauplii and copepodids was compared to the primary production and chlorophyll data assuming a C:Chl ratio of 50 (Strickland 1965).

Results and Discussion

The standing stocks discussed below are those of the water collected for the rate measurements, and are not intended to represent an in-depth analysis of standing stocks within the receiving waters.

PHYTOPLANKTON BIOMASS (Figure 23)

At Seafarm, standing stocks of chlorophyll *a* were similar at all stations during non-discharge periods, probably reflecting the short creeks in the area, and presumably low resonance times. During discharge periods, however, chlorophyll *a* concentration within Pig Creek was greatly elevated over that in Morris Creek or offshore. The situation was similar at Sea Ranch, though the upper reaches of Muddy Creek tended

to have higher chlorophyll *a* concentrations during non-discharge periods than the other creeks.

BACTERIOPLANKTON ABUNDANCE (Figure 24)

At Seafarm, bacterioplankton abundance was similar at all stations during the non-discharge period in June 1998, but in March 1999 bacterioplankton were more abundant in the upper reaches of Morris Creek (the non-discharge creek) than at other stations. The discharge period during October 1998 resulted in only slightly elevated bacterioplankton numbers in the upper reaches of Pig Creek, but in December 1998 all of Pig Creek had bacterioplankton densities similar to that of the prawn ponds themselves. At Sea Ranch, non-discharge periods had similar numbers at all stations, but in the discharge period of November 1999 Muddy Creek was slightly elevated in abundance, but in September 1999 the upper reaches of Muddy Creek had greatly elevated numbers.

PRIMARY PRODUCTION (Figure 25)

At Seafarm, areal primary production ranged between 20 and 708 mg $C.m^{-2}.d^{-1}$ during non-discharge periods (Figure 25). In the October 1998 discharge period primary production was higher at all stations, including those in the non-discharge creek, where these rates were twice those measured during non-discharge periods. In the upper and lower reaches of Pig Creek primary production was 4-fold and 2-fold higher respectively, than at other stations. However, in the December 1998 discharge period primary production in the upper reaches of Pig Creek exceeded that in the pond itself, at about 5 g $C.m^{-2}.d^{-1}$. Offshore and in Morris Creek primary production was at background levels, at less than 600 mg $C.m^{-2}.d^{-1}$. The lower reaches of Pig Creek were intermediate in value.

At Sea Ranch background levels during non-discharge periods, especially in the lower reaches of Muddy Creek, tended to be higher than those observed at Seafarm. The discharge period in September 1999 had primary production rates in the upper reaches of Muddy Creek comparable to those observed during discharge periods at Seafarm, but these dissipated to background levels in the lower reaches and offshore. In November 1999 primary production actually increased in the upper reaches of Muddy Creek over the rates observed in the ponds themselves, to a level of about 4.5 g $C.m^{-2}.d^{-1}$. For comparison, a sugar cane field, one of the most productive ecosystems known, produces ~10 g $C.m^{-2}.d^{-1}$. We interpret the increase in production downstream of discharge to the effects of mixing nutrient rich waters with nutrient-limited natural phytoplankton communities, and to the effects of tidal mixing. However, in the lower reaches of the estuary primary production rates had fallen to levels only marginally higher than background.

Figure 23. Chlorophyll *a* concentrations in mangrove creeks at Seafarm (left panel) and Sea Ranch (right panel). Discharge periods are represented by black bars, non-discharge periods by grey bars.

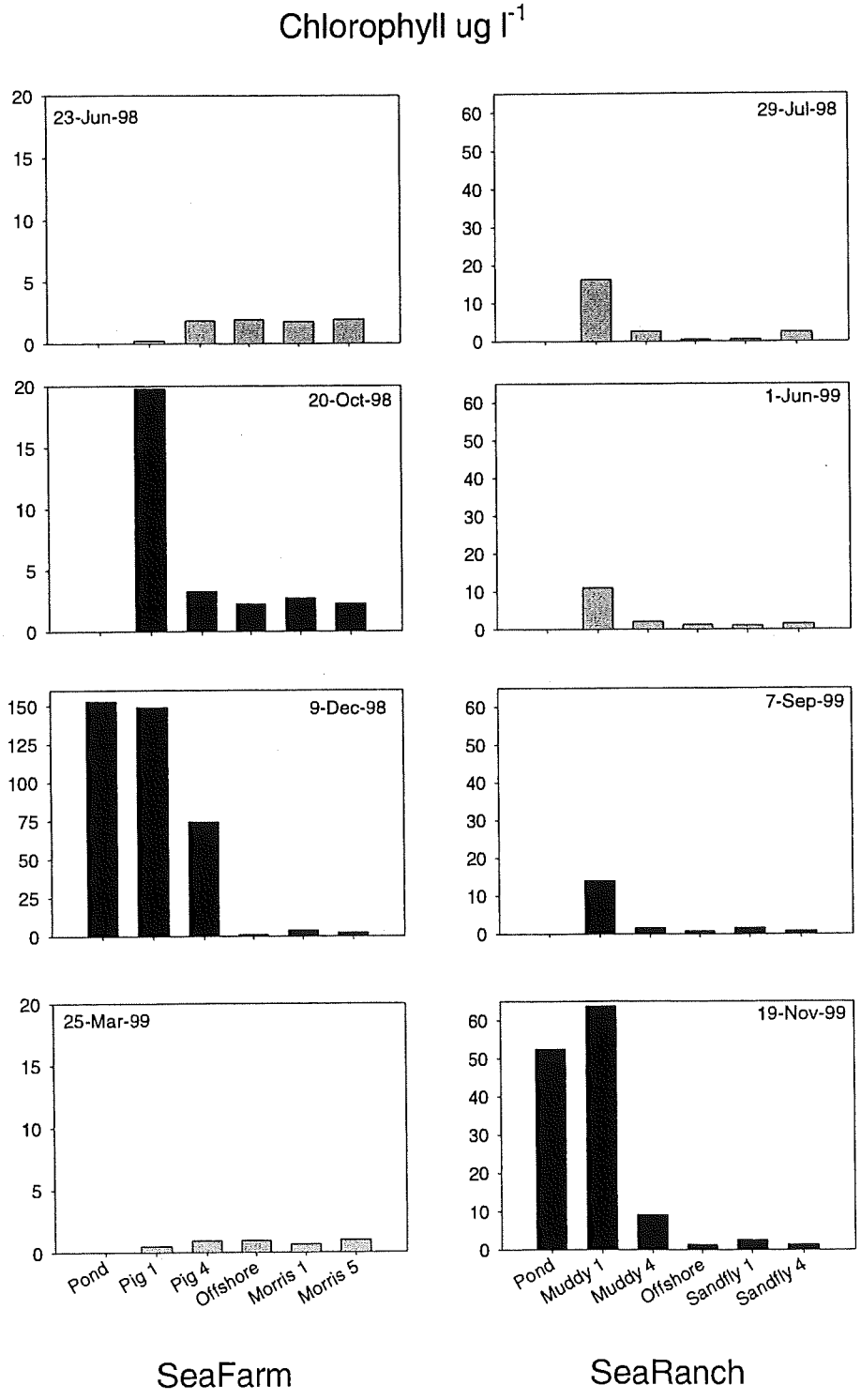


Figure 24. Bacterioplankton abundance, as for Figure 23.

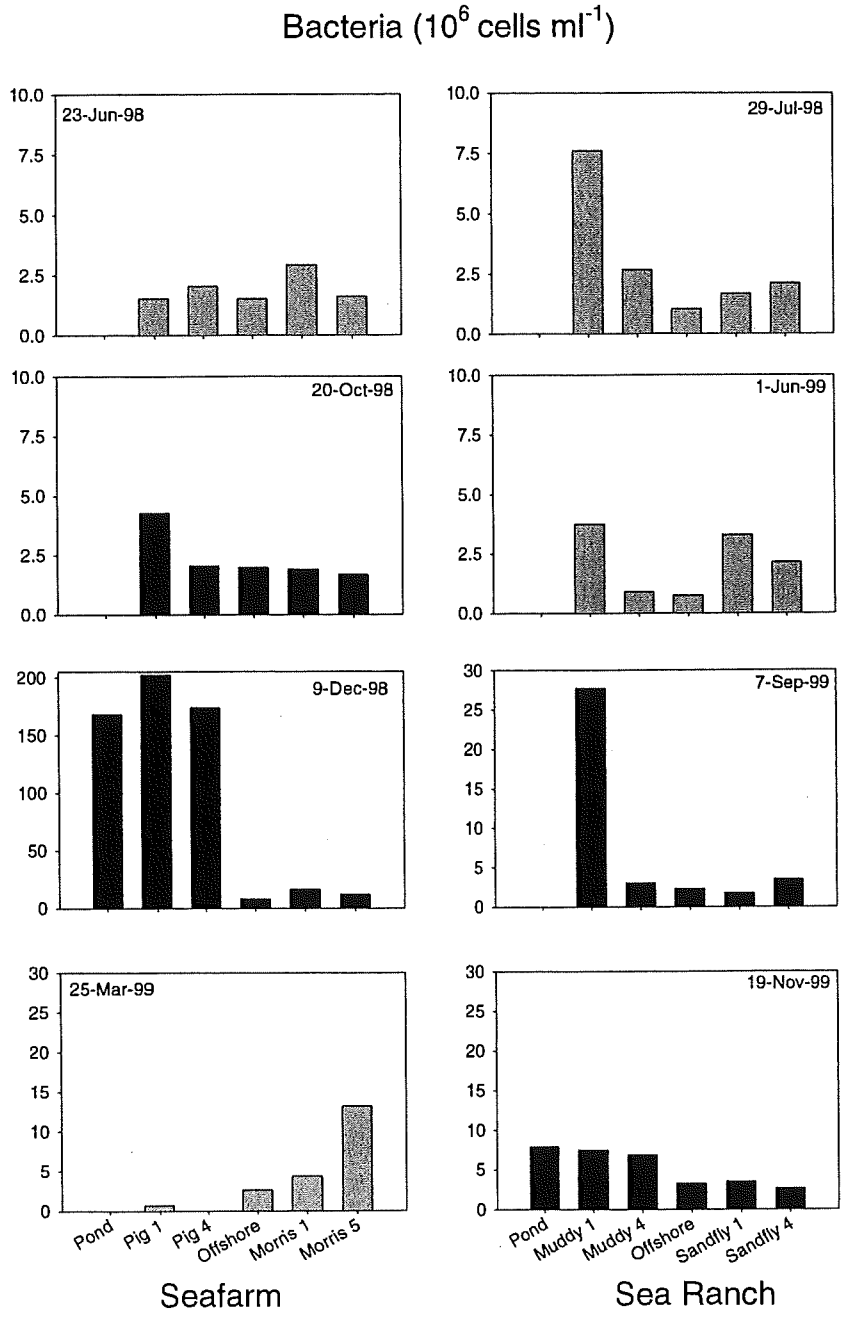
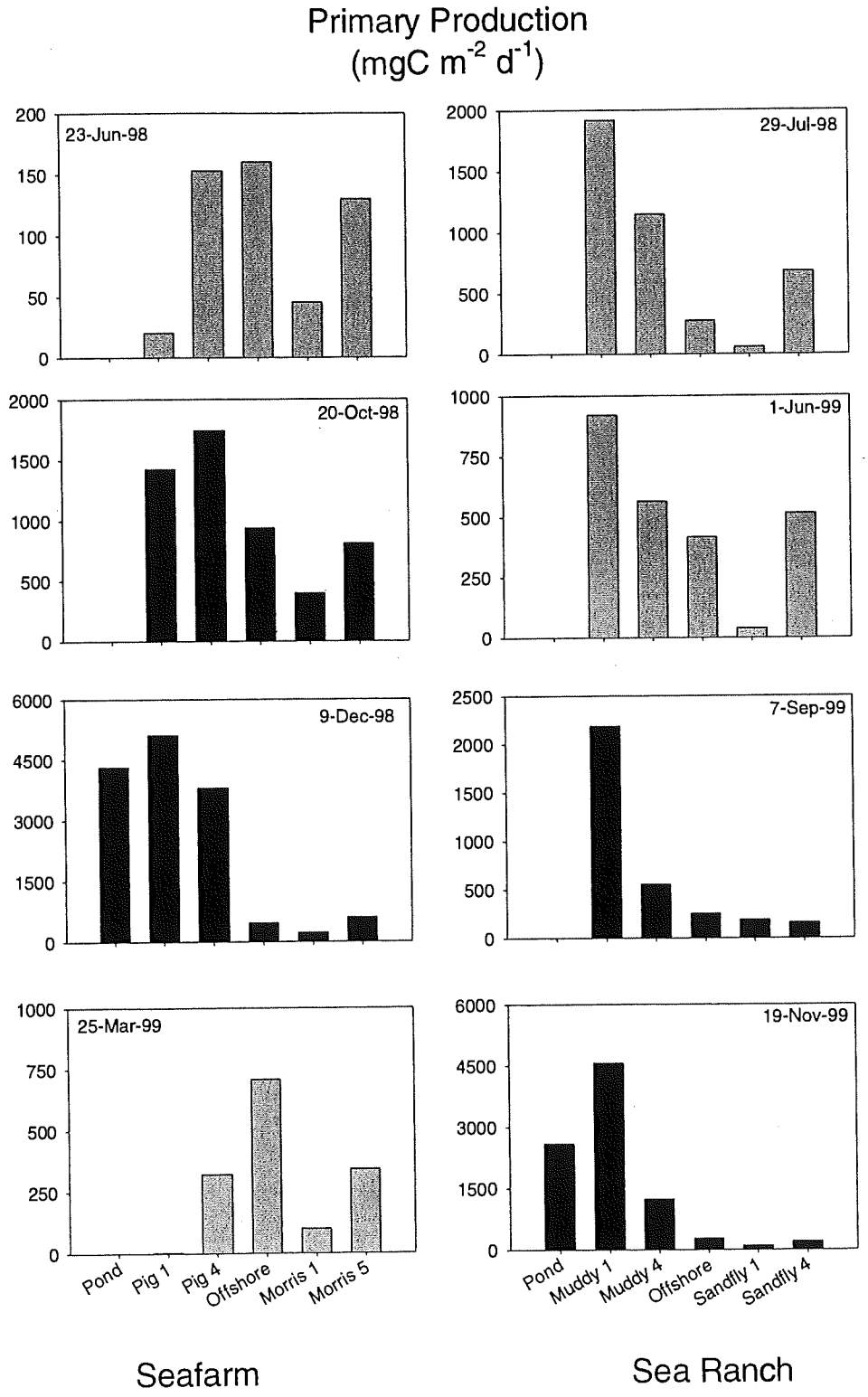


Figure 25. Primary production, as for Figure 23. Areal production rates were modelled as described in the Methods, except for 9-Dec-98 when the light extinction coefficient measured within prawn ponds by Burford (1997) of 3.67 was used for the Pond and Pig 1 stations because of unusually high chlorophyll concentrations (see Figure 23).



BACTERIAL PRODUCTION (Figure 26)

To minimise the effects of variable water depth, we report bacterial production rates by volume rather than by area. Non-discharge rates of bacterial production were similar at both Seafarm and, between 20 and 90 mg $C.m^{-3}.d^{-1}$, though the upper reaches of Muddy Creek (Sea Ranch) were consistently 4-higher than elsewhere. During discharge periods, bacterial production rates increased approximately 4-fold in the upper reaches of Pig Creek (Seafarm) or Muddy Creek (Sea Ranch).

CILIATE ABUNDANCE (Figure 27)

The abundance of ciliates was higher in the upper reaches of the discharge creeks during periods of discharge at both Seafarm and Sea Ranch. In December 1998 at Seafarm the highest abundances were recorded, and may reflect the incorporation of a pond community (often dominated by *Euplotes*) into the naturally occurring community.

COPEPOD ABUNDANCE (Figure 28)

With one exception (Sandfly 4 in November 1999) copepod abundances were highest in the lower reaches of the creek systems, and offshore.

MICROZOOPLANKTON GRAZING (Tables 4, 5 and Figures 29, 30)

We conducted one dilution experiment at Seafarm (Station P2 on 25-Mar-99), and 7 at Sea Ranch. The experiments in March and June 1999 were during non-discharge periods, and those in September and November during discharge periods. In June and September1999 we conducted experiments at two locations at Sea Ranch, and in November 1999 at three locations (Table 4). Significant effects of dilution on apparent growth rates of phytoplankton, measured as chlorophyll *a*, occurred in all 8 experiments. However, we were unable to detect any effect of dilution on bacterioplankton growth rate in 4 experiments, all of which were in the detritus-rich upper areas of the discharge creeks.

Three of the chlorophyll-based dilution experiments had non-significant regression statistics in the less dilute treatments, indicating saturation of microzooplankton grazing by the availability of food resources (Figure 29). Saturated grazing did not always occur in experiments with the highest phytoplankton concentrations in natural water. For example, the experiment of 25-Mar-99 had chlorophyll *a* concentrations of only 0.30 $\mu g.L^{-1}$, although in this experiment the creek system had been inundated with floodwaters and the salinity was only 5. In both September and November 1999, there was non-saturated grazing immediately downstream from the discharge point (M2, 6-Sep-99 and 18-Nov-99), but grazing was saturated further downstream at M4. In November 1999, grazing was again non-saturated offshore.

With one exception, microzooplankton grazing equalled or exceeded phytoplankton growth in the discharge creek and nearby offshore waters (Table 4). This exception

occurred in the 18-Nov-99 experiment at M2, during the discharge of a phytoplankton bloom (chl = 56 $\mu g.L^{-1}$). Grazing was saturated in the 20-Nov-99 experiment at M4. Offshore, in the 21-Nov-99 experiment, the expected equilibrium condition of growth and grazing in balance was obtained.

In the case of bacterivory (Figure 30), grazing was saturated in all experiments. The grazing rates obtained in the highest dilution levels exceeded bacterial growth approximately three-fold. In the 21-Nov-99 experiment at M6, two significant regressions were obtained, one for dilution levels ~ 50% and one for dilution levels < 50%. In all cases grazing exceeded bacterial production (Table 5).

The high levels of microzooplankton grazing observed here imply that there is an effective biological mechanism for uptake of particulate organic matter discharged into the creek.

Table 4. Phytoplankton community growth, production and grazing parameters based on chl *a*, assuming a C:chl ratio of 50.

Station	Initial Chl *a* µg Chl l^{-1}	*k*	*g*	P_p µg C l^{-1} d^{-1}	P_r µg C l^{-1} d^{-1}	P_g % d^{-1}
			MARCH 1999			
P2	0.30	0.60	2.13	12.3	-11.7	195
			JUNE 1999			
M3	3.78	0.58	0.61	149	-5.6	104
Offshore	1.06	0.58	0.60	42	-1.0	103
			SEPTEMBER 1999			
M2	29.59	0.82	0.94	1880	-167	109
M4	2.75	1.19	2.56	314	-103	133
			NOVEMBER 1999			
M2	56.34	0.67	0.38	2688	948	65
M4	4.33	1.68	3.64	945	-186	120
Offshore	1.82	1.10	1.08	182	1.8	99

Table 5. Bacterioplankton community growth, production and grazing parameters assuming $2 * 10^{-14}$ g C $cell^{-1}$ (Lee and Fuhrman 1987)

Station	Initial cells ml^{-1} $*10^6$	*k*	*g*	P_p g C m^{-3} d^{-1}	P_r g C m^{-3} d^{-1}	P_g % d^{-1}
			JUNE 1999			
Offshore	1.55	2.64	10.14	0.40	-0.03	108
			SEPTEMBER 1999			
M4	1.40	1.90	5.23	0.16	-0.03	117
			NOVEMBER 1999			
M2	1.50	3.31	11.79	0.79	-0.03	104
M4	1.87	1.28	5.70	0.10	-0.04	138
Offshore	1.87	0.04	0.11	0.00	0.00	266

Figure 26. Bacterial production, as for Figure 23.

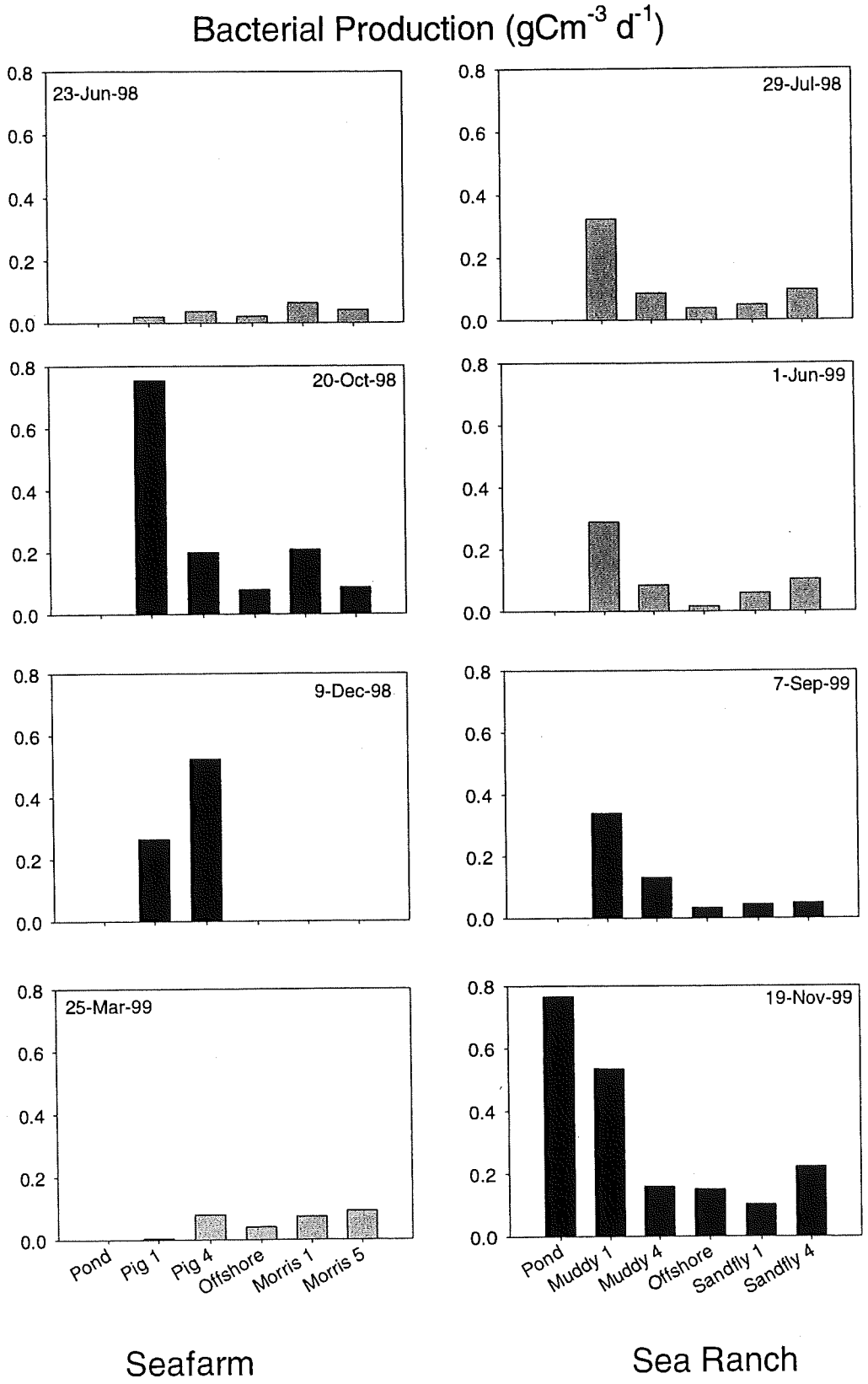


Figure 27. Abundance of ciliates, as for Figure 23.

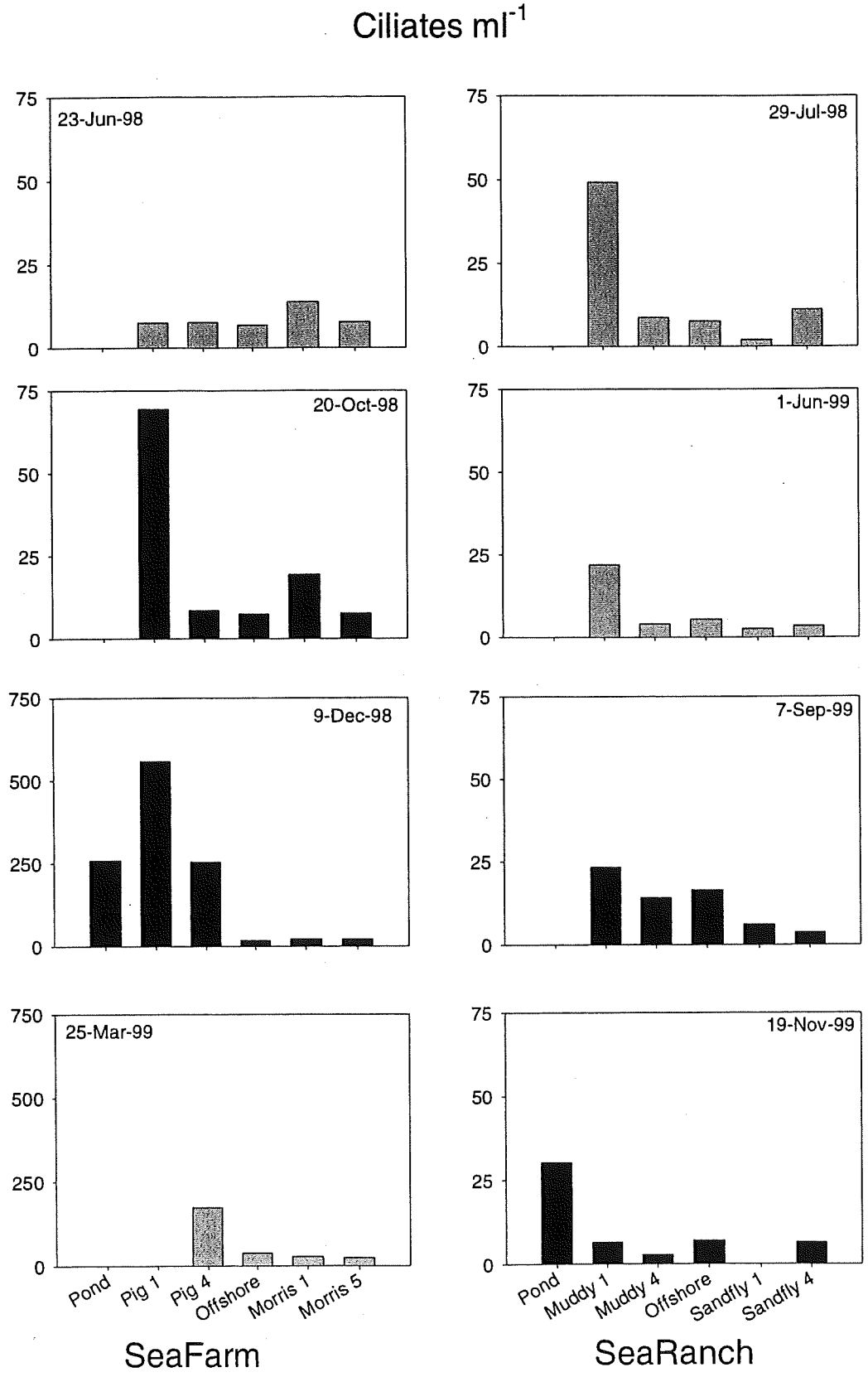


Figure 28. Composition and abundance of copepodids L^{-1} at each station. Discharge periods are indicated by bold borders.

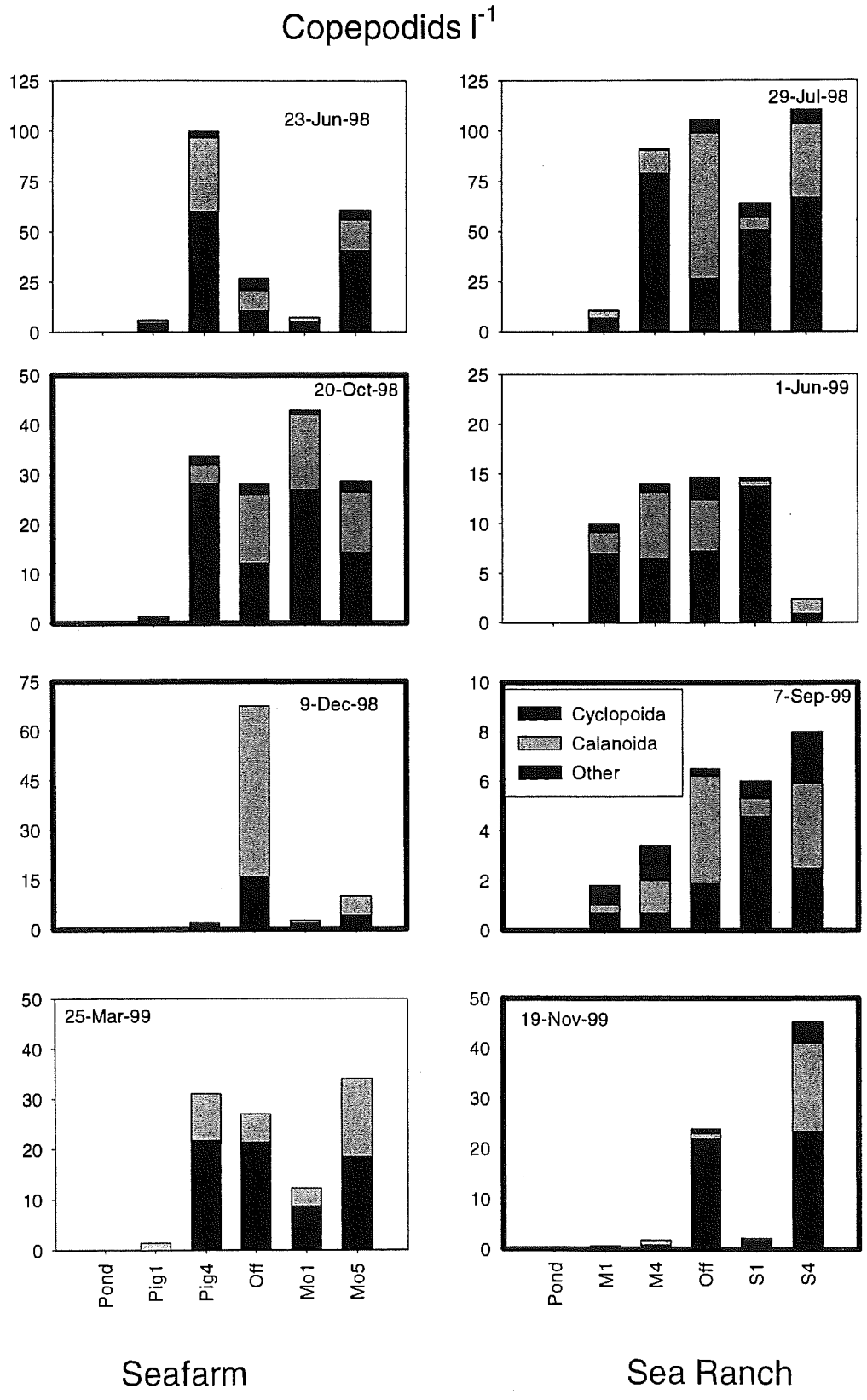


Figure 29. Dilution experiment plots based on chlorophyll *a*. March and June experiments were conducted during non-discharge periods, September and November experiments during discharge periods.

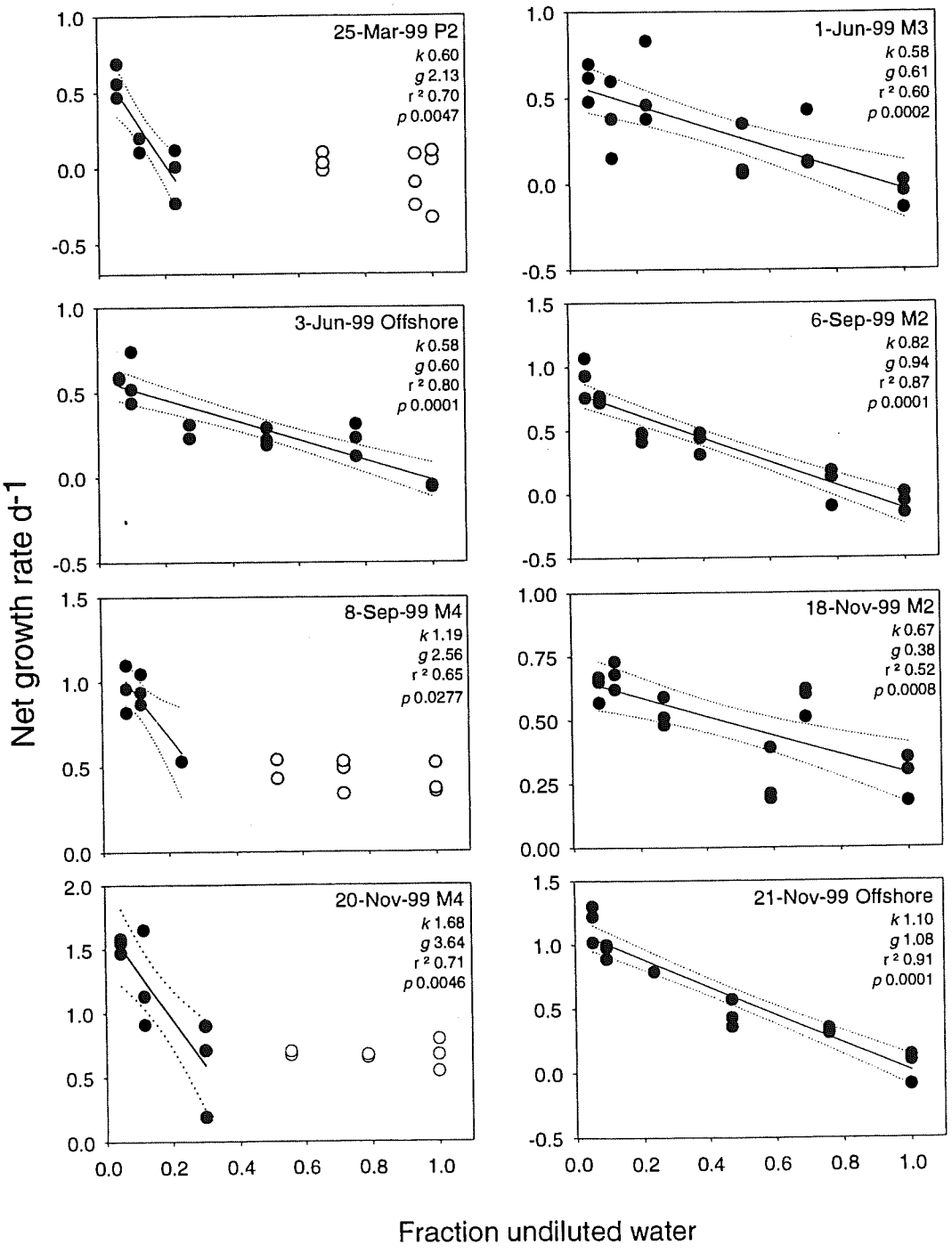
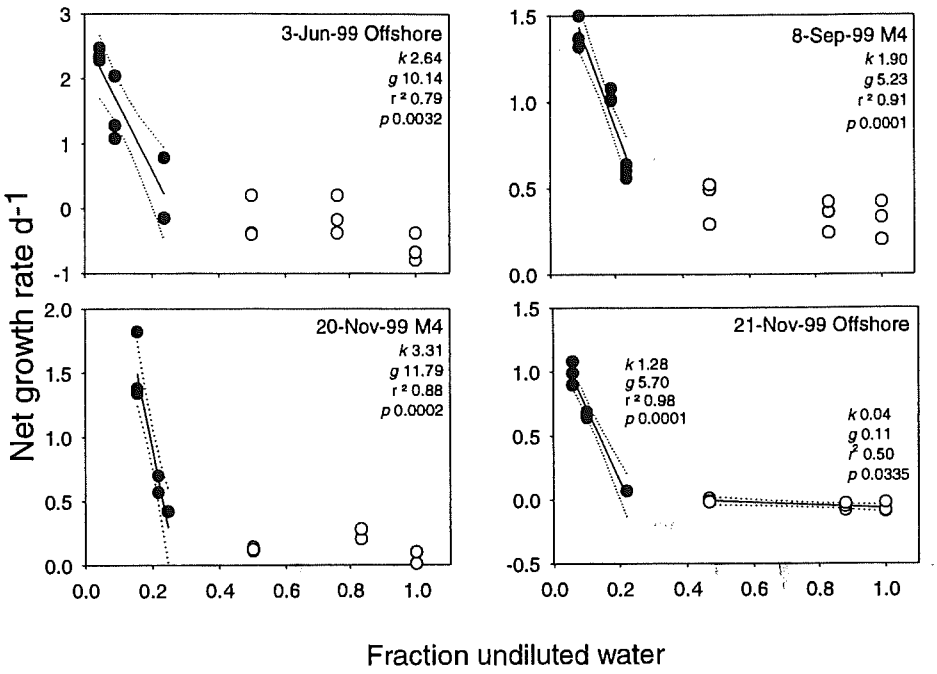


Figure 30. Dilution experiment plots based on bacterioplankton abundance (as for Fig. 29)



ZOOPLANKTON GRAZING (Figures 31, 32)

The potential grazing impact of ciliates far exceeded that of copepod nauplii and copepodids during periods of effluent discharge, and always in the upper reaches of the discharge creeks (Figure 31). Grazing by nauplii and copepodids was usually more important than that of ciliates in Sandfly Creek, the non-discharge creek at Seafarm. Grazing pressure by copepodids was highest during non-discharge periods (33-40 µg $C.L^{-1}.d^{-1}$), though this was approached offshore from Seafarm in December 1998. In most cases, copepodid grazing exceeded that of copepod nauplii, and usually exceeded that of ciliates during non-discharge periods.

Carbon removal by ciliates and copepods represented between 32 and 67% of primary production during non-discharge periods at Seafarm, except at P4 in Mar-99 when it peaked at 146% of primary production (Figure 32). During discharge periods the proportion of carbon removal was usually somewhat lower, between 5 and 21% of primary production. In December 1998, high copepod abundances offshore resulted in removal equivalent to 69% of primary production. Within Pig Creek in December 1998, grazing was mediated by ciliates that probably originated from the ponds themselves. At Sea Ranch the picture was a little more complicated, with grazing rates offshore and at the creek mouths generally representing a larger proportion (up to 85% in July 1998) of primary production than in the upper reaches of the creeks. During discharge periods at Sea Ranch, the extremely high rates of primary production within the

effluent plume (4.5 g $C.m^{-2}.d^{-1}$) combined with a modest pond ciliate fauna resulted in carbon removal by these organisms accounting for negligible proportion of primary production.

The proportion of the standing stock of phytoplankton carbon potentially grazed was similar to that of primary production, except in July and December 1998, and March 1999 (Figure 32). On these three sampling dates, the carbon grazed greatly exceeded phytoplankton carbon.

Grazing within the water column of mangrove creeks, principally by microzooplankton, is the biological process most responsible for the observed decreases in standing stocks of particulate materials occurring between the effluent outlet and the coastal waters adjacent to the creek mouth. High respiration rates and excretion rates of small protist grazers lead to inefficient transfer of carbon and nutrients through bacterivores to higher trophic levels (Strom 2000). Once repackaged as zooplankton, this material becomes available to a wide range of larger grazers, including fish.

Figure 31. Estimated carbon ingested by components of the plankton. Discharge periods are indicated by bold borders.

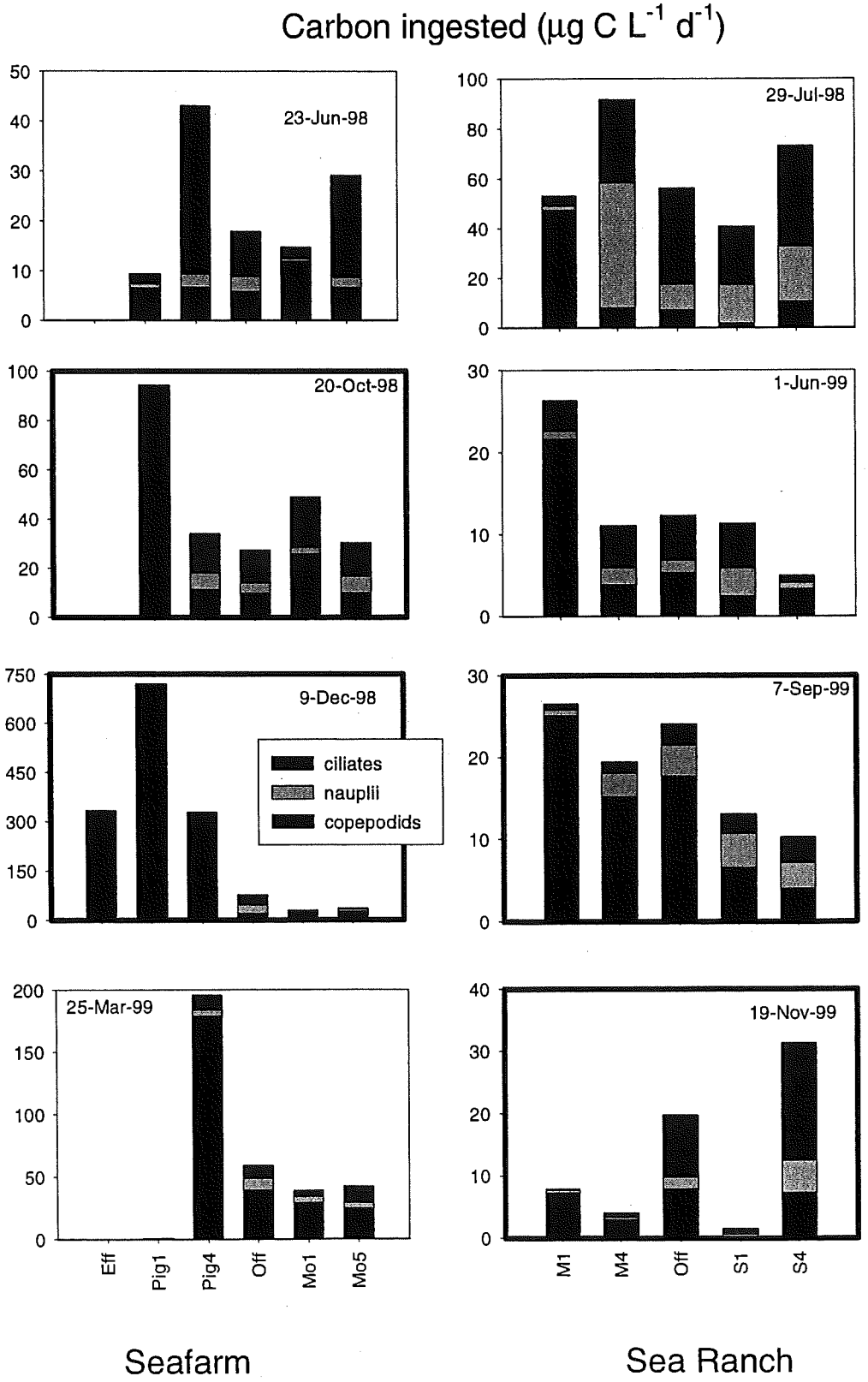
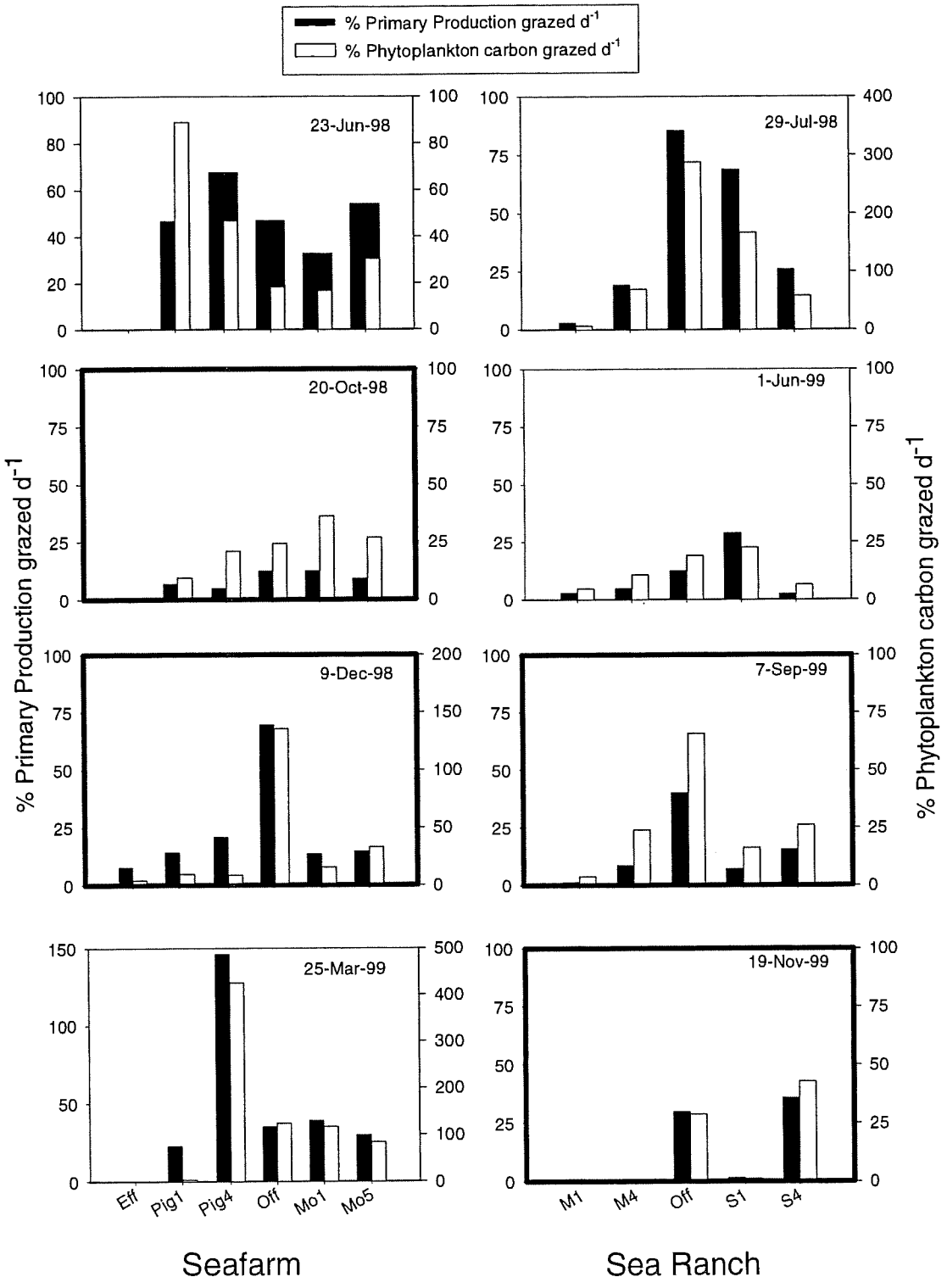


Figure 32. Percentage of primary production (left hand axes) and phytoplankton carbon (right hand axes) consumed by plankton at each station. Discharge periods are indicated by bold borders.



Discussion and Recommendations

C and N are transported beyond the upper end in to the middle reaches of Muddy Creek. During the stronger currents of ebb spring tides, resuspended nutrient rich particulate material from the farm appears to be transported further downstream beyond our study site. This conclusion is supported by

a) tidal cycle studies which estimated that the net flux of nutrients and sediments is in excess and this is being exported during later cropping stages,
b) transect studies which indicate resuspension of nutrient rich material during strong ebb tide currents, and
c) very high primary production and bacterial growth rates which are consumed only after passage through several kilometres of mangrove creek.

There appears to be little immediate damage to the mangrove, pelagic or benthic ecosystems, as most labile C and N is transformed or used by the food chain within the confines of Muddy Creek under the present conditions. However, the cumulative and long-term impacts from the bank of nutrient rich particulate material, which is being moved downstream by tidal currents, are unknown. A sustainable load of farm discharge to this creek would be less than the current levels if precautionary principles were applied here. Effluent from the prawn farm is entering the food web of the tidal creeks *via* the link between nutrients, phytoplankton, zooplankton and fish. We did not attempt to address the possible impacts of raised pelagic production, food supply and grazing by juvenile fish populations in these estuaries, nor did we carry out sufficient sampling to assess impacts on fish population diversity. However, altered fish communities (biomass or biodiversity) could lead to unpredictable effects that are undesirable, despite the obvious conclusion that there are more baitfish and hence more predatory fish in prawn farm discharge creeks.

We suggest that an extended transect, from the farm discharge to the creek mouth, be monitored in 2-3 years time in order to assess if transport of nutrient rich particulate material has moved beyond the present location and if benthic processes have been affected further downstream. That study could also include an assessment of the primary production, pelagic dynamics and fish production in discharge and non-discharge creeks and could include a study of the stable isotope signature of the fish populations. Such a study could identify the source of the nutrients present higher in the food chain, and the extent to which prawn farm nutrients or other land based sources are contributing to coastal nutrient inputs.

The current level of treatment of prawn farm effluent by Australian prawn farms is an issue that is receiving some attention by the prawn farming industry, government (QDPI) and some research groups (CSIRO). Our research has identified that the bulk of nutrients emanating from these farms are in particulate form. This particulate matter

was not fully assimilated by our study area, and moved into the seaward regions of the creek. The reduction of this particulate material through the use of settlement ponds and bio-filtration (such as mangroves or oyster) is an area of current interest (Robertson and Phillips 1995, Robertson 1999, Preston *et al.* 2000). It would seem that the challenge of significantly reducing the particulate nutrient load discharged to the environment by prawn farming is a practical, and apparently achievable goal within the next few years. Best management practice requires that all possible action be explored and undertaken which assists in the reduction of impacts on the environment.

This project is an integral part of a co-ordinated program funded by the CRC for Aquaculture (CRC), Fisheries Research and Development Corporation (FRDC), Australian Prawn Framers Association (APFA), and an environmental levy paid by Australian prawn farmers. The research covered three main areas: pond management, effluent management, and impacts of effluent on coastal waters. The pond management component is described in the CRC for Aquaculture Final Report (Preston et al. 2001a), effluent management is described in the FRDC Project 95/162 Final Report (Preston et al. 2001b). The impacts on coastal waters is described in this report (AIMS component) and the UQ component is in the CRC for Aquaculture Final Report (Preston et al. 2001a). The results of this project and results from the co-ordinated research program with CSIRO, UQ and APFA should contribute to the development of a sustainable prawn farming industry which meets the expectations of the industry, the regulators, and the general community.

Benefits

Direct Benefits and Beneficiaries

The immediate benefits and beneficiaries will be to the prawn farm managers and owners, and the environmental regulators. The benefits consist of methods for the determination of the capacity of the receiving environment to assimilate effluent from prawn farms, methods to develop sustainability indicators for aquaculture, and a scientific basis for the objective evaluation of sustainable aquaculture management options. This is vital information for the responsible growth of the prawn farming industry and protection of valuable fisheries and habitat resources in Australia.

In the short term, it will allow environmental regulators to operate with more certainty regarding new farm licenses and operating levels of existing farms, while still adhering to precautionary principles. The results of this should see more consistency and fairness in regulatory requirements and a reduction in the costs of environmental monitoring and impact studies currently borne by the aquaculture industry. It should also provide more accurate estimates of the real, rather than the theoretical impact of prawn farm effluent on Australian coastal ecosystems.

In the longer term, the Australian community will benefit from a better information base for the protection of the coastal environment, better protection of fisheries habitats and resources, and the basis for a more equitable use of the nation's marine resources.

The substantial body of knowledge has been incorporated by members of the research team and made available for inclusion into the following policy documents and industry guidelines:

- Queensland Environmental Protection Agency, Marine Aquaculture Licensing
- Great Barrier Reef Marine Park Aquaculture Regulations, 2000
- Australian Prawn Farmers Code of Practice
- Australian Prawn Farmers R&D Plan
- Environmental Management of Prawn Farming in Australia – National Workshop Report, FRDC

The CSIRO team members are also influencing international decisions on good management practices and legal arrangements of prawn farming through their presentations to an international case history study of the environmental management of prawn farms (Preston et al. 2001c).

The Australian prawn farming industry is predicted to expand predominantly in Queensland and other areas of Australia's tropics. It was our goal to that the results of this co-ordinated research would contribute to the sound and scientific basis for the

decision making process regarding investment and legislation controlling the industry. It is important that the results of this research are communicated to all stakeholders effectively in order that benefits of that goal are realised.

FLOW OF BENEFITS

Fisheries managed by	Commercial Sector	Recreational Sector	Other Fisheries Beneficiaries
NSW	15	-	-
NT	10	-	-
QLD	50	-	-
WA	10	-	-
AFMA			
TOTAL	85	-	-

NON-FISHERIES BENEFICIARIES

State and Federal Environmental regulating agencies	15

SUMMARY FLOW OF BENEFITS

Total Commercial Sector	85
Total Recreational Sector	-
Total Other Fisheries Beneficiaries	-
Total Non-Fisheries Beneficiaries	15
Summary Flow of Benefits	**100**

Further Development

Prawn farms are not the only, nor the largest contributor to land based nutrient inputs to coastal areas. However, improvements in effluent quality and quantity can be gained through wider adoption of some of the techniques currently in use or in development in Australia and overseas (recirculating ponds, settlement ponds, treatment systems such as filter feeders or mangroves, fully recirculated farms, re-use of nutrients, heterotrophic ponds). Some of these techniques may even require the farming of species other than *P. monodon* in order to achieve the sustainable farming of prawns in sensitive coastal areas adjacent to areas with seagrass, coral or other valued environments. This will require field testing and assessment of alternate species and techniques which will certainly require further collaborative work between the research agencies and the farming industry.

On a broader scale, the Australian Prawn Farmers Association has made a commitment to the development of an environmentally sustainable industry. In order to achieve that goal, a suite of "sustainability" indicators is needed that are useful throughout various climates (tropical and temperate) and useful across the range of receiving environments (creek, river, estuary, ocean) which are capable of detecting and measuring the different types of stress that prawn farming activities may cause. Pursuit of these indicators is a major undertaking. This issue goes well beyond that of investigating the effects of short-term pulsed or chronic perturbations in water quality or mangrove ecosystem processes and requires the input from a diverse range of specialists including sociologists, economists, scientists as well as the industry. Briefly, the goals of sustainable development are to:

- maintain the functional basis of the ecosystem,
- maintain biodiversity,
- optimise the benefits to the community,
- maintain options for future generations.

Issues related to these goals that the industry could pursue in future development are:

- independence from wild broodstock collection,
- increasing disease monitoring, quarantine and health management activities,
- investigating polyculture in order to more fully utilise the on-farm resources,
- exploring recirculating/treatment systems to minimise waste
- rationalising industry development plans with Regional Plans and Integrated Coastal Zone Management Plans,
- re-assessing farm stocking rates and productivity,
- quantifying the rate of mangrove loss,
- valuing the environment in economic terms and considering cost-benefit analyses of alternate methods or locations of prawn production.

While the pursuit of some of these issues may not provide immediate economic benefits, the industry would demonstrate that it has matured and has a long term view of it's place in coastal Australia by addressing it's commitment to becoming an environmentally sustainable industry.

Acknowledgements

The staff of Sea Ranch Pty Ltd and Seafarm Pty Ltd made this project possible by allowing our research to be carried out on their farms, by providing on-site laboratory space, providing farm data on feeding rates, water exchanges and harvest weights. Sea Ranch staff made a special effort to assist our research team and made available "all terrain vehicles" throughout the all-night tidal cycle studies, and when requested, patiently retrieved wayward bogged vehicles from salt flats and cane farm drains.

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Appendix 1: Intellectual Property

No patentable inventions or processes have been developed as part of this project. All results will be published in relevant scientific articles and other public domain literature. The intellectual property contained within this report is 38.53% FRDC owned.

Appendix 2: Staff

AIMS Staff	Other Staff
Mr Lindsay Trott	Ms Michele Burford (CSIRO Cleveland)
Mr Andrew Davidson	
Dr David McKinnon	
Dr Eric Wolanski	
Dr Daniel Alongi	
Mr Simon Spagnol	
Ms Katie Moore	
Ms Severine Thomas	
Mr Danny Brooks	
Mr Chris Lauren	
Mr Mike Cappo	
Mr Paul Dixon	

Appendix 3: Project Outputs

Peer –reviewed publications

McKinnon, A.D., Trott, L.A., and Davidson, A. (in press). Water column production and nutrient characteristics in mangrove creeks receiving prawn farm effluent. Aquaculture Research.

Trott, L.A. and Alongi, D.M. 1999. Variability in surface water chemistry and phytoplankton biomass in two tropical, tidally dominated mangrove creeks. Marine and Freshwater Research 50:451-457.

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Wolanski, E., Spagnol, S., Thomas, S., Moore, K., Alongi, D., Trott, L. and Davidson, A. 2000. Modelling and visualising the fate of shrimp pond effluent in a mangrove-fringed tidal creek. Estuarine Coastal and Shelf Science 50:85-97.

Conference presentations

Trott, L.A. and Alongi, D.M. 1999. The impact of shrimp pond effluent on a mangrove ecosystem: a case study in north Queensland, Australia. World Aquaculture '99. Book of Abstracts, The Annual International Conference and Exposition of the World Aquaculture Society, Sydney, 26 April-2 May, 1999, p774.

Wolanski, E. and Trott, L.A. 1999. Environmental impact of prawn farm waste water in mangroves – the importance of visualization. World Aquaculture '99. Book of Abstracts, The Annual International Conference and Exposition of the World Aquaculture Society, Sydney, 26 April-2 May, 1999, p 817.

Manuscripts in preparation

McKinnon, A.D., Trott, L.A., Cappo, M., Miller, D., Duggan, S., Speare, P. and Davidson, A. The trophic fate of prawn farm effluent in mangrove creeks of north Queensland, Australia. *In prep.* Estuarine Coastal and Shelf Science.

Trott.L.A., McKinnon, D.A. Alongi, D.M. and Davidson, A.D. Preliminary annual Carbon and Nitrogen budgets in a mangrove creek receiving prawn farm effluent. *In prep.*

Industry presentations

- DPI Prawn Farm Pond Management Workshop, Innisfail, 17-18 July 1997.
- Australian Prawn Farmers Association, Annual Science Days, Townsville, 9-10 March 1998. CRC Aquaculture and FRDC Project 97/212 progress report.
- FRDC Board Visit to AIMS, 16 June 1998. Project outline and progress.
- Australian Prawn Farmers Association Conference, 24-26 July 1998. Quantified environmental impacts, first year results.
- QFMA Townsville Region ZAC Meeting, 23 February 1999. Impacts of large scale, international shrimp farming.
- National Prawn Farming Environmental Management Workshop, Brisbane, 24-25 May 2000. The fate of effluent in tidal creeks.
- Australian Prawn Farmers Association Conference, Brisbane, 28-30 July 2000. Assessing the capacity of tidal creeks to assimilate prawn pond discharges.

Incorporation into policy documents and management guidelines

The substantial body of knowledge has been incorporated by the CSIRO members of the co-ordinated research team and made available for inclusion into the following policy documents and industry guidelines:

- Queensland Environmental Protection Agency, Marine Aquaculture Licensing
- Great Barrier Reef Marine Park Aquaculture Regulations, 2000
- Australian Prawn Farmers Code of Practice
- Australian Prawn Farmers R&D Plan
- Environmental Management of Prawn Farming in Australia – National Workshop Report, FRDC