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Clarifying the relationship between salmon farm nutrient loads and changes in macroalgal community structure/ distribution

(Existing Student Support)

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Executive Summary

This project was developed in response to questions raised by the salmon industry about the potential for adverse impacts on macroalgae as a result of the additional nutrient inputs from farming operations in marine systems. Two student projects were identified with the intention of further exploring the relationship between salmon farm nutrient loads and changes in macroalgal community structure and distribution. The research took two different but complementary directions, which comprised the body of research for two PhD students. The first project was primarily concerned with how additional nutrient inputs added directly to a subtidal reef system might affect macroalgal ecology and performance. The second project was a desk based modelling study focused on determining whether growing macroalgae in conjunction with salmon farming is a viable mechanism for reducing nutrient loads within a stylized waterbody, what species might respond most effectively to salmon farm derived nutrients, whether there could be additional benefits associated with such macroalgal culture (such as a secondary commercial crop or further environmental benefits associated with the growth of threatened/ ecologically valued species) and where the optimum location would be for growing such species. The outcomes of this research are described in more detail in the following report, both theses and any papers published or in press at the time this report was submitted have been attached as appendices. The key findings for each component are summarized below.

PhD 1 - Determining the effects of nutrient enrichment on rocky reefs communities (observational, experimental and predictive capabilities).

Nutrient sources were added to three reef systems to assess the effects of increased nutrient availability on macroalgal community composition. There was no effect on the abundance of canopy forming algae. The effect on the abundance of opportunistic species (e.g. filamentous algae) was not clear. Although opportunistic algae proliferated at one site where nutrients were elevated, this was not the case at the other reef locations. There was little evidence of change in macroalgal abundance, and reef function appeared fundamentally unchanged. Physiological differences were observed in several canopy-forming species that appeared to be in response to nutrient addition, suggesting that this may be a more sensitive early indicator of change than full evaluation of community structure. The physiological response data appears to suggest that the reef system in the upper part of the Channel may be more impacted by nutrients than the other reef systems in the study. Overall, the three reefs assessed in this study responded differently to equivalent nutrient additions (impacts), suggesting that broad-scale susceptibility/ resilience to nutrient inputs is contingent upon the prevailing environmental conditions and that future assessments may need to consider this.

PhD 2 – Farming macroalgae to mitigate coastal nutrification from finfish aquaculture: a modelling study

Modelling was used to assess the feasibility of growing algae in and around salmon farms in the D'Entrecasteaux Channel/Huon Estuary for integrated multi-trophic aquaculture (IMTA). The results indicate significant potential for algal growth in conjunction with salmon farming for the purposes of IMTA. However, the study also found that the location of algae culture within the system would differ if IMTA is for profit or for nutrient mitigation purposes.

Keywords

Aquaculture, nutrients, eutrophication, environmental monitoring, reef ecology, salmon farming

Introduction

Clarifying the relationship between salmon farm nutrient loads and changes in macroalgal community structure/distribution (Existing student support)

Overview of finfish aquaculture in coastal waters

Global aquaculture production in 2012 reached 66 million tonnes, which was 43% of the world's total fish supply, increasing from 25% in 2000 (FAO 2014). Whilst capture fisheries have maintained steady production since the 1980's, the growth rate of aquaculture for the past 20 years was 6.9% per annum (FAO 2011). Global fish production is projected to increase to 181 million tonnes by 2022 with the major driver being the increase in aquaculture production (Lem et al. 2014). Australian aquaculture currently produces 80 thousand tonnes and the aim is to reach 100 thousand tonnes by 2015 (FRDC 2015). Farmed salmonids (salmon and trout) accounted for 34% of the total volume of aquaculture production by volume in (2007-08) Australia (FRDC 2015). Globally Atlantic salmon produced 1.5 million tonnes (2008), up 11.2% on the 10-year mean with prices up 23% on 10-year mean (Lem et al. 2014). The trend in price depends on the increase in aquaculture production. Locally salmon aquaculture brings approximately \$550 million to the Tasmanian economy employing thousands of people either directly or indirectly (TSGA 2015). This is therefore an important industry both locally and internationally and will continue to be so for the foreseeable future. However, finfish aquaculture has the potential to enhance nutrient loads in estuarine and coastal systems. Consequently the ultimate sustainability and capacity for development of the industry is contingent upon the system being able to cope with these additional inputs. Whilst there is now quite an established understanding of the effects of nutrient inputs on benthic habitats, our understanding of the risk associated with macroalgal reef communities is less well understood.

Previous studies of the influence of fish farming activities on rocky reef communities have had mixed results about the potential for broadscale impacts associated with salmon farming in SE Tasmania. Crawford et al. (2006) found no change in the abundance of the seven most abundant macroalgal species at the Ninepin Point and Tinderbox MPAs over the 10 year time period from 1992-2002. However, Oh (2009) found that the macroalgal community composition at sites 100m distant from 12 active salmonid lease areas was significantly different from that at sites 5 km away in both exposed and sheltered locations. Sites at 400 m varied in their response to farms, with some sites showing characteristics similar to 100 m sites. The change in community composition observed by Oh (2009) was due to an increase in the cover of epiphytic algae and the presence of opportunistic algae, but there was no apparent change in the dominant canopy forming perennial algae.

The main mechanism for the broadscale impact from coastal finfish aquaculture is from soluble nutrient waste interacting with the ecosystem. Fish are farmed in open cages which promote the exchange of water and oxygen to the farmed fish and flush waste products from the cages (Bostock et al. 2010). However, dissolved inorganic nitrogen (DIN), mainly ammonium, can represent a significant proportion of the excreted waste, and this can be readily taken up by phytoplankton (Wang et al. 2012). The amount of waste released is dependent on the type of feed used and feeding procedures. Models for waste output of DIN associated with fish farming (Islam et al. 2005; Wang et al. 2012) have estimated that as much as 85% of total feed nitrogen is released back into the water. Wild-Allen et al. (2010) suggested that 65% of feed nitrogen is released back into the environment from salmon farms in southeast Tasmania, with 85% of this in dissolved form. There is a need to better understand the spatial and temporal environmental impact of these nutrients on macroalgal communities and productivity that might result from caged fin-fish culture and to identify possible management options.

As management practices and feeding procedures improve, feed conversions tend to become more efficient; however, so long as fish are farmed in cages in open waters an amount of waste nitrogen will always be lost to the environment. Enrichment of benthic regions from waste has the potential to change both sediment chemistry and the flora and fauna composition (Keeley 2013;

Keeley 2014.) Accumulation of dissolved nutrients can cause problems in areas with extensive aquaculture production or with otherwise oligotrophic or mesotrophic environments (Bostock et al. 2010). In general increasing inputs of DIN can modify phytoplankton community composition (Buschmann et al. 2009; Bonsdorff et al. 1997), increase algal biomass in general and in the worst case scenario, result in eutrophication (Anderson et al. 2002; Carmona et al. 2006). Modelling undertaken by Wild-Allen et al. (2010) in a southeast Tasmanian estuary suggested that salmon aquaculture had the potential to markedly impact the trophic status of the estuary, and that this could extend to 53% of the system changing from oligotrophic to mesotrophic with a 3-fold increase in production. Whilst it is imperative that we find ways to accurately assess and monitor for these impacts, if we really want sustainable development then we must also provide risk appropriate management solutions.

This project provided research support for two student projects (noting that research funding was primarily associated with Project 1 and supporting the field studies and associated analysis, Project 2 was largely a desk-top theoretical analysis):

Project 1: Determining the effects of nutrient enrichment on rocky reefs communities (observational, experimental and predictive capabilities)

Focused on identifying i) the nutrient uptake potential of key native algal species under differing environmental conditions and ii) the existing uptake potential of algae within the system and what that might mean for ecosystem sensitivity/ resilience.

Project 2: Farming macroalgae to mitigate coastal nutrification from finfish aquaculture: a modelling study

This component of the study was focused on improving macroalgal representation into the existing biogeochemical model in southern Tasmania, so that the spatial and temporal biogeochemical dynamics associated with natural and farmed areas of macroalgae and filter feeders could be explored.

In the current climate of environmental accountability this study provides an opportunity to refine our understanding of the broader environmental effects of finfish practices on algal proliferation and to evaluate whether IMTA is an environmentally sustainable solution to support the expansion of the fin-fish farming industry in Australia. Project 1 provided an improved understanding of how nutrients directly added to a reef system might affect reef function and how the prevailing conditions within the reef might influence that response. Whilst project 2 employed a multiple lines of evidence approach to evaluate the potential for an IMTA approach to mitigate/ offset nutrient loads associated with salmon farming in Tasmania and to improve the representation of macroalgae and filter-feeders in the existing BGC model. The overall objective of this research was to improve understanding of the spatial and temporal environmental impact of nutrients on macroalgal productivity resulting from caged fin-fish culture and to identify possible management options.

Objectives

Objectives of the project, as outlined in the research contract:

- Clarify the effects of nutrient changes on key macroalgal species under a variety of different environmental conditions.
- Characterise macroalgal communities in potential “hotspots” and identify key species.
- Model nutrient changes in key “hotspot” areas under a variety of different natural and anthropogenic input scenarios.
- Examine the cost-benefit of alternative theoretical scenarios for nutrient mitigation

Method

This project comprised 2 complementary PhD studies:

PhD 1 - Determining the effects of nutrient enrichment on rocky reefs communities (observational, experimental and predictive capabilities) undertaken by Luis Henriquez Antipa. In this study nutrient sources were added to three reef systems to assess the effects of increased nutrient availability on macroalgal community composition.

PhD 2 – Farming macroalgae to mitigate coastal eutrophication from finfish aquaculture: a modelling study undertaken by Scott Hadley. In this study modelling was used to assess the feasibility of growing algae in and around salmon farms in the D'Entrecasteaux Channel/Huon Estuary for integrated multi-trophic aquaculture (IMTA).

The completed theses are attached (Appendix 1 and 2) and these provide detailed methods for all of the individual experiments and analyses undertaken.

Results & Discussion

As noted above this study presents the results and findings of two separate but complementary student research projects. In this final report we have included the final theses as appendices and an overview of each of the studies and their findings are provided below.

PhD PROJECT 1: Determining the effects of nutrient enrichment on rocky reefs communities (observational, experimental and predictive capabilities)

1.1 INTRODUCTION

Coastal waterways and estuaries are increasingly having to contend with human impacts, these waterbodies are becoming increasingly urbanised, some even quite industrialised, and subject to a much broader range of agricultural development (e.g. animal stock production, forestry, viticulture, aquaculture) (Cloern 2001). As a result there will be both natural and anthropogenic impact gradients within most estuaries. Macroalgal reefs are a key environment within estuaries and provide important ecosystem services (e.g. nutrient recycling, carbon storage) and essential habitat for a broad range of marine animals (Worm et al. 2000, Kraufvelin et al. 2002, Worm & Lotze 2006a). Despite the fundamental role that macroalgal reefs play in marine ecosystems, we still do not have the necessary information to monitor and manage nutrient enrichment effectively (Cloern 2001, Bokn et al. 2002).

The potential for nutrient enrichment in these coastal habitats, and resultant impacts on macroalgae and seagrasses is well documented (Duarte 1995, Kinney & Roman 1998, McGlathery 2001, Korpinen et al. 2007a). Nutrients enrichment can be the result of many individual processes, some natural such as catchment loadings and oceanic inputs and some human in origin such as sewage treatment plants, agricultural run-off or aquaculture inputs. The extent and severity of these impacts will be influenced by the prevailing environmental conditions (REFXX). The circulation patterns and flushing rates in estuaries tend to be much reduced compared with open coast systems, which will promote the retention and assimilation of nutrients, and within the estuary there will be areas which may be more susceptible to nutrient accumulation, "hotspots", as a result of the natural hydrodynamics (Martins et al. 2001, Nixon et al. 2001, Herzfeld et al. 2008). Understanding, how the hydrodynamics of the system (and resultant water quality conditions) affects the extent to which reef systems might be able to withstand nutrient additions or the tipping points in these systems is important in order to ensure monitoring and management practices that adequately protect these important habitats.

A number of studies have sought to identify the effect of environmental conditions on macroalgal response to nutrient enrichment however, these have largely either been stylised mesocosm manipulations which are hard to relate to the real world (Kraufvelin et al. 2002, Bokn et al. 2003, Kraufvelin et al. 2010) or field impact studies where the comparisons are either essentially within the same environment or there is little or no impact resolution (Bokn et al. 2002, Kraufvelin et al. 2002, Bokn et al. 2003, Eriksson & Bergstrom 2005, Kraufvelin et al. 2006, Kraufvelin 2007). There are currently no studies where realistic nutrient fertilisation loads have been established directly within the reef system. This approach would enable assessment of the direct impact of labile nutrients on reef communities at multiple reefs within the same system, which in turn would provide a much better understanding of the effect of reef location and prevailing conditions on overall impact. Physical characteristics of the environment such as light, water motion and salinity (Worm & Lotze 2006a, Kraufvelin et al. 2010) and biological interactions such as grazing pressure (Eriksson et al. 2006a, b, 2007, Russell & Connell 2007, Connell et al. 2011) and community complexity (Eriksson et al. 2006a, b, 2007, Wikstrom & Kautsky 2007) can all influence the extent of nutrient enrichment.

There are a number of factors considered to be indicative of organic enrichment and proliferation of fast-growing opportunistic species is a common response to eutrophication, and these species are often taken to be indicative of environmental impacts (Schramm 1999, Bokn et al. 2002, Kraufvelin et al. 2002). In fact when these species are present in abundance they can go beyond being simply indicative, and can actually influence reef structure by inhibiting perennial macroalgae (Sand-

Jensen & Borum 1991, Duarte 1995, Pedersen 1995, Valiela et al. 1997, Cloern 2001, Kraufvelin et al. 2002, Russell et al. 2005), changing the community structure and diversity, and thereby impacting the underlying ecosystem services (Duarte 1995, Valiela et al. 1997, Kinney & Roman 1998). However, opportunists by their very nature take advantage of their circumstances and therefore the extent of their response to any nutrients in the environment will be influenced by the prevailing conditions in their physical and biological environment (Mann 1973, Menge & Sutherland 1987, Schramm 1999, Wernberg & Connell 2008). As a result the reliability and sensitivity of these species as indicators can fluctuate depending on the inherent variability of the system (Cloern 2001), and therefore understanding the prevailing conditions is essential to put any response into context.

There are a number of important reef habitats in the D'Entrecasteaux Channel and this study assessed changes at three locations over time (with and without the addition of nutrients) to better understand how the reef communities respond to increased nutrient loadings both in terms of changes in community structure and dynamics but also at a subtler physiological level. The prevailing environmental conditions were assessed at each location to determine whether these might result in the related reef system being more or less susceptible to nutrient enrichment. In addition this study considered the potential effects of nutrient fertilisation not only on the climax macroalgal community but also on establishing/ successional community structure, to consider whether a disturbed environment might be the catalyst for broader environmental change. The objective of this study being to provide information and indicators of impact or change that could be used to more effectively monitor and manage the nutrient balance in the system to ensure healthy reef communities into the future

1.2 RESULTS & DISCUSSION:

1.2.1 Established macroalgal community responses to changes in nutrients availability

In this study the impacts of nutrient addition on established communities at 3 reef locations in the D'Entrecasteaux Channel, Tasmania was assessed. Tinderbox, Green Island and Ninepin Point were chosen as the study locations because they were representative of the main types of reef in this system; Tinder box in the upper Channel; Green Island in the mid-Channel and Ninepin Point in the lower Channel/ mouth of the Huon Estuary (Figure 1). Sample plots were established randomly at each location, and comprised both treatment (in an area adjacent to defined nutrient source - Osmocote) and control sites (Figure 2). All plots had equivalent algal habitat and depth characteristics. The results show that the community structure was similar in the control and treatment plots prior to treatment, indicating that the plots were comparable. Communities were compared at three time periods (Spring and Summer) and any differences in community structure, abundance and diversity (including key species and particularly opportunistic species) were assessed. The environmental conditions at each location were also characterised; in particular temperature, salinity and light conditions, and an estimate of environmental exposure was calculated based on modelled fetch and wave height data.

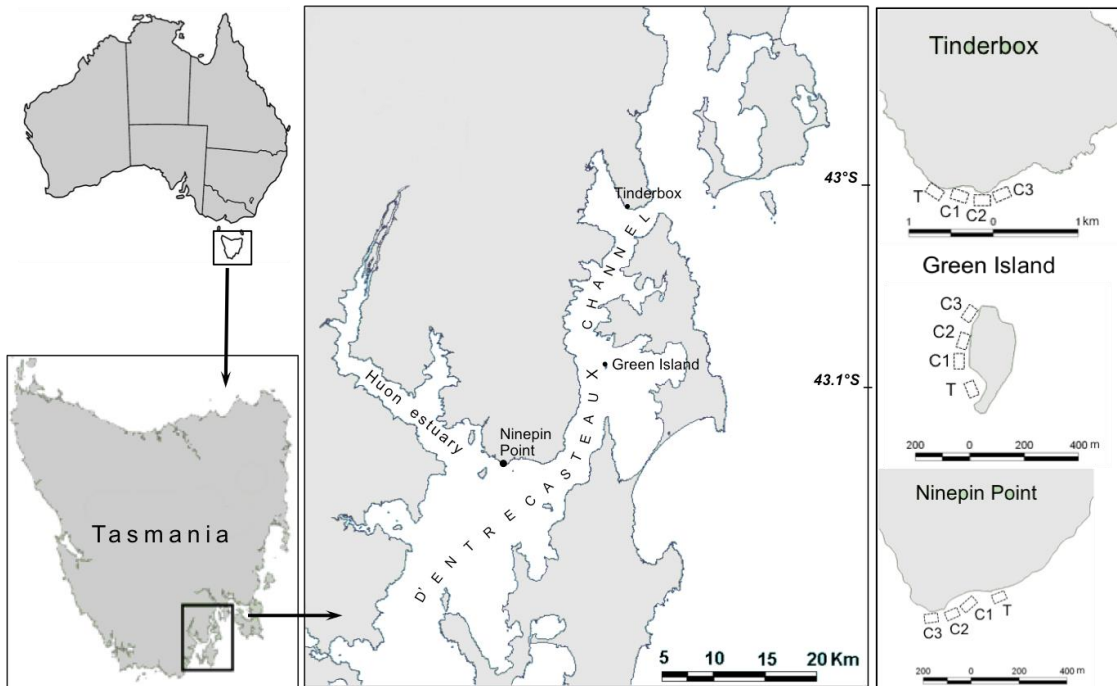


Figure 1. Locations at the D'Entrecasteaux Channel in South East Tasmania (Tinderbox 43° 3'38.33"S; 147°19'15.34"E; Green Island, 43°11'49.88"S; 147°17'23.81"E; Ninepin Point, 43°16'49.64"S; 147°10'31.52"E) showing the distribution of study sites. T=Treatment sites; C1, 2, 3 = Control sites.

Whilst a clear increase in dissolved nutrient concentration (nitrite, nitrate, ammonia and phosphorus) was measured adjacent to the nutrient sources at all study locations, this did not have a measurable impact on the community structure or abundance of the underlying macroalgal reef communities at any location. The nutrients added in this study increased nitrogen concentrations 10-fold over background levels and were calculated to be equivalent to the feed required to produce 880 kg of Atlantic salmon (*Salmo salar*), based on an FCR of 1.4 (Mente et al. 2006). The dissolved nutrient concentration was within the range considered optimal (1-10 μmol DIN) for growth of fast-growing species in previous studies (Fujita 1985, Fujita et al. 1989, Pedersen & Borum 1997). Consequently, it would be reasonable to expect an effect might be observed.

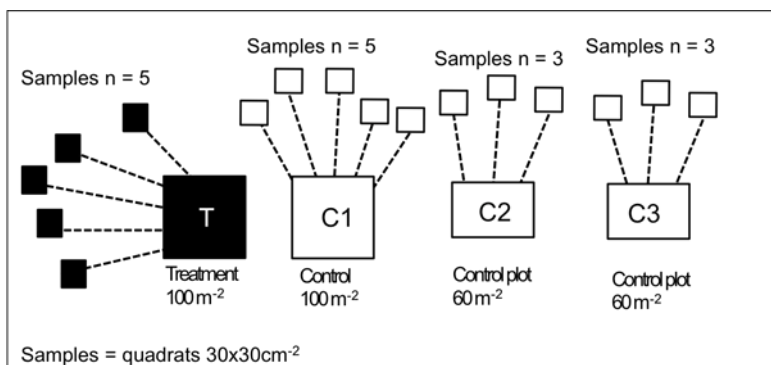


Figure 2. Schematic diagram of community monitoring under experimental additions of nutrients at each location. This sampling design was repeated at each location in spring and summer. T=Treatment plot; C1, C2, C3 = Control plots.

The underlying communities on each of the study reefs differed markedly, particularly in relation to the abundance of canopy-forming species (Fucales and Laminariales), Encrusting algae (Lithothamnion spp.) and Caulerpales. The community in the upper Channel (Tinderbox) was defined by Caulerpales and Fucales (*Sargassum fallax*), whilst the lower Channel (Ninepin Pt.) was characterised by a mix of both canopy and encrusting algae, with *Phyllospora comosa* as the canopy-forming species and *Lithothamnion* spp (encrusting algae). The community at Green Island presented as being intermediate to these two communities. These community patterns are consistent with other studies of macroalgal communities in SE Tasmania (Edgar 1983b, Edgar

1984, Sanderson & Thomas 1987, Barrett et al. 2001). Spatial variation in the composition of canopy-forming species, encrusting algae and Caulerpales, can reflect responses to abiotic gradients such as, wave exposure (Edgar 1983a, Connell 2003, Wernberg & Connell 2008), light, substrate and nutrients (Pedersen & Borum 1997).

Wave exposure can be a major influence in shallow rocky reefs (Connell 1972, Eckman et al. 1989a, Eckman et al. 1989b, Menge et al. 1993), and it has already been suggested that the wave climate may be a key determinant of the macroalgal communities in this region (Hill et al. 2010). Wave exposure can influence the distribution and growth of macroalgae both physiologically and mechanically, affecting the productivity of fast-growing species and the ability of species to become and remain attached (Santelices 1977, Parker 1981, Pihl et al. 1999, Hurd 2000, Kraufvelin et al. 2002, Lindegarth & Gamfeldt 2005, Krause-Jensen et al. 2007a) and defining the underlying light regime (Fong et al. 1996, Kamer & Fong 2000, Lotze & Schramm 2000b, Sousa et al. 2007). In addition canopy-forming species are known to be “ecosystem engineers” and will affect the establishment of other species through shading and associated growth limitation (Bokn et al. 2003, Kraufvelin et al. 2006, Eriksson et al. 2007), but will also provide refuge for herbivores (Duffy & Hay 1991) which in turn can control opportunistic species through grazing (Geertz-Hansen et al. 1993, Hauxwell et al. 1998, Lotze et al. 2001, Worm & Lotze 2006a). A diverse algal community promotes multiple pathways for nutrient assimilation and thereby maintains community stability (McCann 2000, Tilman et al. 2006, Downing et al. 2012). Consequently, higher wave exposure may provide multiple direct and indirect mechanisms that structure the reef community to be better able to manage any deleterious effects of nutrient enrichment, thereby ensuring a level of natural protection/ resilience to these reef systems.

Fast-growing opportunistic species are generally more responsive to changes in nutrient availability, as they have little storage capacity and require high nutrient levels to maintain fast growth (Pedersen & Borum 1997), unlike perennial species which are able to store nutrients (Pedersen & Borum 1996) and so are generally less responsive to changes in nutrient availability (Bokn et al. 2003, Kraufvelin et al. 2006). Consequently, opportunistic species are frequently used as indicators of nutrient enrichment. However, whilst there was evidence of opportunistic proliferation on occasions during this study, this was not clearly correlated with the nutrient inputs, and probably reflects the fact that these species will take advantage of any circumstances that can promote their spread. As a consequence improvements in temperature, light and nutrient conditions all have the potential to enhance growth of these species and the correlation of these factors in the environment makes it hard to tease out specific triggers. Interestingly wave climate and light level distinguished the reef communities at Tinderbox (in the upper Channel) from Ninepin Pt. (in the lower Channel), which in turn is likely driven by the higher light attenuation at Ninepin Point associated with the high levels of coloured organic matter coming down the Huon river (Butler 2006). However, this finding does suggest that the underlying environmental gradient may a stronger structuring force for opportunist species in this system than the addition of low-level nutrients, and that maybe in looking for the effects of nutrient enhancement on opportunist populations these locations should be considered independently.

The findings suggest that for this system, where the macroalgal community structure is well established, then the community appears to be relatively robust to moderate-level nutrient inputs but that the relative sensitivity (or resilience) of the system will be inherently tied to the prevailing environmental conditions. The marine eutrophication process is clearly complex and although opportunistic species did respond to nutrient addition it is clear that this response is very much tied to the broader environmental conditions (particularly those conditions that add to nutrient dispersal/ diffusion) and that this relationship needs to be better understood before such species can be reliably used as quantitative indicators of, or management triggers for, eutrophication. However, the degree of wave exposure may provide an indication of the extent of natural protection/ resilience in reef systems.

1.2.2 Effect of nutrient enrichment on successional stages of macroalgal communities

In the second phase of this study the effects of added nutrients on successional macroalgal was assessed. The experimental design was the same as in the previous study (Figure 1, 2) but in this case plots were initially cleared of all algae and macroalgal abundance was determined every

three months in separate cleared plot areas (i.e. winter, spring and summer 2012) by estimating the percentage cover under 25 contact points of a reticulated quadrat of 30 × 30cm (0.09 m²) (see Appendix 1 for details).

Increased nutrient levels did not visibly affect successional community development. Whilst opportunistic species were a common component in the early successional process, there was no obvious effect of nutrient fertilization that might suggest a shift in species composition, community structure and function caused by the presence of these species. At the end of the study (12 months) the successional community composition for the most part reflected that of the established community, with the sole exception of the mid Channel location (Green Island) where turf-forming algae persisted until the end of the study.

As with the established communities there were location specific differences in the successional community development; with green foliose, filamentous and turf-forming species found in early stage of community development at sites in the upper and lower Channel, and turf-forming algae persisted throughout the study at Green Island (mid Channel). Once again these differences would appear to be explained by environmental factors with temperature differences separating successional communities in the mid/low Channel from the upper Channel. Light levels and to a lesser extent salinity were correlated with the presence of turf-forming algae in the mid Channel. Whilst the lower channel community was consistently differentiated by species commonly associated with high wave action. These physical conditions will influence species tolerances and may affect colonisation patterns; noting that low light levels and low salinity (e.g., ~5 PSU) inhibit opportunistic species growth (Fong et al. 1996, Sousa et al. 2007) and germlings are often more sensitive than mature plants (Kamer & Fong 2000). This could in part explain the location-specific differences between the upper and lower Channel.

The surrounding environment can act as both source (Connell & Slatyer 1977) or constraint for propagules (Bokn et al. 2003, Karez et al. 2004, Kraufvelin et al. 2006, Kraufvelin 2007). In this case it appears that the successional community in the lower Channel had a similar canopy-understorey association as observed in the established community, and there are features of this established community that would help to promote self-colonisation i.e. encrusting coralline algae will limit substrate availability for many successional species by reducing the occurrence of crevices that might offer protection to potential germlings (Dudley & Dantonio 1991), whilst canopy forming species in the adjacent community may inhibit understorey propagules (Kennelly 1989) providing an inherent resilience to the system. Opportunistic colonisers were more frequent in the upper/mid Channel (Tinderbox and Green Island). Whilst turf-forming algae (common colonizing species, Connell et al. 2014) were more common at the mid Channel location, where levels of wave action were lower, suggesting that low wave action may be a prerequisite for proliferation and permanence of turf-algae.

The differences in the successional community development throughout the study area may also reflect the synergistic/ antagonistic interactions of biotic and abiotic factors. Light levels appear to be key in this process but the drivers are many and varied and involve both hydrodynamic and ecological considerations (Duarte 1995, Dixon et al. 2014). The influence of light on internal community processes is also complex, with clear interactions between canopy-forming species, grazing levels and nutrient levels (Lotze & Worm 2002). It seems clear that some combination of environmental and ecological information would be necessary to provide a spatial environmental context for community responses to nutrient fertilization that may be useful in modelling, management and coastal planning. The results suggest that spatial differences in environmental factors may explain the gradient observed in the successional community development. Previous studies have suggested that quantification of wave exposure may represent a reliable predictor of distribution and structure of macroalgal communities (Burrows et al. 2008, Hill et al. 2010). This study also suggests that wave action could provide a very plausible explanation for the spatial variability in recruitment and succession. However, it is important to note that the proportion of the variation not explained by wave exposure might be significant and additional variation should come from factors with the potential to have a major effect on patterns of recruitment and survival, such as grazing and sedimentation (Underwood & Fairweather 1989, Santelices 1990), should be considered – although it is important to note that these too will be strongly affected by wave exposure.

In conclusion, although the early community composition presented no visible effects of nutrient additions, the patterns of community development indicated location-specific relationships with broad-scale environmental variations (e.g., light, wave exposure). The findings of the successional study suggest that macroalgal assemblages in the D'Entrecasteaux Channel are relatively resilient, with a high probability that progeny can be replenished from neighbouring communities (Connell & Slatyer 1977). The monitoring of geographical gradients of wave exposure may provide a useful spatial context/ gradient to identify community characteristics that may help to identify the system's ability to cope with nutrient fertilization. A combined understanding of both the physical environment and successional context would be recommended if the aim is to obtain a reliable indication of the broad-scale nutrient status or to determine the relative nutrient enrichment risk at any given location. Using cleared areas and successional stage to evaluate system response was not deemed to be a particularly sensitive approach and should be undertaken with care, because the recruitment process can be influenced by such a wide range of spatial and temporal factors (Underwood & Fairweather 1989, Coelho et al. 2000, Lotze et al. 2000).

1.2.3 Evaluation of physiological responses of macrophytes to effects of nutrient enrichment.

This final component of the study sought to determine if physiological characteristics (nutrient composition and photosynthetic performance) of key coexistent macroalgal species (*Sargassum fallax*, *Ecklonia radiata* and *Ulva australis*) were influenced by nutrient addition, and what this might mean for i) environmental risk assessment and ii) future monitoring or management actions.

The photosynthetic rates of each species were evaluated in situ every 3 months (winter, spring and summer 2012). The photosynthetic evaluation was conducted in situ using a portable Pulse of Amplitude Modulated fluorescence device (PAM). Samples were also collected to measure tissue loads of nitrogen and phosphorus and C:N:P ratios - See Appendix 1 for detailed methods.

Whilst there was no significant difference in tissue nutrients between treatment and control at any location during spring, all of the species sampled from the northern part of the channel (Tinderbox) had higher tissue levels of both nitrogen and phosphorus than algae from either Green Island or Ninepin Point. In summer, *Sargassum fallax* and *Ecklonia radiata* from the northern part of the channel had higher nutrient storage capacity (in both treatment and control specimens) than equivalent plants from the middle and lower channel, in fact these specimens appeared close to saturation. This suggests that there were sufficient nutrients available in the upper Channel for specimens to remain close to saturation. Tissue nutrient levels varied seasonally, with all plants having highest levels in spring. Nutrient levels in control specimens were typically lowest in summer, but interestingly this was when there was the greatest discrepancy between Tinderbox and the other locations. There was no evidence of nutrient limitation in the tissue samples at any site or time, although C:N ratios do suggest N limitation in specimens from the mid and lower Channel.

Different species absorb and store nutrients differently, and this changes depending on where the plants are located within the system. Long-lived macroalgae such as *Sargassum fallax* and *Ecklonia radiata*, are better adapted to grow under low nutrient conditions, with very efficient nutrient uptake strategies and the capacity to store these nutrients long-term (Chapman & Craigie 1977, Fujita 1985, Duarte 1995, Pedersen & Borum 1997, Pfister & Van Alstyne 2003). Consequently these long-lived species can be useful indicators of the prevailing nutrient regimes (Pedersen & Borum 1997), reflecting both past and present nutrient regimes (Fujita 1985, Lapointe 1985, Wheeler & Bjornsater 1992) and effectively filtering out the noise of any transient nutrient pulse (Krause-Jensen et al. 2008).

Nutrient availability within this system will be affected by both the hydrodynamic circulation patterns and the reservoirs of nutrients available in the particular regions. The hydrodynamics suggest nutrients will accumulate in the northern part of the channel (Ross & Macleod, 2013). In addition the upper Channel has several supplementary nutrient sources; three wastewater treatment plants (processing approx. 300 kL day⁻¹ of domestic and industrial wastes), three finfish farms leases and a number of freshwater streams which would increase the natural nutrient "base-load" (Ross & Macleod 2013). At Tinderbox neither *Sargassum fallax* nor *Ecklonia radiata* were affected by the addition of nutrients in this study, possibly suggesting that at this location the algae already had all

of the nutrients they needed, and that the upper Channel may represent nutrient saturated growing conditions. These findings might suggest a level of physiological preconditioning and enhanced nutrient storage capacity in the marine flora at Tinderbox, possibly as a result of the elevated background nutrient levels. In the lower Channel the main nutrient sources are the Huon River and oceanic inputs, with some additional load from fish farms (Ross & Macleod, 2013). The hydrodynamics associated with the Huon River tends to result in nutrients being distributed relatively homogeneously across the entire region (Herzfeld et al. 2008). Spring rains will bring additional nutrients into the system and the macroalgal nutrient loads in the current study reflect this, with levels being relatively high in this season. However, in summer the perennial algae species (*S. fallax* and *E. radiata*) were nutrient depleted. Consequently, macroalgae from the mid/low Channel may be more susceptible to nutrient inputs, particularly in summer.

Fast-growing species (e.g., sheet-like and filamentous algae) are well known for their rapid nutrient absorption, high growth rates and high net productivity (Littler & Littler 1980, Duarte 1995). Consequently, mass development of opportunistic macroalgae represents provides a clear indication of increased nutrient availability (Duarte 1995, Schramm 1999, Oh 2009). However, they will disappear just as quickly when resources such as nutrient and light are depleted or seasonally constrained (Duarte 1995, Pedersen & Borum 1996, 1997), and therefore are good indicators of short-term nutrient pulses but can be a poor measure of sustained nutrient enrichment. Opportunists may even represent a transient biological mechanism of remediation, absorbing excess nutrients. However, these species tend to be easily influenced by environmental variations (e.g., salinity, temperature oxygen concentration) which in turn will affect their physiological response and nutrient uptake potential (Peckol & Rivers 1995, Fong et al. 1996, Lotze & Schramm 2000). In the current study the opportunist *Ulva australis* was unresponsive to nutrient additions, suggesting that this species was nutrient saturated throughout the study period at the background nutrient levels.

These findings suggest that physical drivers and location-specific nutrient loads seem to be the key drivers of spatial-temporal physiological responses in the macroalgal community composition across the study region. The two perennial species sampled showed similar response patterns, and appeared to be good indicators of long-term nutrient condition in the D'Entrecasteaux Channel. While the fast-growing "opportunistic" *Ulva australis* showed considerable small-scale spatial variability, it was not clearly and directly correlated with nutrient availability, and therefore without a clear understanding of the broader environmental context the presence or proliferation of such species should be interpreted with caution.

Examining the nitrogen and phosphorus composition in seawater and algae can help clarify the extent to which the system might be nutrient limited (Lapointe & Clark 1992). N:P ratios < 10 indicate nitrogen-limitation while N:P ratios > 30 indicate phosphorus-limitation (Smith 1984, Wheeler & Bjornsater 1992). Anthropogenic nutrient discharges can add to the variability (Lapointe et al. 1992); salmon farming clearly increasing water column nitrogen availability (Wild-Allen 2005, Wild-Allen et al. 2010). The findings of the current study suggest that the system was highly nitrogen limited during spring/summer, with a N:P ratio of < 9, well below the Redfield ratio (16:1 – the ratio of N:P found in phytoplankton and a standard measure of eutrophication potential) (Redfield 1958). Deviations from the Redfield ratio may be expected in estuarine systems as a result of changes in freshwater inputs or other anthropogenic inputs (Wheeler & Bjornsater 1992, Atkinson & Smith 1983). Although low the seawater N:P ratio remained relatively constant at Tinderbox (< 4) over time, but varied greatly at both Green Island (N:P ratios 0.6 - 9) and Ninepin Pt. (N:P ratios 4 - 1.5), and suggested greater N-limitation over summer. This result does not suggest significant nitrogen inputs and the level of variability might be a result of greater mixing of waters in the mid Channel with the significant decrease in the N:P ratio (greater N-limitation) at Ninepin Pt. between spring and summer perhaps as a result of changes in the Huon River inputs (Butler 2006). However, the fact that perennial species are able to store nutrients means that changes in the N:P ratios likely reflect longer-term fluctuations rather than current water conditions. Overall, the findings supports previous observations that waters in this region are nitrogen-limited during spring/summer (Ross & Macleod 2013).

Nutrient enhancement has been shown to increase photosynthetic activity (Wykoff et al. 1998, Longstaff et al. 2002), as measured by O₂ evolution (gross photosynthesis) or ETR_{max} (electron

transport rate) (Longstaff et al. 2002, Cabello-Pasini & Figueroa 2005, Abreu et al. 2009, Figueroa et al. 2009). Although there was quite a lot of variability in the results it appears that photosynthetic activity in *S. fallax* increased with nutrient addition at all locations over summer. *E. radiata* activity increased in spring at both mid-Channel (Green Island) and the lower Channel (Ninepin Pt.) and in the mid-Channel (Green Island) during summer, with a simultaneous rise in tissue nitrogen content. The response in the mid-lower Channel is consistent with N-stimulation (Longstaff et al. 2002). The response in the upper channel (*S. fallax*) might also suggest more nitrogen availability (N:P ratios > 40) (Pedersen 1995). These results imply that rapid assessment of photosynthetic activity is a useful tool for the determination of location-specific physiological responses and can inform broadscale process interactions.

Environmental factors (e.g. light, hydrodynamics, temperature and salinity) along with nutrient availability will clearly have a major effect on physiological processes in macroalgae (Hurd et al. 2014). In the current study light and wave exposure had an important influence on the nutrient composition of the selected macroalgae at a regional scale. As wave exposure increased water nutrient concentration decreased (dispersal/ dissolution), and nutrient impacts were reduced. Light level/ attenuation in this system is strongly affected by the tannins (coloured dissolved plant polyphenolic compounds) carried by the Huon River (Butler 2006), this is tied to seasonal rainfall patterns but has the potential to clearly affect photosynthetic activity in the mid/lower Channel locations particularly. Interestingly where wave action was reduced there was likely to be less mixing, greater potential for temperature and salinity variation, and this manifested in quite a different interaction mechanism with nutrient acquisition and storage in the selected study plants, and which supports the constrained circulation patterns of this embayment (Herzfeld et al. 2010). Noting that in the upper Channel, treatment conditions (i.e. nutrient addition) were differentiated physiologically by the phosphorus ratio in the selected plants. Water motion and turbulence control the diffusion boundary layer adjacent to the algae surface (Lobban & Harrison 1994, Hurd 2000), which in turn dictates the rate of diffusion of nutrients into the algal cells. Consequently changes in the hydrodynamics can have a considerable impact in areas where anthropogenic nutrient inputs are relatively high. Although moderate changes in salinity and temperature are unlikely to have a major effect on photosynthetic response (Kirst 1989), changes in the light environment will have an immediate and significant impact on photosynthetic reactions (Lobban & Harrison 1994). Consequently, understanding the effects of changes in the hydrodynamics and the Huon River transport (particularly particulates and coloured dissolved organic matter) are as critical as knowing the prevailing nutrient loads in evaluating the risks of nutrient enrichment on the productivity and physiology of macroalgal reefs.

PhD PROJECT 2: Farming macroalgae to mitigate coastal nutrification from finfish aquaculture: a modelling study

2.1 INTRODUCTION

Integrated Multi-Trophic Aquaculture (IMTA) is the process by which different aquaculture species are farmed together in a way that allows the waste products of one species' to be recycled as feed for another; for example, co-production of salmon (as a fed species) with macroalgae (deriving nutrients from salmon wastes). IMTA of fin-fish, shell fish and algae in coastal systems is increasingly being identified as a way to manage (remediate) nutrient inputs from intensive aquaculture in Europe, Canada and the USA (Troell et al. 2009; Buschmann et al 2008; Carmona et al. 2006). Macroalgal culture has the added attraction of potentially providing a new market to offset costs. Consequently, algal species with high growth rates, particularly in summer when natural production is high, and which are easily cultivated and have economic potential are especially attractive (Troell et al. 2009.) The use of local species is generally encouraged because these are suited to the conditions (Carmona et al. 2006) and would not have the biosecurity and public perception issues that may be associated with introduction of non-endemic species. Much of the research on IMTA to date has focused on matching the ratio of extractive species to fed in order to optimise IMTA (Ren et al. 2012; Broch et al. 2013). However, given the range of macroalgal species and farm implementations possible, and the environmental variability that may exist between IMTA sites within an estuary, optimisation requires a greater understanding of the interaction between these components.

The success of macroalgal based IMTA is dependent on the individual species used and local conditions. Buschmann et al. (2008) in a comparison of 2 species found that both benefitted from farm effluent (increased growth rates) but at different cultivation depths. Sanderson et al. (2010) similarly found enhanced algal growth rates using an IMTA approach but concluded that knowledge of the hydrodynamic flow around finfish cages is necessary to take full advantage of the plumes of nutrients emanating from them. There have been many experimental trials and pilot studies into the potential of IMTA for sustainable aquaculture (Abreu et al 2009; Westermeier et al. 2011; Buschmann et al. 2008; Carmona et al. 2006); however, the results from these experiments do not necessarily extrapolate to full-scale operations due to inherent non-linear feedbacks. For this reason a modeling approach may be preferred by researchers when exploring a range of potential scenarios possible in an IMTA approach (Ren et al 2014; Broch et al 2013). A modeling approach provides a way of extrapolating the results from small-scale field based IMTA studies to greater scales. Furthermore, this type of approach enables investigation of a range of species and IMTA scenarios that are beyond the reach of field-based studies or at a much lower cost than a full scale farming operation.

General approach to problem

In this research the aim was to quantify the capacity of IMTA to bioremediate the impact of salmon aquaculture in the D'Entrecasteaux Channel and Huon Estuary (DCHE). The approach was to develop a process model that simulated macroalgae - finfish based IMTA and then apply it within a 3D ecosystem model of the region developed using CSIRO's Environmental Modelling Suite (EMS) platform. The EMS model is a coupled hydrodynamic, sediment and biogeochemical model. It has been used in many case studies of coastal ecosystems in Australia including the DCHE the focus of this study (Wild-Allen et al. 2010; Skerrat et al. 2013; Herzfeld et al. 2010). A modelling based approach was thought to be ideal for this type of investigation. It is unfeasible to setup actual large-scale experimental IMTA operations within the DCHE. It also does not follow that the results of small-scale experiment can be translated to full-scale operations. The results of this investigation will ultimately be used to provide management level information about the potential of IMTA and how it would be best implemented.

The IMTA process model was applied to distinguish between three potential species of macroalgae to see which performed best in terms of nitrogen (N) removal. Each species identified was local, fast growing and with potential for economic development; all key attributes for IMTA (Carmona et al. 2009; Buschmann et al. 2009; Troell et al. 2009). Furthermore each species possessed a particularly strong claim: *Macrocystis pyrifera* was chosen for its potential heritage value to the area; *Ulva lactuca* is an extremely fast growing species; and *Porphyra umbilicalis* (nori) has known pre-existing market. Once a species had been selected it was then to be used in the 3D model to examine its capacity to bioremediate an estuary impacted by finfish aquaculture. In particular the approach was to examine the spatio-temporal variability in bioremediation when applying large scale IMTA within a coastal estuary. The majority of investigations on IMTA aim to optimise farm implementations (Ren et al. 2012; Broch et al. 2013; Abreu et al. 2009). These studies focus on matching ratios of fed to extractive species to optimise waste removal. They are not necessarily aimed at examining the potential to reduce the impact of finfish aquaculture on primary phytoplankton production, which is not necessarily driven by the farm waste. This has implications in general for application of macroalgae based IMTA within and estuary.

2.2 RESULTS & DISCUSSION:

2.2.1 Comparison study using IMTA model

Results of the comparison study into bioremediation potential of the three candidates for IMTA found *Macrocystis pyrifera* was the most successful at removing dissolved inorganic nitrogen (DIN) in a near-field scenario. The giant-kelp was assessed as potentially removing 70% of waste finfish DIN under moderate flow rates; however this result did not include competition from phytoplankton. Each species was investigated under a range of environmental conditions known to affect growth. This included varying optical depth and flow rate. At depths of 5,3 and 1m there was no discernible

difference in DIN removal by *Ulva lactuca* or *Porphyra umbilicalis*, whereas *Macrocystis pyrifera* showed lower DIN removal at 1m with no difference for the other two depths. The lowering in *Macrocystis* remediation potential when cultivated at 1m was assessed as being caused by photoinhibition, which this species is known to be sensitive to when grown for IMTA (Buschmann et al. 2008). Further investigation showed *Ulva lactuca* removed more DIN at higher flow, whereas *Porphyra umbilicalis* performed worse as flow rate increased. For *Macrocystis pyrifera* flow did not impact on the removal of DIN. The reason why *Macrocystis pyrifera* was able to outperform the other species of algae in removing waste DIN is down to its size. The vertical distribution of this species within the water column makes it better suited to accessing nutrients emanating from the fish cages (than the smaller species) when grown nearby. The IMTA model developed for use in the comparison study allowed for the macroalgae to have varying height and this proved to be decisive.

A key feature for successful IMTA is that any cultured species needs to have an existing demand / market. The kelp, *M. pyrifera*, is a valued species in the coastal context but in large parts of the D'Entrecasteaux Channel and Huon Estuary it has almost vanished (Johnson et al. 2011). Consequently, cultivating this species would provide not just nutrient reduction benefits but also conservation benefits. *Macrocystis pyrifera* also has the added benefit that it can be used for production of biofuels, alginates and abalone food. For offshore IMTA strong kelps, designed to withstand increased currents would potentially be more valuable than small filamentous algae.

2.2.2 Improving model with Empirical Data.

Model validation forms an essential part of any modelling study. Traditional methods involve comparison between observations and model output through skill metrics, which assess performance (Stow et al. 2009). Correlation and instantaneous relationships both establish confidence in the model and provide for interpretation of the results. The Bayesian method used in this study provides another dimension, enabling model learning based on observations (Parslow et al. 2012.) This is essential given the uncertainty surrounding the actual value of parameters. The ability to determine the best parameter set relative to all available parameters is a really important result and allows for more realistic model output in general. If the observations were taken from the D'Entrecasteaux Channel and Huon Estuary, a parameter set for this region could be determined which would give further confidence in the results. Obviously external forcing will vary spatially and temporally; and work is being done to extend this method into three-dimensional models. This would enable general transferability of the model using a set of robust parameters that could be used to return accurate results for a range of physical settings.

The IMTA model was reformulated as a stochastic model. Data from an IMTA experiment assessing growth of *Macrocystis pyrifera* next to a salmon farm in Calbuco, Chile was used to inform the model parameters using a Bayesian inference approach. Ensemble runs involving perturbations of all parameters simultaneously offered an improvement on individual parameter perturbations, which are currently favoured for determining model sensitivity. This approach also provided a method of reducing uncertainty in a way that incorporates prior understanding of the underlying processes. New metrics such as Kullback-Leibler divergence, and visualization methods such as the parallel coordinate plots allowed for an interpretation of the reduction in uncertainty. Uncertainty in the underlying IMTA model was shown to be quite large and in general BGC process models can encompass a large solution space, so any reduction in this space is welcomed. However the new model must be physically realizable not a shift in the process model unrepresentative of the actual system.

In Parslow et al. (2012) the authors described how different observations may improve the modelling results for their NPZD model. In this study the observed variables were macroalgal height and weight. Observations of these variables reduced uncertainty but did not necessarily provide more information on parameter values. If observations of total internal nitrogen of macroalgae were also included in the experimental process, this may provide additional information with which to constrain parameter values. It is possible to set up synthetic data sets reflecting observations of different variables to assess how each variable (individually and in combination) constrains the model output and contributes to parameter learning. This provides a method to determine which variables should best be observed in an actual field experiment in

order to improve model results and inform parameter values; potentially also reducing the overall cost of conducting monitoring experiments.

2.2.3 Generalised spatial resolution of IMTA.

In order to test the capacity of IMTA to bioremediate an estuary negatively impacted by finfish aquaculture a theoretical 'test' estuary was developed using the EMS platform. This estuary was similar to those found in Tasmania and forced with environmental conditions typical of the region. The effectiveness of IMTA (as a solution to the negative impacts of DIN loading from finfish aquaculture) was determined by first defining the property of the estuary that is being negatively impacted. Focusing on phytoplankton production and aligning this with the ANZECC guidelines for 'good' water quality in terms of chlorophyll concentration provided an excellent metric for quantifying the success of this method. ANZECC guidelines stipulate the concentration should not exceed the threshold value for three readings taken within the period of a month (ANZECC 2000). These guidelines recognize the spatio-temporal variability inherent in natural production particularly in estuaries. An important outcome of a modelling study such as this is to aid in the development of risk appropriate monitoring programs that are 'capable' of detecting farm impacts. Having demonstrated the importance hydrodynamics forcing plays in driving primary production from the aquaculture output, it would be advisable to monitor in those areas where naturally high production occurs. If monthly or seasonal means are considered then farms placed in areas of high natural production would have more of an accumulated effect on primary production, and monitoring around such farms is encouraged. Conversely monitoring around farms placed in areas of low natural production may not provide much understanding of the overall effects of finfish released DIN.

The results of this simulation showed how the hydrodynamic set up by the river flow drove phytoplankton production within the estuary. The waste from finfish farms grown in the path of the river flow had little impact on the system primary production whereas those grown away from this area had a significant impact. Estuarine primary production was calculated at increasing intensities of finfish aquaculture. The relationship was determined to be non-linear due to a sustained phytoplankton bloom appearing in autumn at 'critical' aquaculture load. Macroalgae farms were simulated next to the finfish leases and estuarine primary production was then examined again under the same range of finfish loads. The overall effect was that IMTA considerably reduced the chlorophyll concentration. The autumn bloom was not evident at any load examined and ANZECC threshold was only exceeded at the highest load used and in summer only whereas without IMTA the threshold had been exceeded at the middle range of forcing used for 9 months. Although the investigation was theoretical and the aquaculture loads used were excessive at the upper end, some key findings were apparent. Only the macroalgae farms around those finfish leases situated away from the river flow were responsible for reducing the increased primary production. However, the farms in the path of the river produced more biomass.

This result has implications for IMTA. If macroalgae farms are being introduced to reduce the negative impacts of finfish waste i.e. increased phytoplankton production then a relationship between the waste and primary production needs to be established. This study highlight how the cost of implementing IMTA could be considerably lowered through reducing the amount of farms required. Current research on IMTA is involved with farm implementation for optimal N sequestering; however, this research shows this N may not in fact be contributing to any negative impacts. Another key finding from this approach was the non-linear relationship between finfish loads and primary production within the estuary. This has implications for the potential risks posed through unregulated aquaculture.

2.2.4 IMTA in the D'Entrecasteaux Channel and Huon Estuary.

The final part of the study examined the potential for IMTA to support sustainable aquaculture in the D'Entrecasteaux Channel and Huon Estuary, building on the previous work. It should be noted that this was a theoretical study and in the absence of data from actual macroalgae based IMTA experiments we can only speculate on the implications of the results. The 3D model used in this

study has been applied in numerous case studies (Herzfeld et al. 2010; Wild-Allen et al. 2010; Skerrat et al. 2013) and a validation of model output showed it performed compared with observation in the region. It is mainly for these reasons the results should be treated with some confidence. The model would benefit from empirical experiments on IMTA in the region; however, the overall conclusions from the scenarios are well founded.

In this final simulation primary phytoplankton production in the DCHE was determined for three scenarios: no finfish aquaculture; 'low' loads at 2008-2009 levels; 'high' loads that were a 10-fold increase on the 'low' loading. The results showed an overall increase in system production with aquaculture forcing. This increase was highest in the spring, then summer and finally autumn. Secondly the increase was most noticeable in the upper D'Entrecasteaux and around areas more densely populated with salmon leases in the lower Huon connecting to the western edge of the lower D'Entrecasteaux and also the southeast D'Entrecasteaux. There was an observed natural pattern of production within the estuary and this appeared to be enhanced with increased loading.

IMTA was determined to be most effective around the finfish leases. Furthermore, the %N removal by macroalgae of finfish farm loads varied among the three regions; Huon Estuary, upper and lower D'Entrecasteaux. The N removal also varied with finfish loading rate. Overall the IMTA was capable of removing up to 100% of the excess production due to finfish aquaculture under 'low' loads and up to 80% under 'low' loads. This result was dependent on the season and implementation strategy of which there were three; cultivation period; area doubling and harvesting.

Based on the enrichment experiments conducted there should be an observable increase in phytoplankton production as aquaculture intensity increases. Empirical studies from the D'Entrecasteaux Channel and Huon Estuary have shown no increase in phytoplankton production, despite a significant increase in salmon aquaculture; although ammonia levels have been detected at elevated levels consistent with this increase (Ross and Macleod 2012). Studies like those of Pitta et al (2012) showing the role of zooplankton in grazing down aquaculture driven increases in oligotrophic waters, offers one explanation of those observations. In general though the absence of data comparing this region with previous years, particularly on decadal time-scales make it difficult to contextualize the observations. The model does indicate that the upper D'Entrecasteaux is one area that shows increased phytoplankton production due to increased finfish aquaculture (consistent with Wild-Allen et al 2010). Although other areas showed production in even higher levels, these contained multiple salmon leases whereas increased production in the upper D'Entrecasteaux is being driven in general by aquaculture in the rest of the region. It is possible that a change in loading of N from an individual salmon lease may result in significant change in local production, therefore biasing any results from a sustained monitoring program. In contrast the upper D'Entrecasteaux is not as obviously tied to local changes but instead it captures the overall change across multiple leases, and so individual lease loads would not have such an impact.

Siting macroalgae farms next to the finfish aquaculture leases was the most effective management strategy. This result stems from the fact that DIN was consistently highest around the salmon leases. Given that DIN drove biomass growth, which in turn drove removal of DIN, placing macroalgae farms next to leases seems the best course if removing DIN is the ultimate aim of IMTA. Of course high biomass was not restricted to sites near the leases, particularly under high finfish loads. In the event that growing macroalgae were not permitted near salmon leases then other areas may allow reasonable bioremediation. Conversely siting salmon aquaculture in locations that do not contribute to the system wide phytoplankton production is another consideration. This would restrict production from farms to local regions. If these locations do not affect areas in the system with high environmental importance such as reefs or seagrass meadows, then they might be acceptable. More environmentally valuable areas or areas sensitive to DIN increases could also be directly protected by IMTA, with farms placed near these regions to buffer them from excess DIN.

One attractive quality of aquaculture from a planning perspective is it provides control over species production (FAO 2009.) This is true of macroalgae farming where harvesting, choice of species, cultivation period and farm size all enable control over production. However these strategies need to be investigated properly. Harvesting too early or frequently could potentially result in lower

bioremediation than non-harvesting. Similarly, increasing farm area when farm loading is low would result in greater cost for no significant return in N removal. In fact dead macroalgae sporelings, resulting from lack of nutrients, would only serve to increase total N in the region. The key is optimisation of IMTA by the choice and implementation of farming strategy. Establishing an optimal harvesting regime that both satisfies market demand and retains high growth rates would be an ideal strategy. Given that this study showed macroalgal biomass was so tied to the output from the salmon farms, it stands to reason that both industries (algae and salmon) would need to be closely aligned in terms of development strategies; particularly if the overall goal is bioremediation as both parties would have an interest in the outcome. If the overall goal were to supply the market with macroalgae then the salmon farmer may have no interest in the result.

Conclusion

PhD PROJECT 1: Determining the effects of nutrient enrichment on rocky reefs communities (observational, experimental and predictive capabilities)

General Conclusions and Next Steps

Understanding and predicting the likely consequences of nutrient enrichment is critical for coastal management. This study found that natural spatial variability in biological and physical drivers can make it hard to distinguish early or subtle changes as a result of nutrient enrichment. Consequently, it is important to establish what level of change is considered important (significant) and ensure subsequent monitoring is sufficiently sensitive – this may also include redefining the regional scope of the assessment, and adjusting for local scale rather than broadscale changes. In a dynamic system such as the D'Entrecasteaux Channel it was the site level responses that were the most informative.

Overall, the results show that at a regional scale there is little evidence of major nutrient enrichment effects on the study reefs. The findings suggest that abiotic drivers may be the key determinant of impact/ variation in these macroalgal communities. Predictions based on indices of these environmental drivers may help explain and predict the spatial and temporal extent of nutrient impacts within this system. The results have enabled assumptions to be made about the inherent sensitivity or resistance of the observed macroalgal assemblages to nutrient increases. However, given the complexity of the estuarine system it is suggested that a study (even of a reduced suite of criteria) over a longer timeframe is necessary to clearly determine the impact status.

Opportunistic species should not always be considered bad, they are a natural part of an the functional ecology of an estuary and serve a very useful role in “mopping up” excess nutrients. Consequently their presence can actually help ameliorate/ remediate the effects of nutrient fertilization. It is when they actually alter the structure and function of communities that they should be considered undesirable. Variation in the response of opportunistic species through time need not necessarily be indicative of “un-natural” nutrient enrichment, it may be a response to a range of underlying processes of change and environmental variation and it is important to establish the mechanism at play when interpreting algal community change.

In the current study macroalgal species were shown to have different sensitivities to nutrient enrichment and the physiological assessments showed that regional differences could be detected and that these were associated with changes in environmental conditions (wave exposure, circulation patterns, and freshwater flows), as well as, abiotic effects (light attenuation patterns, wave action, temperature and salinity) and influences of anthropogenic nutrients (catchments inputs, sewerage treatment plants and finfish aquaculture). Long-lived macroalgal species (e.g. *S. fallax*) provided a promising approach for detection and monitoring of broad-scale and long-term nutrient variations, whilst fast-growing species were less reliable, having highly variable responses which may be seasonally restricted.

The evaluation of the nutrient enrichment status through physiological responses in situ appeared to be quite effective. This technique is particularly suitable for estuarine habitats, as it provides a mechanism to assess the variability within the regional nutrient system and examine different nutrient species, which is critical for understanding the significance of each nutrient (N:P). Specific physiological processes are dependent on the availability of particular nutrients, and this may be affected (magnified) by anthropogenic inputs and hence it is possible to predict effects. However, it needs to be recognised that anthropogenic effects may promote adaptive responses that may lead to specific physiological patterns of storage and productivity and that this could markedly change the impact/ outcomes. Previous studies have shown the potential for such adjustment with nutrient sequestration and growth in species exposed to marine farming effluents (Abreu et al. 2009, Kim et al. 2014).

To our knowledge this study is the first instance where physiological performance of macroalgae has been used to distinguish environmental and anthropogenic driven changes on macroalgal-dominated reefs at a system-wide scale. Application of this approach and development of specific physiological indicators of impact would provide a useful tool for contextualising current ecosystem nutrient status, and could help to predict potential impacts, which could in turn be used to improve ecosystem modelling and inform coastal planning.

Next Steps

Understanding the location-specific small-scale environmental variability and obtaining information on the local macroalgal communities should be pre-requisites in the development of reef monitoring and management programs. This would enable a realistic framework to be developed that would reflect the various risk gradients and sensitivities for the particular study system, and which could better categorise the macroalgal community responses, with a particular focus on identification of the most vulnerable situations.

A better understanding of the relative influence of other environmental drivers may help explain the spatial variability in community responses to nutrients. In this study, only between 32-48% of the total variation in community structure was explained by the selected environmental factors. Further experiments are needed to better define the contribution of other important factors such as horizontal water transport, sedimentation rates, and trophic interactions and productivity drivers among algal communities.

PhD PROJECT 2: Farming macroalgae to mitigate coastal nutrification from finfish aquaculture: a modelling study

General Conclusions and Next Steps

Simulated near field macroalgae based IMTA showed that for a temperate estuary there were a range of species specific conclusions that can be drawn. Notably, giant kelps such as *Macrocystis pyrifera* attain higher rates of nutrient removal than smaller faster growing species, due to their vertical distribution. Increasing flow rate had an overall neutral effect on *Macrocystis pyrifera* uptake when averaged over a nine-month period. For the smaller species examined the results varied. Increasing flow rate increased nutrient uptake for *Ulva lactuca* but decreased uptake for *Porphyra umbilicalis* over the same period. Varying cultivation depth from 0-5m had no effect on total N removed by *Ulva lactuca* or *Porphyra umbilicalis*, whereas *Macrocystis pyrifera* removed less N at 1m and more at 3m. Harvesting had the potential to increase total N removal by up to 15 fold, depending on the strategy used, with the most effective schemes being those that allowed a three-month establishment phase.

In general the data assimilation method used here demonstrated the large levels of doubt associated with the model output as a result of uncertainty in the underlying parameterisation. This uncertainty in state variables, both observed and unobserved, can be greatly reduced through conditioning on sparse data. Furthermore the process allowed for learning in the parameter space, enabling greater confidence in the model for future runs, and also allowed for a more realistic model processes.

3D simulation of an estuary showed that effective placement of macroalgae farms is dependent on the primary production cycle within the estuary. Placement of macroalgae farms is important, some sites produce high biomass but still have only minimal impact on reduction of finfish aquaculture derived chlorophyll concentration. In contrast if placed judiciously IMTA farms can bioremediate a seriously impacted estuary. In a simulation of IMTA in the D'Entrecasteaux Channel and Huon Estuary it was shown that the increase in natural production driven by finfish aquaculture can be reduced by 100% under low and %80 under high forcing from finfish aquaculture. Finally, this study showed that the control and capacity of IMTA can be greatly enhanced by g harvesting, cultivation period and farm area.

In future work it is suggested that experimental trials of macroalgal culture based IMTA be set up at different sites in the region to obtain realistic growth rates under a range of environmental conditions. It is also suggested work be undertaken on monitoring long term macroalgae respiration and growth rates and the effect of and on differing nutrient concentrations. This data would help to refine the models and underpin more accurate predictions of both the nutrient removal potential and associated impacts of IMTA.

OVERALL CONCLUSIONS

The findings have improved our understanding of the system wide effects of nutrients on local macroalgal populations, an improved understanding of the factors affecting proliferation of nuisance algae and an evaluation of the potential for IMTA as an operational management strategy. This will enable the industry to better address local concerns regarding nuisance algae, to better understand and manage their interactions with local algal and reef systems and to determine whether IMTA is a viable management option and how this might be incorporated into a strategic planning process.

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Implications

The findings of the research suggest that whilst the relative sensitivity and resilience of reefs within the D'Entrecasteaux channel varies depending on their location within the system, the communities as a whole appear to be functioning well and show little evidence of any major adverse impacts. The spatial observed variability would appear to be influenced by the combined effects of the prevailing natural conditions and the broad range of anthropogenic influences within the system. Future monitoring/ assessment may need to take this spatial variability into account. The research suggests that there may be differences in algal physiology associated with the location of reefs within the system and that this in turn may be influenced by external nutrient additions; as such this appeared to be the most sensitive indicator of nutrient impacts and therefore would potentially be a useful indicator of future reef health/ performance. These results may provide some reassurance that, at a regional scale, the reefs included in this study do appear to be relatively healthy and functioning consistent with previous studies and expectations.

The modelling of the effects of nutrient responses on macroalgae showed that for the stylised estuarine system (based on the parameterisation of the Huon Estuary/ D'Entrecasteaux Channel) co-culture of macroalgae can have a positive effect on overall nutrient loads within the system. However, it is important to consider the purpose and therefore species for culture as this can influence where such culture should be located.

Recommendations

In order to manage reef interactions effectively it is important to establish what level of change is considered important (significant) and ensure that any monitoring/ assessment is aligned accordingly. Given the complexity of the estuarine system, a study over a longer timeframe may provide a better understanding of the generalised impact status and any potential deterioration trajectory associated with coastal reef systems in SE Tasmania, and would enable subsequent management strategies to be risk appropriate (and implemented well in advance of any major impacts). Understanding the relative influence of other environmental drivers is important, as these factors (e.g. horizontal water transport, sedimentation rates, trophic interactions and productivity drivers) can have a major influence on algal communities. Establishing a local understanding of the reef systems and environmental context (risk/ sensitivity levels) should be a prerequisite for meaningful and effective reef monitoring and management programs. This would enable realistic risk gradients and sensitivities to be established, and ensure monitoring is focused on the most vulnerable situations.

A better understanding of the response of opportunistic species through time is also needed, as this study showed that these species may respond to a range of underlying environmental change processes and it is important to establish the specific mechanisms at play when interpreting this in terms of the broader algal community change. In the current study long-lived macroalgal species provided a more promising approach for detection and monitoring of broad-scale and long-term nutrient variations than fast-growing species, which were less reliable. The physiological responses in situ appeared quite effective in discerning localised changes in environmental conditions but further work is needed to clarify specific spatial relationships with individual nutrients (N:P), and to identify whether adaptive responses may confound this approach. Additional information on the physiological performance of targeted species at a range of sites in the Channel may also be useful in confirming and expanding the current findings.

In relation to improving the modelling outputs it would be worthwhile field trialling macroalgal culture (IMTA) at a range of different sites in the region to validate the growth rates proposed in this study and assess how these might change under different environmental conditions. Similarly collection of additional data on long term macroalgae respiration and growth rates, and how the target species respond to differing nutrient concentrations would be very useful in validating the findings to date, calibrating and refining the models and therefore would ultimately ensure the accuracy of outputs.

Extension and Adoption

Outline how the project was (and will continue to be) extended and communicated to the end user, such as managers, other researchers, industry and where applicable the broader community.

If possible outline where project outputs were adopted – this may not always be possible at time of writing the final report.

The results and findings of this project have been communicated to industry stakeholders through a range of student seminars and workshops, as well as through targeted discussions with individual stakeholders on request. As such the findings have already contributed to strategic planning discussions within the industry.

The final report will be made available to interested parties via the FRDC and IMAS websites and through various industry fora. A summary of the findings will be prepared for Fishing Today and contributed to the D'Entrecasteaux Channel and Huon Estuary program for inclusion as part of their regular reporting process. The key findings of this project will also be discussed with the steering committee and both community/ science reference groups associated with the FRDC project 2015-024 (Managing ecosystem interactions across differing environments: building flexibility and risk assurance into environmental management strategies), noting that the results are highly relevant to the development of ongoing monitoring and assessment approaches in that project.

Appendices

Appendices should include (where applicable):

- List of researchers and project staff (boat skippers, technicians, consultants)

PhD PROJECT 1: Determining the effects of nutrient enrichment on rocky reefs communities (observational, experimental and predictive capabilities)

Name	Role
Luis Henriquez Antipa	PhD Student
Dr Catriona Macleod	Primary Supervisor/ Principal Investigator
Dr Jeff Ross	Supervisor/ Co-Investigator
Dr Neville Barrett	Supervisor/ Co-Investigator
Andrew Pender	Senior Technical Officer
Various Students/ Casual Staff	Field Support

PhD PROJECT 2: Farming macroalgae to mitigate coastal nutrification from finfish aquaculture: a modelling study

Name	Role
Scott Hadley	PhD Student
Dr Catriona Macleod	Supervisor/ Principal Investigator
Prof Craig Johnson	Primary (Academic) Supervisor
Dr Karen Wild-Allen	Primary (Research) Supervisor

- Complete Final Theses for both Luis Henriquez Antipa and Scott Hadley are attached.
- Copies of publications from this thesis are also attached as follows:

Hadley, S., Wild-Allen, K., Johnson, C., Macleod, C. (2014). Modelling macroalgae growth and nutrient dynamics for integrated multi-trophic aquaculture. *Journal of Applied Phycology*. doi: 10.1007/s10811-014-0370-y.