Controlling biofouling of pond aerators on marine prawn farms

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Non-Technical Summary

Project 2011/734. Controlling biofouling of pond aerators on marine prawn farms.

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PROJECT OBJECTIVES:

1. Review biofouling control options and select those with greatest potential for application on prawn farms.
2. Assess the impact of aerator biofouling on prawn farms.
3. Transfer methods for implementing aerator biofouling controls to the prawn farming industry.
4. Evaluate selected biofouling control options under commercial conditions.

OUTCOMES ACHIEVED

The overarching output from the research conducted under this project is an improved understanding and quantification of the problem of biofouling in the use of aerators in marine prawn ponds. Farms are under pressure to become increasingly efficient production systems and the information arising from this project will substantially contribute to the farm knowledge base drawn on to optimise strategies that reduce aerator fleet management costs. The benefit and practicality of the most cost effective biofouling control method investigated by the project, 'paddlewheel off duty days' is supported by its practise on at least three farms.

LIST OF OUTPUTS PRODUCED

Project outputs of practical significance to prawn farms that will assist those managing aeration improve efficiency and production system sustainability include:

- Biofouling does not compromise the oxygen transfer capacity of the commonly used aerators which is of critical concern towards the end of the crop. There is a trend for improved oxygen transfer rate with increasing biofouling for paddlewheels but at the cost of efficiency.
- Paddlewheel 'off-duty days' is the most cost effective approach to reducing the impact of biofouling but is limited to controlling accumulation on above waterline surfaces.
- Non-toxic surface coatings can be an effective biofouling control for constantly submersed aerator surfaces but implementation and maintenance costs are currently prohibitive to their use for this application.
- The upper limit for the cost of biofouling prevention measures is approximately $1050/ha/crop which represents the current total real cost of aerator biofouling.

These outputs were supported by a series of technical reports that were provided to the industry throughout the conduct of the project.

SUMMARY

The project was designed to assist the Australian prawn farming industry improve aeration efficiency through providing farms with new information pertinent to cost-efficient management of their aerator fleet. The project focussed on the impact of biofouling on aeration and measures to control its accumulation, though broader aspects of aeration were also considered. The combined prawn farming industry aeration fleet is estimated at 6,000 aerators in simultaneous operation during the peak production period in summer. Efficiency gains per unit are therefore significantly magnified when considering the industry as a whole.

Information on the following aeration aspects was disseminated to farms:-.

- Full cost of aerator biofouling
- Impact of biofouling on energy use
- Impact of biofouling on oxygen transfer to the water
- Comparative energy use by the main types of aerators on farms
- Comparative impact of biofouling on the main types of aerators used
- Potential options for biofouling control
- Economic and practical assessment of two leading approaches to minimising biofouling cost

Improved farm aeration efficiency will be achieved through utilisation of this information to refine current farm aerator fleet management strategy and by adoption of biofouling control measures. The impact of this work on farm practises is likely to be realised over subsequent production seasons.

Aeration management schemes vary among farms though typically approximately two thirds of pond aerators are of the Taiwanese paddlewheel design and the rest are the propeller aspirator (‘aero’) design. Paddlewheels are by far the most impacted by biofouling and incur the highest maintenance costs. The total per hectare cost of biofouling for each grow-out cycle was estimated to be $1055, derived from the additional costs for electricity and maintenance labour and parts that are directly attributable to device biofouling.

On-farm monitoring of aerators determined a huge variation in aerator electrical performance within and among farms. Around 60% of the electrical use variability among paddlewheels is due to biofouling accumulation. This also means that around 40% of differences among paddlewheels is attributable to mechanical factors such as degree of wear and tear. The electrical performance of propeller aspirators is not significantly affected by biofouling load.

There is a strong relationship between load of biofouling and critical electrical and aeration measures. Both power use and oxygen transfer rate increase with increasing power load however the electrical efficiency of oxygen transfer declines. There is a trend for fouling of the paddle blades to affect paddlewheel performance relatively higher than fouling load on other surfaces however this was not consistent among devices.

A comprehensive review of biofouling controls detailed a range of potential options among six categories; physical settlement/ attachment inhibition surfaces (non-biocidal coatings and surface micro-texture), biocidal surfaces (antifouling paints etc), non-coating foulant disruption (eg electrical field, ultrasound), aerator design, aerator and pond management, and biocontrols.

Two biofouling control approaches met the selection criteria set by the prawn farming industry, non-toxic fouling release coatings and regular dry-out, and the practical and economic benefit of these were assessed. Two commercially available fouling release products were identified as suitable for application on paddlewheels and these were tested in farm production ponds. A relatively cheap wax-based coating was not effective in controlling barnacle settlement and growth, though had been effective for mussels on a Thai shrimp farm. A silicon-based coating showed high effectiveness in both inhibiting colonisation by barnacles as well as restricting attachment strength. Constraints to implementation by farms are however the high investment cost and low resistance of the coating to mechanical damage. Practical and economic assessment of the silicon product indicates it is not an attractive investment for aerator biofouling control due to its high cost and low resistance to mechanical damage. However the product has demonstrated effectiveness in prawn pond conditions so it has potential application for other critical surfaces in constant contact with pond water.

The regular dry-out biofouling control approach, termed paddlewheel off-duty days, entails switching selected paddlewheels in a pond off for an entire day on a routine basis. All upper surfaces are dried at regular intervals preventing foulant accumulation, particularly filamentous algae which can rapidly create a high weight loading. For relatively low farm implementation costs this approach can significantly reduce the cost of biofouling for farms experiencing high infestation of filamentous green algae.

In the absence of a whole of aerator biofouling control option it is recommended that ‘off-duty days’ be applied to inhibit growth on the upper splashed surfaces of paddlewheels. Development of environmentally friendly antifouling solutions for marine industries has a high priority world wide so the search for a viable method to control biofouling of submersed aerator surfaces on prawn farms should continue.

Maximising the proportion of propeller aspirator aerators (‘aeros’) in the aeration fleet by replacing paddlewheels will reduce overall biofouling costs but farm operator knowledge will be required to ensure that pond management is not compromised.

ACKNOWLEDGEMENTS

A number of prawn farms contributed to the conduct of work, particularly Australian Prawn Farms, Gold Coast Marine Aquaculture and Seafarm who hosted the fouling release testing work. Significant project support through review of project reports was also provided by Andrew Crole, Seafarm, Tony Charles, APF and Brian Paterson, DAFF Qld.

Body of Report

1. Introduction and Background

The biofouling issue is a persistent issue throughout the history of prawn farming in Australia however it has elevated in priority as labour and electricity costs have risen in recent years. Aerators, including paddlewheels and aspirators, are critical to the health and performance of stock. Reduction in aerator efficiency or breakdowns can cause severe stock loss if not managed effectively. Currently the approach taken to control biofouling is regular manual defouling as required and it is anticipated that a preventative approach would be more cost effective and reliable and provide significant farm management benefits.

As part of the development of this project proposal a written survey of a number of farms was conducted to gather relevant data on the issue. This exercise provided preliminary estimates on the practical and economic cost to farms and farm approach to biofouling and determined a strong economic case for implementing control measures even if those measures required a high investment.

Biofouling in marine aquaculture has been subject to intensive R&D in Australia and around the world. A number of investigations supported by the CRC for Aquaculture in 1994-2001 and the Aquafin CRC in 2001-2008 were directed towards marine fish cage culture and oyster culture. More recently a FRDC supported project sought to develop fouling prevention coatings for the pearl oyster industry. Marine cage operators and oyster growers continue to investigate improved antifouling systems. Currently there is a substantial amount of information on the mechanisms of biofouling and an array of options are available that have shown promise in combating the problem for specific marine applications, eg ship and boat fouling prevention, electricity generator coolant water intake pipes, bivalve aquaculture structures in inshore waters, fish cage farms. Biofouling on marine pond farms has received little, if any, attention so that currently the primary means of dealing with fouling is manual cleaning.

Preventative aerator biofouling control is not pursued in other shrimp farming regions. According to Matthew Briggs, a well recognised shrimp farming expert based in Thailand, there could be several reasons for this; the use of pesticides on farms reducing foulant loads; high levels of water recycling also minimising foulant loads particularly in combination with the use of chemical controls; or the availability of cheap labour. Aerator manufacturers and suppliers also confirm that there has previously been no interest expressed to them regarding biofouling control options. In Australia some prawn farms have conducted low-key tests of biofouling reduction methods but nothing concrete has arisen.

A broad range of antifouling options are now commercially available or being developed, including:- chemical, biological, electrical, ultrasound irradiation, surface microtexture, novel materials approaches. The use of biocidal coatings with persistent or broadly toxic active ingredients, such as copper or organic toxins, may have APVMA approval issues for the enclosed or semi-enclosed water bodies of marine pond farms and is not a preferred option for farmers. Biofouling control options for pond aerators should therefore focus on non-toxic approaches, including fouling release coatings, mechanical and physical systems or operational schemes.

The Australian Prawn Farmers Association and individual prawn farms expressed a need to reduce the impact of aerator biofouling. This project was developed to address that need and was designed to provide clear information on the benefits, practicality and costs of biofouling control for farms to make informed decisions on efficient aerator fleet management.

1.1 Need

Biofouling of aeration equipment is a significant farm management issue and production cost for Australian marine prawn farms. Defouling aeration equipment has a high labour demand and once fouled the energy efficiency of paddle-wheels and other aerating equipment can be markedly reduced, leading to elevated electricity costs and shorter equipment life. The estimated cost of biofouling is a minimum of $1,000 per hectare per crop when considering the additional labour, maintenance and electricity costs that it creates. This cost figure however does not include the impact of aerator fouling on prawn production levels which potentially could be far greater.

The industry uses up to 12x aerators per hectare and they consume 70-80% of total farm energy use. It is estimated that at the peak of the production season around 6,000 2hp aerators are in use in ponds across the prawn industry alone.

Ensuring appropriate and timely aerator defouling is conducted is a significant farm issue. Manual defouling is one of the least desired tasks on the farms as it is dirty, laborious and workers are susceptible to multiple skin cuts that are prone to infection. Consequently it can be difficult to maintain staff to undertake this task for any length of time. There is no data available on the impact of biofouling on the aeration efficiency, for example the oxygen transfer rate, and this information is critical to maximising benefit from mitigation strategies from both a practical and economic stand point.

The relevant industry body, the APFA through the R&D Committee, has assessed prevention of aerator biofouling as a priority issue and has recommended that the project collaborate with the industry to detail the impact of biofouling and identify strategies to mitigate it.

1.2 Objectives

1. Review biofouling control options and select those with greatest potential for application on prawn farms.
2. Assess the impact of aerator biofouling on prawn farms.
3. Transfer methods for implementing aerator biofouling controls to the prawn farming industry.
4. Evaluate selected biofouling control options under commercial conditions.

2. Methods

2.1 Identification of biofouling controls for prawn farms

Objective: Review biofouling control options and identify those with greatest potential for application on prawn farms.

A wide ranging review of scientific and grey literature and discussion with suppliers and manufacturers of products and systems of relevance to biofouling control identified a list of potentially effective control agents under pond conditions. This list was then assessed against the following selection criteria formulated by the APFA to identify options with the best potential for application on prawn farms:

i) Does not require a lengthy period of development and attaining APVMA approval
ii) Is non-toxic
iii) Is readily available for immediate implementation
iv) Has real potential for farm adoption and benefit

2.2 Impact of aerator biofouling

Objective: Quantify the impact of biofouling on aerator operation and estimate the total cost of aerator biofouling to farms.

2.2.1 Part A. Survey of prawn farm aeration and biofouling.

A 36 point questionnaire was sent to all Australian prawn farms in June 2012 that was designed to establish the impact biofouling has on aeration equipment and farm management as well as information about the characteristics of biofouling and aerator use. Phone contact with farms followed farm receipt of the questionnaire to assist timely completion and return.

Questionnaire responses included qualitative and quantitative data which were used to derive industry-wide ranges and averages.

2.2.2 Part B. Farm aerator monitoring in situ

A monitoring program for aeration units used on Australian prawn farms was undertaken to determine the real electrical performance aerators and quantify the impact of biofouling under normal operating conditions. Non-standard aeration equipment means that to obtain a true indication of electrical performance of farm aeration equipment it is necessary to monitor aerators in use on farms rather than rely on manufacturer's specifications. Additionally, the age of mechanical parts and maintenance history also have a strong influence on aerator performance.

Of the various parameters measured current and power are critical for the farms. Current, in amp, is frequently measured on farms as it indicates the operating load of the motor and is a good indicator of unit mechanical 'health'. Power, in kilowatts, is related to current but is what farms pay for as kWh. Aerator power use is not usually measured on farms.

To monitor electrical parameters an accurate purpose built meter was wired in-line at the pond-side distribution board for each aeration device. The aerator was run for up to 10 minutes and the meter continuously logged values for a variety of parameters, including voltage, current, power and power factor, for each of the 3 phases separately. A total of 77 aerators from 7 farms were monitored. Mechanical status of each monitored aerator if known, as well as a rating for level of biofouling of the three colonisation zones, was also recorded. The biofouling loading was assessed through visual observation and then ranked into five categories; 0 (no macrofouling) to 4 (very high loading) (Figure 1). Aerators tested included a diversity of characteristics and operating conditions to ensure good representation of typical farm situations.

The monitoring data were statistically analysed to draw out key information describing operating parameters of aerators and the impact of biofouling. All analyses were conducted using GenStat (2013).The data were analysed using general linear models (McCullagh and Nelder 1989). The distribution of residuals was approximately normal for all variates, so no transformations or alternate distributions were required. Independent terms which were highly correlated or near-aliased were fitted in alternate models rather than together.

2.2.3 Part C. Standardised testing of biofouled paddlewheels

An aerator testing system was constructed at the Bribie Island Research Centre (BIRC) following international guidelines for standardised evaluation of oxygen transfer devices. The system consists of a 50,000L tank filled to 1.21m deep (40,000L) with fresh, clean tap water (Figure 1). Three dissolved oxygen probes at different depths and locations in the tank log data every 30 secs to 1 min. Electricity is supplied to tested aerators through a multi-meter that logs the main electrical parameters. Over multiple test replications the system has demonstrated consistent, reliable results for testing paddlewheels. Each test provides data for characteristics of the electrical use, oxygen transfer rate and aeration efficiency of the aeration device.

Fouled paddlewheels were sourced from three farms and subjected to a testing scheme designed to identify the differential impact of paddle blade fouling and fouling of all other surfaces. Fouling load was calculated from initial weight of the fouled paddlewheel as well as subsequent weights following any defouling undertaken, minus the totally cleaned weight. Electrical and oxygen transfer performance in the fouled condition was compared with that in the totally clean condition to assess the impact of the fouling. Triplicate tests were run for each condition of the paddlewheel, original fouled state, partially defouled and fully defouled. Terms used for describing oxygen transfer performance are:-

SOTR = Standard Oxygen Transfer Rate
kg of oxygen transferred to water in an hour (kgO_2/h)

SAE = Standard Aeration Efficiency
kg of oxygen transferred to water for a kWh energy (kgO_2/kWh)

In addition to the assessment of 'naturally' biofouled paddlewheels a series of tests were conducted on a single paddlewheel using simulated biofouling loading to provide a reliable model of the impact of weight loading on electrical and oxygen transfer performance. For this work the paddlewheel was kept constant and only the additional weight was varied. Five additional weight loadings were tested, 10 to 50kg in 10kg increments, covering the full range possible under typical farm conditions. Duplicate tests were run for each weight loading. In addition to the parameters typically evaluated, two additional parameters were measured during each test, the rotor rotation rate and aerator lateral pulling force, which provide indications for the extra physical forces caused by the loading and its mechanical effect on the drive system. Biofouling load was simulated using bricks and blocks attached to the underside of the floats and the final load calculated as the weight when the paddlewheel is in its normal floating position, not the weight when suspended in the air. The density of water makes a considerable difference to the actual weight of submersed objects, for example 27kg of barnacles out of the water weighs 10kg when submersed in seawater.

Figure 1. Oxygenation test tank. Under test conditions the tank contained 40,000L of fresh water at 1.21m deep. Paddlewheels took up to 2h to return water DO to near saturation from the deoxygenated state.

The response of paddlewheel electrical performance parameters to additional weight loading derived from the tank tests was compared with that for farm biofouled paddlewheels where before and after defouling characteristics were recorded. Weight loading of these paddlewheels was estimated from the difference in the total weight of the device before and after cleaning and the relative contribution to this weight of the different foulants and their location. The estimated weight of barnacles below the water line was adjusted to account for their actual weight in water and filamentous algae weight on the upper surfaces was adjusted to allow for water entrapment during operation.

2.3 Evaluation of selected biofouling control measures

Objective: Evaluate the performance of selected biofouling control measures and estimate their potential economic benefit.

2.3.1 Experimental design

Two fouling release coating products were selected as appropriate for further examination of performance under farm conditions:

- Protecta-hull® (Enviro Hull Solutions) – silicon based paint-on coating applied directly to the surface. It had been tested on surfaces under off-shore seacage conditions where good potential for biofouling control was demonstrated. It was also being applied to boat hulls.
- AFwax® (Ecozean Pty Ltd) – wax based paint-on or dip coating that requires a primer for HDPE surfaces. This product had shown promise in reducing fouling accumulation on seashore intertidal structures and a small scale test at a prawn farm in Thailand had shown a high level of control against pest mussel settlement.

The standard paddlewheel as used in Australia has 4 rotors and 3 floats and only paddlewheels of this design were used in the trial. For the purposes of demonstrating the effectiveness of the two fouling release coating products only the floats received the coating and when applied, the entire surface area of the float was coated in one continuous coating. A total of three experimental float treatments were applied, Protecta-hull coating, AFwax coating and non-coated, with all three treatments represented on each paddlewheel.

Host farms were selected to represent different geographic regions of the Australian prawn farming industry to ensure coating products tested under a range of conditions (Table 1).

Table 1. Test locations and duration of biofouling exposure duration.

Farm	Latitude	Start date	Finish Date	No. days
South	-27.7	14/11/12	12/02/13	90
Central	-21.6	6/12/12	28/02/13	84
North	-18.3	29/11/12	7/03/13	98

On each of the three farms two ponds were each allocated two test paddlewheels so that each farm had a total of four paddlewheels. Since paddlewheels had three floats each treatment was represented on each paddlewheel giving four replicates of each treatment on each farm. Therefore across the whole trial there were 12 replicates of each treatment.

Two float positions were identified for each paddlewheel, internal (the middle), and external. Float position for each coating treatment was allocated to achieve a close to balanced exposure of each treatment within each farm.

The test paddlewheels were switched on immediately upon installation and on two farms thereafter operated continuously. On the other farm the paddlewheels were turned off for a single diurnal period every week as per the farm's standard practice for control of biofouling on upper surfaces. The paddlewheels were deployed in the manner standard for each farm and were operated for 84 to 98 days (Table 1). However for three paddlewheels operation was interrupted prior to the final assessment day and data collection was limited for these units.

At the end of the test period paddlewheels were floated to the pond bank and suspended near vertically so all surfaces could be closely inspected without affecting the biofouling. High resolution photographic digital images (16 megapixel) of the top, side and bottom float surfaces were recorded. Barnacle attachment strength was compared among the three treatments by comparative force required to dislodge a medium sized barnacle (~10-12mm base diameter) under laterally applied index finger pressure. Attempts to dislodge the barnacles were recorded on video.

All floats were then cleaned by high pressure water jet and the relative jet intensity, as distance of the jet nozzle from the float surface, was noted. The appearance and integrity of the coating was assessed prior to re-deploying the paddlewheel.

2.3.2 Coating application

Test floats at two farms were drawn from the existing paddlewheel fleet and at the other farm were new. Used floats were removed from the paddlewheel frame and thoroughly cleaned with a high pressure water jet prior to treatment. All floats to receive a coating were roughed with an abrasive disk prior to coating application to promote product bonding.

For the AFwax coating a white surface primer was first painted on with a brush. Solid AFwax was heated to approximately 80°C and was applied thickly over the primer with a brush. The product cooled upon contact and rapidly solidified. If a large number of floats were to be coated it would be more practical and efficient to use a 'hot dip' method of application.

A single coat of Protecta-hull was applied direct to the prepared float surface with a standard paint brush. The product is a viscous liquid and a relatively thick coating could be achieved with a single coating. For a thicker final coating two coats can be applied however this would greatly increase the amount of product used and therefore the cost. The coating was allowed to cure overnight before reattaching the float to the paddlewheel frame. Once floats were coated great care was taken while handling and transporting them to prevent damaging the coating. Cardboard or fabric was used to protect the surfaces from direct contact with hard surfaces and the ground. Test paddlewheels were always lifted into place rather than dragged.

2.3.3 Data collection and analysis

The steps taken and labour needed to coat paddlewheel floats were documented to assess the practicality and labour requirement for applying the products on farms. Similarly the process of defouling, as well as the final integrity of the coating and its repair where damage was sustained, was assessed as an indication of ongoing maintenance demand. Attachment strength of barnacles on the different surfaces, and therefore the force required to remove them, was assessed by; the relative force applied laterally to a single barnacle of 10-12mm diameter by the index finger, and; the relative distance of the nozzle of a high pressure water jet to effect complete removal of a patch of barnacles. The amount of product applied to each float was recorded by weighing floats individually before and after coating. Additionally, paddlewheels with test floats attached were weighed prior to pond installation and at the end of the test period. Electrical parameters of each test paddlewheel were measured upon installation and at the end of the trial period except for three units where this was not possible.

Image analysis software was used on the digital images of end-of-trial float surfaces to calculate the area of float surface covered by macrofouling and each of the three main groups of macro-fouling organism, barnacles, tubeworms and filamentous algae. Macrofouling coverage estimates were made from manual traces of either foulant covered area or clear area depending on the extent of the coverage in the images and converted to percent cover for statistical analysis. Biofilm, present as a thin, brown layer with no defined structure that commonly occur on surfaces in ponds was not considered for assessment as it has no significant implications for paddlewheel performance.

All statistical analyses were conducted using (GenStat 2013). The data were analysed using general linear models (McCullagh and Nelder 1989). The distribution of residuals was approximately normal for all variates, so no transformations or alternative distributions were required. The ANOVA models took ponds within farms as the blocks, with the individual aerators being the experimental units. In these analyses, position on the aerator (and it's interaction with treatment) were always non-significant, so were dropped to improve precision. Independent terms which were highly correlated or near-aliased were fitted in alternate models rather than together. The relationship between percent biofouling cover and weight of coating product originally applied was analysed by regression.

2.3.4 Economic assessment

Estimates of total costs for fouling release coating application and maintenance were derived from the cost/labour information generated during the trial. The fouling release use scenario was compared with the current standard practise based on farm survey data on paddlewheel operating and maintenance costs (Mann 2012b) as well as paddlewheel performance measures under simulated and real biofouling loads conducted at the Bribie Island Research Centre (Mann 2012c) and industry averages for paddlewheel electrical performance measures (Mann 2013). The benefit of the Protecta-hull coating on operating and paddlewheel maintenance costs was calculated from its impact on macro-fouling load accumulation rates.

A standard model describing biofouling accumulation over time, derived from measured biofouling load of farm paddlewheels and pond manager figures, was used as the basis for comparing electrical use and biofouling cost of treated with untreated paddlewheels. A wide range of biofouling conditions are experienced on farms, varying considerably among ponds and year to year, including community structure and rates of accumulation, however the biofouling accumulation model used was developed to represent the most common type of float biofouling, barnacles, accumulating at a moderate to high rate as experienced on farms. The load contributed by immersed barnacles when the paddlewheel is operating is less than the weight as measured in air due to the density of water. Barnacle load for operating paddlewheels was adjusted using a barnacle specific gravity of 1.4 (Woods-Hole Oceanographic Institute 1952). Note that the weight is for floats only and is the extra loading on the unit with the paddlewheel in normal floating operating mode. The weight of applied coating was also taken into account.

To ensure direct relevance to the Australian prawn farming industry modelling of the impact of biofouling on paddlewheel electricity use and cost with and without fouling release coating treatment incorporated figures derived from a representative group of farms. A detailed farm survey determined management costs associated with biofouling (Mann 2012b) and monitoring of aerators in operation on multiple farms provided measurements for operating costs (Mann 2013). Figures for the effect of biofouling weight on aerator performance that contributed to formulation of electricity use and cost models were generated under controlled test tank conditions using actual and simulated biofouling (Mann 2012c).

3. Results and Discussion

3.1. Identification of biofouling controls for prawn farms

The dominant form of biofouling control in use throughout the world is biocidal coatings containing primary biocides, commonly copper, and a suite of secondary organic booster biocides in a polymer matrix. These antifouling paints slowly release the biocides to inhibit settlement and attachment of organisms. This antifouling approach is undesirable for pond aquaculture and the prawn farming industry has indicated its preference to pursue non-toxic options.

In light of studies that have clearly determined significant adverse impacts on the environment by conventional antifouling paints, there has been a recent strong push world-wide to develop environmentally friendly antifouling systems. The two main directions taken for surface coatings are; replacement of the standard biocides in antifouling paints with natural chemical biocides which can have far less impact on the environment; and, benign surface coatings with particular surface physical properties that deter organism settlement and strong attachment. While there are several antifouling paints based on natural chemicals potentially available, it is the coatings with functional surface physical properties, termed fouling release coatings, that are the most immediate and viable option for pond aerators. These fouling release coatings do not require Australian Pesticides and Veterinary Medicines Authority (APVMA) approval for use. Fouling release coatings will not however completely prevent biofouling. They primarily achieve greatly restricted organism attachment strength so that only minimal force, for example a gloved hand or low pressure water jet, is required to dislodge even the most tenacious biofouling organisms.

There are also non-coating measures that can reduce or prevent biofouling on at least some of the aerator surfaces exposed to fouling. For example, regularly turning a paddlewheel off during the day will stop biofouling growth on the paddles and upper surfaces of the appliance, though this approach will not solve biofouling of submersed surfaces. Similarly, a high level of filtration or disinfection of pond waters prior to use will remove the larval stages of barnacles and tubeworms that readily colonise all constantly wetted solid surfaces in ponds. Biocontrol options, such as using fish or snail species to clean surfaces, do not appear to be practical alternatives for prawn farmers.

The review identified six main approaches to biofouling control and each grouping contains options that have been shown to have some effectiveness in reducing the rate of accumulation of biofouling organisms or assist in its removal from the surface (Table 2).

The choice of biofouling control measure adopted by the prawn farming industry will be directed by the economic and practical benefit provided, that is, it needs to be cheaper and/or more practical to employ compared with the *status quo*, using manual labour to regularly defoul aeration devices.

Table 2. Summary of biofouling control alternatives with potential application to pond aerators.

Method	Pros	Cons
1. Biocidal surfaces **1.1. Biocide releasing coatings**		
Standard antifouling paints containing copper, zinc and organic biocides.	Most commonly used antifouling coatings and readily available. Most effective settlement and growth inhibiting coating. Potential long service life – up to 5 years. Damage resistant coating. Bioavailable copper and zinc are likely to remain within environmental tolerance levels for prawns, however sediment accumulation is a concern.)	Biocides are released into the environment. Primary and organic booster biocides toxic to prawns. APVMA approval required for application to prawn culture ponds.
Metallic copper and alloys	Effective in preventing settlement and growth of fouling organisms. Releases less copper into the environment than most biocidal antifouling paints. Bioavailable copper likely to remain within environmental tolerance levels for prawns (however sediment accumulation is an issue)	Releases copper into the environment. Requires regular sanding of surface to maintain effectiveness. Copper persistent in the environment and accumulates in sediments. APVMA approval required for application to prawn culture ponds.
1.2. Natural biocide releasing coatings		
Sea-Nine 211®	Effective at low release rates. Biodegrades rapidly and not persistent in the environment. Effective against the major foulants of prawn ponds. Commercially available for incorporation into a range of antifouling paints (effective life is affected by type of paint used).	Biocide is released into the environment. APVMA approval required for application to prawn culture ponds.
Furanones	Preliminary investigation indicates strong potential to control problematic biofouling groups. Should be safe for prawns ponds when used only for aerators.	There are currently no products approved for use in Australia. Biocide is released into the environment. Effective life unknown however maybe less than 1 year. APVMA approval likely required for application to prawn culture ponds.
Selektope® (medetomidine)	Highly specific activity – primarily barnacles but also tube worms and mussels affected. Not biocidal, ie does not kill or affect organism health. Affect localised to close to the coated surface. Can be incorporated into a range of antifouling paints.	Not effective for algae. APVMA approval required for application to prawn culture ponds. Not currently approved for general antifouling use in Australia.

Method	Pros	Cons
1.3. Biocidal construction materials		
Biocide release from plastic polymer	Appropriate construction plastics (eg HDPE) with eco-friendly biocides (eg furanone, Sea-Nine 211) have been developed.	Biocide is released into the environment. Effective life unknown however maybe less than 1 year. APVMA approval required for application to prawn culture ponds.
Cold spray embedment of metallic copper or other metal particles	Metal particles are embedded in the plastic polymer and is therefore more durable. Copper and zinc are well known effective antifouling agents. The process can be used on most plastic surfaces and can be performed repeatedly.	Requires specialised equipment and unlikely to be possible on-farm by farm staff. Effectiveness and longevity, particularly under prawn farm conditions, requires further assessment as it is a relatively new product. Releases copper or other metal ion biocide into the environment.
2. Non-biocidal coatings and surfaces **2.1. Fouling release construction materials**		
Settlement and attachment inhibitory physical surface properties	Chemically benign and completely safe for prawns. Does not require APVMA approval – can be implemented immediately. Simple for on-farm operations, ie no coating required (though greater care to avoid surface damage is required). Fouling organisms more easily and quickly removed, eg low pressure water jet or wiping with gloved hand. Potentially reduces rate of macrofouling accumulation (affected by conditions).	Products not currently available. Aerator manufacturers not currently using this technology. Manufacture may not be economically viable. Surfaces likely to reduce effectiveness after exposure to UV and high temperature. Does not prevent fouling. Mechanical damage will greatly reduce effectiveness – extra care required. Surfaces will still need cleaning (though should be simpler and quicker).
2.2. Fouling release coatings		
Settlement and attachment inhibitory coating physical properties	Chemically benign and completely safe for prawns. Does not require APVMA approval – can be implemented immediately. Fouling organisms more easily and quickly removed, eg low pressure water jet or wiping with gloved hand. Potentially reduces rate of macrofouling accumulation (affected by conditions). Effective life 2-5 years depending on conditions. Several products are commercially available (see following).	Farm labour required for coating. Does not prevent fouling. Surfaces will still need cleaning (though should be simpler and quicker). Coating not highly resistant to mechanical damage (can be patched).

Method	Pros	Cons
2.2. Fouling release coatings *con't*		
Ecozean AFwax®	Fouling release coating with no toxins. Applied by brush or dipped. Preliminary evidence that it can be effective in prawn ponds. Can be readily patched.	Fouling release rather than prevention. Yet to be comprehensively tested to determine longevity and durability Very high temperatures can weaken it. Susceptible to mechanical damage (eg scraping along the ground).
Protecta-Hull®	Fouling release coating with no toxins. Applied by brush. Can be readily patched. Relatively robust. Potentially applied to any part of a paddlewheel.	Fouling release rather than prevention. Susceptible to mechanical damage (eg scraping along the ground).
2.3. Surface microtopography		
Surface microtopography Nanoscale contours Sharklet®	Chemically benign and completely safe for prawns. Does not require APVMA approval – can be implemented immediately. Fouling organisms more easily and quickly removed, eg low pressure water jet or wiping with gloved hand. Potentially reduces rate of macrofouling accumulation (affected by conditions). Can be combined with low surface energy compounds to greatly improve effectiveness. One product found that can be retrofitted as an adhesive film to the larger exposed aerator surfaces.	Number of products with potential application to pond aerators very restricted. Suitable only for the larger surfaces of the floats and motor cover of paddlewheels. Not applicable to the spindle and blades of paddlewheels. Effectiveness under high organic loading conditions of prawn ponds is questionable. Effective life highly dependant on use and management.
Surface texture covering Thorn-D®	Chemically benign and completely safe for prawns. Does not require APVMA approval – can be implemented immediately. Reduces rate of macrofouling. Can be retrofitted as an adhesive foil to the larger exposed aerator surfaces.	Effectiveness under high suspended solids and organic loading conditions of prawn ponds is unknown. Suitable only for the larger surfaces of the floats and motor cover of paddlewheels. Not applicable to the spindle and blades of paddlewheels.

Method	Pros	Cons
2.4. Sacrificial covering		
Replaceable film covering	Simplifies defouling of the larger exposed surfaces. Can be flexible plastic with inherent fouling release properties and UV stabilisers to extend deployed life. Sock style coverings could be reusable and biofouling easily removed.	No products currently available. (though likely not difficult to organise custom fabrication). Applicable to floats and motor cover of paddlewheels. Aerator may need some modification to facilitate cover ease of use and effectiveness. Requires manual replacement throughout operation (though could be relatively quick and simple). May lead to high temperature of paddlewheel motor. Dislodged covers can foul aerators and pumps.
3. Aerator design		
Long arm paddlewheels	Reduces the total surface area subject to biofouling.	Not a favoured aeration configuration in Australia. Only marginally reduces the amount of surface fouled.
Opaque cover over aerator	Prevents algal growth on aerators. Relatively simple retrofit to aerators.	Does not affect non-algal biofouling organisms. May affect oxygen transfer efficiency (can be easily tested using existing test system). Could create extra surface area for barnacle and tubeworm colonisation (unless managed to stop this).
Alternative aerator types	Potentially can reduce extent of biofouling and/or reduce its impact on performance, eg less solid wetted surface area. Cheaper construction design and materials may allow for regular replacement rather than defouling and redeployment, eg use of recycled packaging materials in airlift systems.	No alternative aerators designed to limit biofouling on the market. Oxygen transfer efficiency and water flow characteristics cannot be compromised. All aerators require a solid surface in contact with water so alternative designs will only reduce extent or impact of biofouling.
Simplified surfaces (less ridges and contours)	Potentially reduce rate of biofouling accumulation. Quicker manual defouling.	No products specifically designed with this in mind are available from aerator manufacturers. Potential benefit is not accurately known.
Air curtain over submersed surfaces	Simple in concept and non-toxic.	Benefit limited to submersed surfaces only. Requires additional systems attached to aerators and a source of compressed air. Fouling of the air diffusers. Does not prevent microfouling organisms.

Method	Pros	Cons
4. Aerator and pond management		
Regular sun drying – paddlewheel on/off cycle or removal from water	Does not involve direct removal of organisms by hand (different from ‘manual defouling’) On/off cycle easily achieved – potentially automatically or centrally.	Involves manipulation of the aerator in some way Labour involved in replacing aerators. On/Off cycle ramifications for motor and condensation. On/off cycling could lead to lower oxygen and process failure can be catastrophic. On/Off cycling only effective for upper surfaces, submerged biofouling remains. Removal of aerator requires replacement – therefore extra labour for handling and transport.
Regular cleaning – application of safe disinfectant	Potentially simple process of spraying the exposed surfaces. Can use environmentally safe quantities of relatively low toxicity chemicals.	Paddlewheels need to be turned off for short period. Likely needs to be done regularly (Interval duration would be influenced by local conditions)
Biofouling organism exclusion by filtration and disinfection	Aerators would likely last entire crop cycle without cleaning without macrofouling organisms.	High infrastructure costs for filtration and potential water reuse. May require change to standard pond management regimens. Disinfection may require use of a chemical disinfectant though other methods such as UV or ultrasound may be appropriate. Filtration only will not exclude algal spores. Possibility of other vectors for spores and larvae, eg birds, wind.
5. Non-coating foulant disruption		
Ultrasound	Potentially could reduce biofouling organism spore and larval survival or settlement through-out a pond, thereby reduce aerator colonisation rates. No chemicals used or toxins generated.	Application in aquaculture ponds is not well understood though use on boat hulls is becoming more common. The complicated surfaces of aerators and bubble fields create treatment protection zones. Plastics do not conduct ultrasound well enough. If ultrasound devices are required for each aerator then cost is prohibitive. Impact of ultrasound on zooplankton is not well understood, though current devices do not appear to affect rotifers or copepods. Will only be directly effective on submersed surfaces.

Method	Pros	Cons
5. Non-coating foulant disruption con’t		
Electrically generated biocide	Copper ion generation method may just require replacement of electrodes.	Copper ion generation method has same risk to non-target organisms and environment as biocidal coatings. Chlorine generation method requires application and maintenance of an electrically conductive coating on all surfaces at risk of biofouling. A period of design and testing would be required to assess potential application to ponds.
Direct electrical disruption	No biocide release. Very low electrical potentials required.	Requires application and maintenance of an electrically conductive coating on all surfaces at risk of biofouling. A period of design and testing would be required to assess potential application to ponds.
6. Biocontrol		
Micro-organisms	Could be simple addition of a commercial preparation.	No product available to achieve this (and unlikely to be one that could be broadly effective).
Planktivores and grazers	Removes nutrient rich waste (though amount would likely be very small)	Added level of complexity since requires production and management of another animal. Would only be effective for submersed surfaces.

3.2. Impact of aerator biofouling

3.2.1 Part A. Survey of prawn farm aeration and biofouling.

Summary

The number of farms responding to the questionnaire analysis was over half of the total number of grow-out farms and represents more than $^2/_3$ of total prawn production.

Wide variability in the conditions on farms, including farm size and design and source waters, can lead to pronounced differences in management. Additionally, the Australian prawn farming industry is spread over a wide geographic area, ranging from the sub-tropics to the tropics. For these reasons it was important that the questionnaire program include a group of farms representing the diversity of farming experiences. This was achieved through a commendable ten farm completion of the questionnaire ensuring that the full size range of farms, 10 ha to greater than 50 ha, from south to north of the industry distribution are represented. The questionnaire provides valuable information on the subject of aerator use and biofouling on prawn farms as well as figures on energy use. The latter would be useful industry-wide data for considerations of farm energy efficiency.

It is clear that problematic biofouling organisms for prawn farms are confined to barnacles, filamentous algae and tubeworms, listed in order of the problem they create across the industry. Though for tubeworms particularly there is a wide variation among farms from nil to very high. Occurrence and extent of the three biofouling organisms does not appear to be predictable based on farm location.

Paddlewheels make up $^2/_3$ of the industry aerator fleet and the other $^1/_3$ are propeller aspirators, predominantly the 'aero' type. It is clear that paddlewheels present the greatest management 'headache' in terms of defouling, repairs and maintenance, breakdowns and impact from biofouling. Therefore focussing biofouling control efforts on paddlewheels makes sense in terms of maximising benefit, though it is anticipated that aspects of paddlewheel biofouling control will also be applicable to propeller aspirators. It is also apparent that shifting the balance of aerator numbers from paddlewheels to aspirators would have a significant impact on total aerator operating costs. The issues and practicalities of achieving this may be a topic for further assessment and discussion.

Farms report that most of the biofouling issues for paddlewheels are associated with the submersed surfaces of the floats and the upper splashed surfaces. The paddle blades received a lower average problem rating however individual farm values were highly variable so biofouling control of the blades would still provide significant benefit, at least to half of the industry.

Some farms are already successfully employing proactive biofouling control through regular 'off' cycles of paddlewheels during the day. To avoid adversely impacting pond dynamics only 1 or 2 of a ponds paddlewheels are turned off at a time. If this is

done with appropriate regularity then one sunny day is sufficient to kill the colonising filamentous algae on the upper surfaces, including the paddle blades. Where filamentous algae is a big problem this action will be highly effective in avoiding the impact on the aerator created by additional weight loading on the unit and paddle clogging which leads to increased electricity consumption and maintenance costs. No farms have a successful control for submersed surface fouling by barnacles and tubeworms.

The labour required for defouling represents the largest component of the costs (38%) associated with aerators biofouling. A number of farms now undertake defouling in the pond, saving labour time by not having to move the aerator to the bank or central cleaning area. Similarly, most farms find it is easier to defoul using a high pressure water jet than scraping the surfaces with a metal blade, though most still do use the latter method at least in some circumstances.

It was estimated that the total cost of biofouling amounts to approximately $1,050 per hectare of production pond. This includes the most obvious budget components; labour, electricity and parts. Figures for costs associated with defouling equipment, potential loss of productivity, employment costs, and contribution to electrical peak demand are not included in the calculation as data were not available.

There are some inaccuracies associated with estimating the total cost of biofouling to farms as the calculations rely on farm information not necessarily recorded in detail, including labour used for different activities and repair frequencies. Results of this questionnaire were averaged across a statistically robust number of farms so it is anticipated that the figure provides a good industry-wide indicative estimate.

The real cost of biofouling provides a critical context to the development of biofouling control methods. To have economic benefit the total cost of any biofouling control program on a farm cannot exceed this figure, and preferably will be significantly below it.

Farm response data in detail

A. Aerator management

i) Types of aerators

- Aeration of ponds is entirely achieved with paddlewheels and propeller aspirators with the industry fleet consisting of the following proportion of each type: Paddlewheels - 66.4% : Prop. Aspirators - 33.6%
- Paddlewheels are dominated by Chenta and Futi brands and aspirators by Aire-O2.
- Aerators are almost entirely 2hp (1.5kW) motor rating. A minor number of 1.5, 2.5 and 3hp units are in use.

ii) Aerator use

- Most farms increase aerator number throughout the crop, going from 4 per ha (average 4.2, range 2 to 12) at the start of the crop to 10 per ha (average 9.85, range 8 to 14) towards the end.
- At peak aerator demand, on average the aerator fleet in each pond consists of 70% paddlewheels and 30% propeller aspirators, though balance of aerator types varies among farms from 45% to 100% paddlewheels.
- The average rate of aerator deployment per ha was calculated for peak pond production period and over an entire crop cycle (Table 3). The phased aerator deployment figures provided by farms were used to calculate average aerator hours for an entire crop cycle. Data for aerator power and production rates were then used to calculate energy used per hectare and tonne of production.
- 60% of farms either employ scheduled 'aerator off' periods or consider that it would be an effective approach to reduce biofouling. This entails regular turning off 1 or 2 paddlewheels per pond during the day on rotation or 'as required' to control algal growth on the upper surfaces. A couple of farms turn some pond aerators off when not required for oxygenation to reduce electricity costs.

Table 3. Deployment stats for pond aerators during the peak use period and estimated average over an entire crop cycle.

	Average	*Range*
Peak pond aerator use		
aerator No. per ha	9.9	8 to 14
kW per ha	14.9	12 to 21
Estimated average over a full crop cycle		
aerator No. per ha	7.2	
kW per ha	10.8	
kWh per ha	43,550	
kWh per tonne produced	5,270	

iii) Dissolved oxygen levels

- Normal minimum daily DO during peak pond loading is around 3ppm though it does go lower. This indicates that during periods of high pond biomass, on average there is little to no redundancy in the amount of aeration applied to ponds.
- Daily DO maximums are generally at well supersaturated levels on all farms.

iv) Aerator mechanical maintenance

- Most farms follow a scheduled maintenance and repair program, eg replacement of bearings and seals in the off-season.
- Unscheduled repairs are still required during the production season - including motor and gearbox replacement. Combined motor and gearbox replacement cost is typically $300-$500 per aerator.
- Most farms only replace motors and gearboxes as required, ie when problems are noticed.
- When a paddlewheel or aspirator fails, repair parts are expected to cost an average of $200 (range $70 to $300), and repair labour time required 1.8 h (range 1 to 3 h) for a paddlewheel and 0.8 h (range 0.3 to 1 h) for an aspirator.
- Total labour used for mechanical repairs and maintenance on average per year is 39.8 h per ha at a cost of $995 per ha. [The farm estimate for total labour hours used for aerator mechanical repairs and maintenance was divided by the production area to provide a labour per hectare value to standardise across farms.]

v) Aerator durability and reliability

- Aerator major component durability estimates by farms are listed in Table 4. Farms commented that the longevity of motors and gearboxes is greatly affected by the servicing frequency, eg replacing bearings and seals.
- For new paddlewheels, an average breakdown rate of 10% in the first season is anticipated.
- For new aspirators, an average breakdown rate of 2% in the first season is anticipated.
- 8.8% of the industry's paddlewheel fleet is replaced annually
- 2.5% of the industry's propeller aspirator fleet is replaced annually

Table 4. Length of time that major components of aerators are expected to last.

Aerator component	*Average (years)*	*Range (years)*
Paddlewheel gearboxes	4	2 to 7
Paddlewheel motors	3.6	2.5 to 6
Aspirator motors	5.4	3 to 9
Paddlewheel frames	effectively forever	-
Aerator floats	5.8	3 to 9

B. Biofouling

i) Types of biofouling organisms

- A farm rating for the extent of the problem created by different fouling organisms is listed in Table 5.
- Barnacles and filamentous algae are prevalent and problematic on all farms.
- Tubeworms are no issue on some farms while prevalent on others.
- There is no indication that farm location, by latitude, affects fouling organism type or extent of the problem.

Table 5. Farm rating of extent of the problem created by fouling organisms on a scale from 0 (no problem) to 5 (big problem).

Organism	*Average*	*Range*
Barnacles	4	3 to 5
Tubeworms	1.6	0 to 5
Macroalgae Algae	4.1	3 to 5
Oysters	1	1 record only

ii) Biofouling of paddlewheel zones

- A farm rating for the extent of the problem created by biofouling for the 3 main zones of paddlewheels is listed in Table 6.

Table 6. Farm rating for extent of the problem created by biofouling for the main surface zones of paddlewheels. Scale is 0 (no problem) to 5 (big problem).

Zone	*Rating*	*Range*
Surfaces above water	4.1	2 to 5
Submersed part of float	4.3	3 to 5
Paddle blades	2.6	0 to 5

iii) De-fouling of aerators

- It is generally considered that of the different aerators used, paddlewheels are the most difficult to defoul.
- 80% of farms defoul aerators within the pond and some of these also conduct defouling on land
- 20% of farms defoul on land only
- 60% of farms use high pressure water jet to clean aerators. Some also scrape.

- 40% only use scraping with a metal blade (eg spade)
- The number of times aerators are defouled during a crop is listed in Table 7.

Table 7. Number of times paddlewheels and aspirators are defouled during a crop cycle, typical and maximum averaged across farms.

	Typical	*Maximum*
Paddlewheel	1.7	3.4
Propeller aspirator	0.3	0.8

iv) Cost of aerator biofouling

- Labour
  On average 18.4h of labour, at a cost of $405 (assumed $22/h rate), is used for defouling aerators on a per hectare basis. [The farm estimate for total labour hours used for defouling was divided by the production area to give a defouling labour per hectare value to standardise across farms.]
- Electricity consumption
  All farms acknowledge that biofouling causes higher electricity consumption. Some farms provided an estimate for the increase cost, ranging from 5 to 20% for paddlewheels.
- Mechanical maintenance
  All farms consider that biofouling causes higher requirement for mechanical maintenance. This becomes a greater issue if defouling is not conducted in a timely manner. Estimates for the extra mechanical maintenance caused by biofouling ranged from 20 to 50%.
- Productivity
  Around 20% of farms consider that biofouling has lead to reduced pond productivity. No estimates were provided.

C. Total biofouling cost calculation

The various data provided by farms was used to calculate the total cost of biofouling (Table 8). Costing assumptions made in the calculations include unskilled labour, $22/h; skilled labour $25/h; electricity, $0.20/kWh. Level of labour and parts for maintenance cost increase were conservatively placed within the range of farm estimations.

Table 8. Farm costs directly attributable to biofouling of aerators. All costs are standardised to $ per ha.

	Cost	*Description of calculations and assumptions*
Defouling labour	$405	$22 hourly rate
Increased electricity	$305	electricity cost = $0.20 per kWh increased consumption for paddlewheels only over a full crop cycle = 5%. Av. total electricity use of paddlewheels = 43,550kWh x 70% = 30,485kWh. final increase due to biofouling = 30,485kWh x 5% = 1,524kWh.
Increased mechanical maintenance - Labour	$250	$25 hourly rate total MM labour cost = $868/ha MM labour increase due to biofouling = 25% (farms estimated 20 to 50% extra maintenance requirement)
Increased mechanical maintenance - Parts	$95	an average 1.9 paddlewheels per ha per year will fail requiring an average $200 each in parts to repair (paddlewheels last av. 3.6y and used at 6.8 per ha) average increase maintenance parts due to biofouling = 25%
Total cost biofouling per ha	$1,055	does not include costs associated with equipment used for defouling, potential loss of productivity, employment costs, contribution to electrical peak demand level.

3.2.2 Part B. Farm aerator monitoring *in situ*

Summary

On-farm electrical monitoring of aerators under normal pond operating conditions identified that aerators subjected to standard use on prawn farms exhibit a wide range of electrical performance. Both current and power vary markedly from values provided by suppliers or listed in manufacturer's specifications. The largest part of the observed variation is explained by the various makes and models of paddlewheels deployed on farms, particularly the motors and gearboxes, as well as highly variable aerator mechanical condition, taking into consideration age and maintenance history. Once known paddlewheel specifications are taken into account, for example motor size, the accumulated biofouling load is responsible for around 60% of the observed current draw and power use variation among paddlewheels. The electrical performance of paddlewheels is strongly influenced by biofouling of each of the colonisation zones distinguished in this study, paddle blades, upper surfaces and submersed surfaces of the floats. There was no indication that biofouling of the submersed surfaces of aspirator aerators affected electrical performance. Biofouling load has a significant influence on paddlewheel operating and maintenance costs as well as oxygen transfer performance and these aspects are examined in a separate report to follow. Additionally, the aerator electrical measures of farm aerators in typical operation taken during this monitoring program will be used in formulating the economic assessments of biofouling control options for farms.

Aerator monitoring results

Pond aerators used on prawn farms exhibit high variability in electrical performance (Table 9). Some of this variability is obviously due to the range of models and motors with different power ratings being used, however even within the most common aerator group, 2hp paddlewheels with 4 rotors, there is wide variability. Biofouling of the paddlewheels explains around 60% of the observed variability in power use and current draw (r^2=0.61) (Figure 3). This means that around 40% of variability in the two critical electrical measures is influenced by basic electrical and mechanical specifications of the unit and imposed factors such as wear and tear on the gearbox and bearings.

To maximise motor longevity motors should not be operated at above the manufacturer's power output rating for extended periods. Particularly cheaper motor models are sensitive to the higher heat levels generated by overloading. 50% of aerators monitored were operating at over their rated output power value by an average of 300W. Aspirator aerators had a higher proportion of units operating over their rated power use than paddlewheels, 85% and 42% respectively. It is not known why this is the case.

Paddlewheel power use appears to be most sensitive to fouling of the paddle blades and other above water surfaces (Figure 3). The relative quantity of macro-fouling was assessed for each zone independently (Figure 2) which means a high fouling ranking for upper surfaces is not equivalent to a high ranking on submersed surfaces in terms of contribution to additional weight loading of the unit. Therefore the zones can not be directly compared with each other. Due to the density of seawater, submersed fouling contributes less to weight loading than an equivalent fouling load on upper surfaces where the full weight of the fouling plus the water that it traps adds to the total weight of the paddlewheel.

As fouling of all upper surfaces has a strong effect on power use, if cleaning resources are limited then efforts should focus on upper surfaces. Potentially the blades and upper surface zones can be cheapest to maintain since a regular program of turning off paddlewheels during the day, eg every week or fortnight, can keep growth controlled to minimum levels so manual defouling requirement is greatly reduced.

No evidence of biofouling affecting propeller aspirator electrical performance was found though ‘very high fouling’ category on this aerator type was not observed during the monitoring program. A nil effect of fouling loading is expected however since the aspirator design is not considered sensitive to varying immersion depth within the range typically seen on farms. Additionally, the moving parts in contact with water rotate very rapidly, around 1400rpm (4-pole motors) or 2800rpm (2-pole motors), so fouling of these critical surfaces does not occur.

The influence of biofouling weight loading on paddlewheel oxygen transfer performance was examined in a separate investigation, ‘Measuring performance of biofouled aerators under standard conditions’.

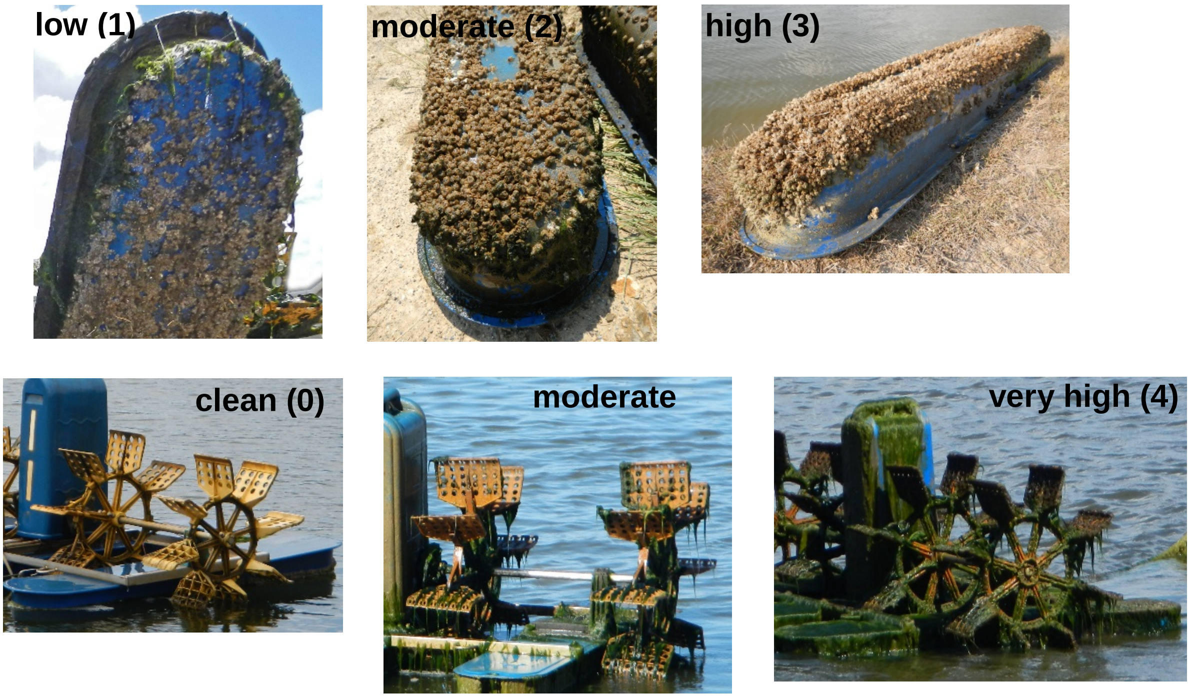

Figure 2. Fouling categories for different paddlewheel zones.

Table 9. Average (*range*) for various groupings of aerators monitored on prawn farms. Two 2 hp paddlewheels had two rotors, all other 2 to 3 hp paddlewheels had four. Propeller aspirators ('aeros')

included trans-surface type ('Aire-O2' design) and the submersed type (Force-7 design). The two long-arm paddlewheels had 11 and 13 rotors.

	No.	Current (amp)	Power (kW)	Power factor
All 2 to 3 hp paddlewheels	50	2.781 *(1.28-4.04)*	1.597 *(0.79-2.54)*	0.782 *(0.63-0.90)*
All propeller aspirators	22	2.781 *(2.43-3.10)*	1.622 *(1.19-1.86)*	0.813 *(0.68-0.93)*
2 hp paddlewheels	32	2.708 *(1.28-3.93)*	1.541 *(0.79-2.36)*	0.767 *(0.63-0.90)*
3 hp paddlewheels	11	3.072 *(2.18-4.04)*	1.803 *(1.35-2.54)*	0.806 *(0.73-0.89)*
Long-arm paddlewheels	2	5.148 *(4.59-5.70)*	2.878 *(2.32-3.43)*	0.703 *(0.64-0.76)*

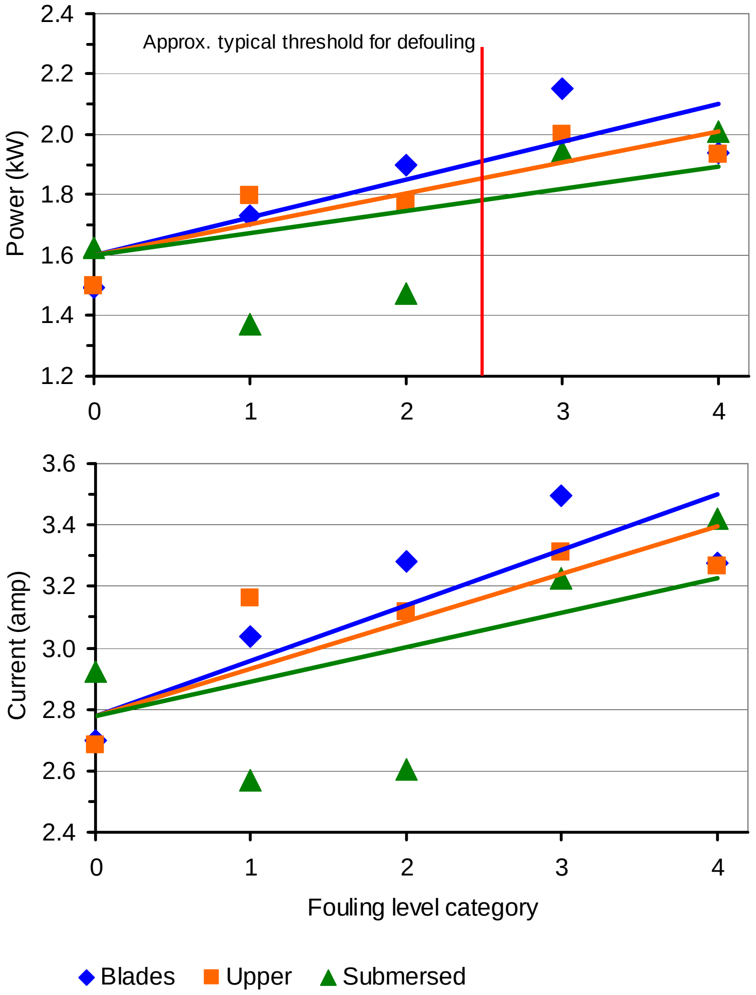

Figure 3. Effect of relative biofouling level of paddlewheel colonisation zones on electrical power use and current draw. All relationships with fouling category are statistically significant ($p<0.05$): Blades = only the flat blades on the rotor; Upper = all surfaces above the water line except the blades; submersed = all surfaces below the water line.

3.2.3 Part C. Standardised testing of biofouled paddlewheels

Summary

An aerator testing system was constructed at the Bribie Island Research Centre to test oxygenation performance of aerators under standard conditions. Naturally biofouled paddlewheels were tested to identify the differential impact of paddle blade fouling and fouling of all other surfaces. Electrical and oxygen transfer performance in the fouled condition was compared with that in the totally clean condition to assess impact of the fouling.

The highest biofouling load measured was 35kg, consisting of microbial biofilm, filamentous algae and barnacles, however due to the density of water and the high level of airborne water the actual additional weight on the paddlewheel is different to the total weight of fouling as measured out of the water.

Twenty one standard oxygen transfer tests were conducted on three biofouled paddlewheels derived from production ponds providing data for the effect on performance of rotors only biofouling and overall biofouling load. Biofouling significantly ($p<0.05$) increased power use however this was partially offset by a significant ($p<0.05$) increase in the oxygen transfer rate. Therefore the change in oxygenation efficiency was not directly proportional to the change in power consumption though still significantly reduced by biofouling.

The maximum additional operating cost per day caused by biofouling is estimated to be approximately $3.50 for an excessively fouled paddlewheel. However more typical maximal additional cost is in the range $0.70 to $1.40 per day per paddlewheel as farms usually defoul paddlewheels when they are in the 10 to 20kg loading range.

A model of the impact of paddlewheel weight loading on six electrical and oxygen transfer parameters was developed using simulated fouling in the form of concrete blocks covering a range of weight potentially occurring on farms. These tests determined a significant linear relationship between weight loading and electrical power, current, power factor, oxygen transfer rate, rotation rate and lateral pulling force. Aeration efficiency was not significantly ($p>0.05$) affected by weight, though there was a trend for reduction with increasing load, as the increase in power use was largely offset by a proportional increase in oxygen transfer rate. The models electrical performance relationship with weight loading was compared with values from farm biofouled paddlewheels and found to be in close agreement though farm derived figures varied markedly.

On farms the operator can expect that oxygen transfer by paddlewheels will not be compromised by biofouling, even improved, but additional electricity costs as well as increased maintenance requirements due to the additional loading will be incurred.

Paddlewheel performance testing results

This investigation included three components that contribute to fully understanding the impact of biofouling on paddlewheel performance and aeration costs:-

(i). Testing pond biofouled paddlewheels
(ii). Biofouling load simulation tests
(iii). Energy cost of biofouling

(i). Testing pond biofouled paddlewheels

The highest biofouling load measured for the test paddlewheels was 35kg (Figure 8), consisting of microbial biofilm, filamentous green algae and barnacles. The actual weight loading of this paddlewheel when operating will be considerably less than this since the barnacle load was predominantly submersed. Most algae colonised the upper surfaces and when constantly wetted will contribute its own weight plus that of the water entrapped in its dense aggregations. The paddlewheel tested that showed the most extensive filamentous algae growth had a total biofouling load of 20.7kg (Figure 6). Some of this growth occurred at the water line and with the paddlewheel in normal operating position would not contribute additional weight as it is almost neutrally buoyant in water. However given the extensive nature of the algae above the water line on this paddlewheel a large part of the algae weight would fully contribute to weight loading. It was not possible to measure the total weight of the fouled paddlewheel while operating but it is observed that a considerable amount of water is retained in the algal mass as water flows over all upper surfaces. This water volume would therefore contribute substantially more weight during operation. It is considered possible that total additional loading on paddlewheels due to biofouling

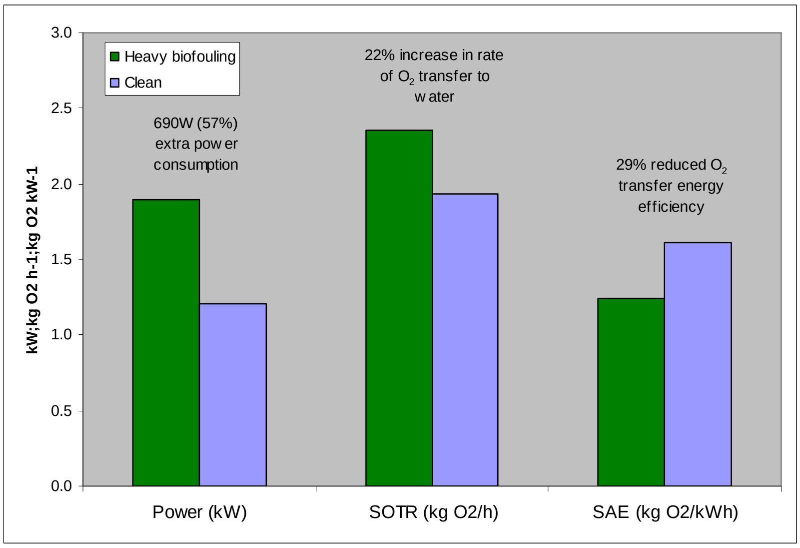

Figure 4. Comparison of matched clean and algae biofouled paddlewheels showing the effect of heavy filamentous algae (*Ulva* sp) biofouling on performance of a 4x rotor paddlewheel.

could reach 50kg in situations where there is high barnacle colonisation and high algal growth on all upper surfaces.

Twenty one individual standard oxygen transfer tests were conducted on three biofouled paddlewheels derived from production ponds providing data for the effect on performance of rotors only (paddle assembly) biofouling and overall biofouling load. Results show clearly that biofouling significantly increased power use (kW) of the device (Figure 4, 5 and 7). However this is offset to some extent by a significant increase in the oxygen transfer rate (kg O_2 per hour). Oxygenation efficiency (kg O_2 per kW) is significantly reduced by biofouling though not directly in proportion to the increased power consumption due to the improved rate of oxygen transfer. Under pond conditions where oxygen transfer rate is critical, farms therefore get some benefit from the increased electrical costs though it should be noted that biofouling also contributes to increased wear and tear and maintenance costs.

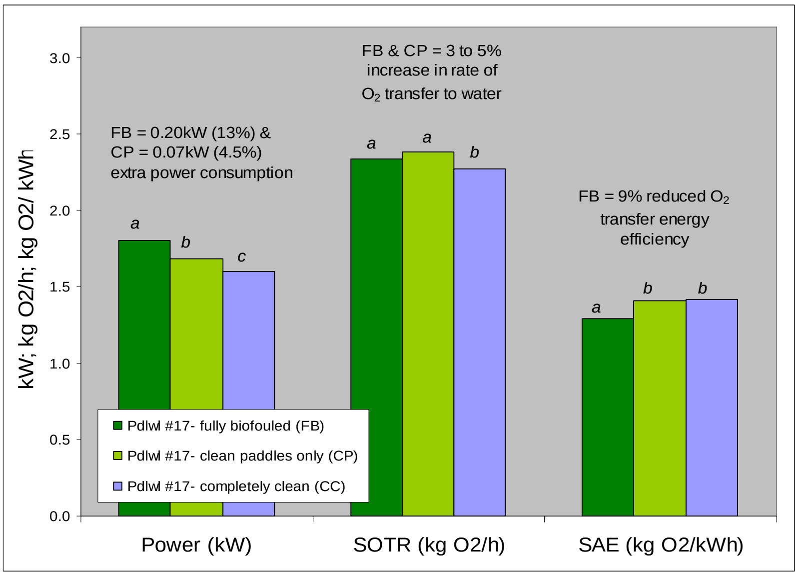

Figure 5. Effect of biofouling on the performance of a 4x rotor paddlewheel, in original fouled condition, with only the paddles defouled and in fully cleaned condition. Bars in each group with the same letter tag are not significantly different.

Biofouling of the paddles can potentially affect several aspects of paddlewheel performance directly. It contributes to increased weight of the aerator, affects the characteristics of splash and water droplet dispersion created by the paddles and affects the physical forces involved in blade motion into and through the water. Paddlewheel blades are designed with a specific profile and array of holes and biofouling, particularly algae, can close the holes and add extra bulk to the profile (Figure 9). The standard oxygenation test that assessed highly fouled rotors on an otherwise clean paddlewheel (Figure 7) and paddles only cleaned on a fully biofouled paddlewheel (Figure 5) determined that the biofouling effect on power use and the aeration efficiency (SAE) is in excess of that expected for the weight loading influence alone. This indicates that for fouled paddlewheel blades non-weight related influences are also contributing to the observed oxygenation and electrical performance changes.

Figure 6. Futi 2hp paddlewheel tested. Heavily fouled, predominantly filamentous algae (Ulva sp). Total wet weight of fouling in air = 20.7kg. As algae covers the upper surfaces this weight will be a large underestimate of additional weight loading during operation due to entrapment of water.

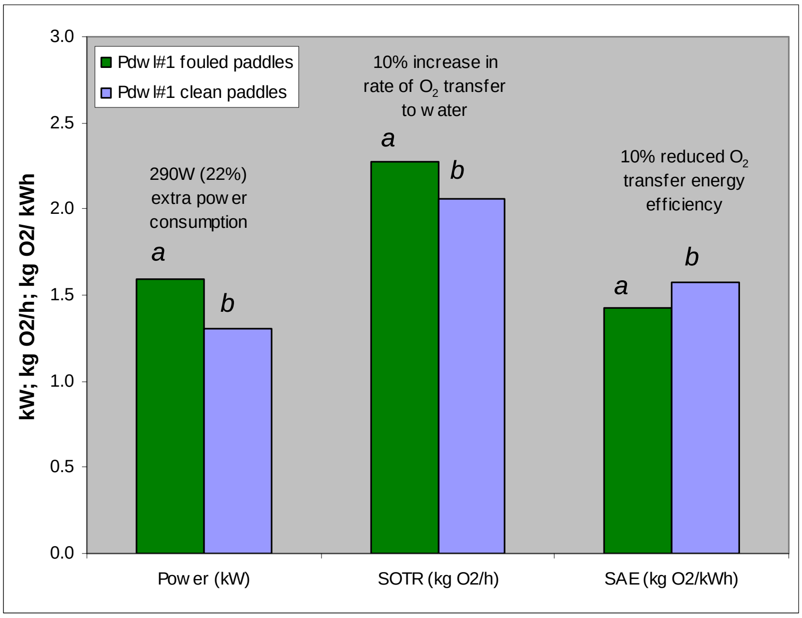

Figure 8. Effect of filamentous algae biofouling of the rotors (paddle/spindle assembly) only on performance of a 4x rotor paddlewheel. Bars in each group with the same letter tag are not significantly different.

Figure 7. Chenta 2hp paddlewheel tested. Heavily fouled with barnacles and algae. Dense covering of barnacles on the float submersed surfaces, algae (filamentous and slime) and barnacles on the paddles and upper surfaces. Paddles not heavily fouled, with little filamentous algae but covered in dark biofilm. Total weight of fouling in air = 35.1kg.

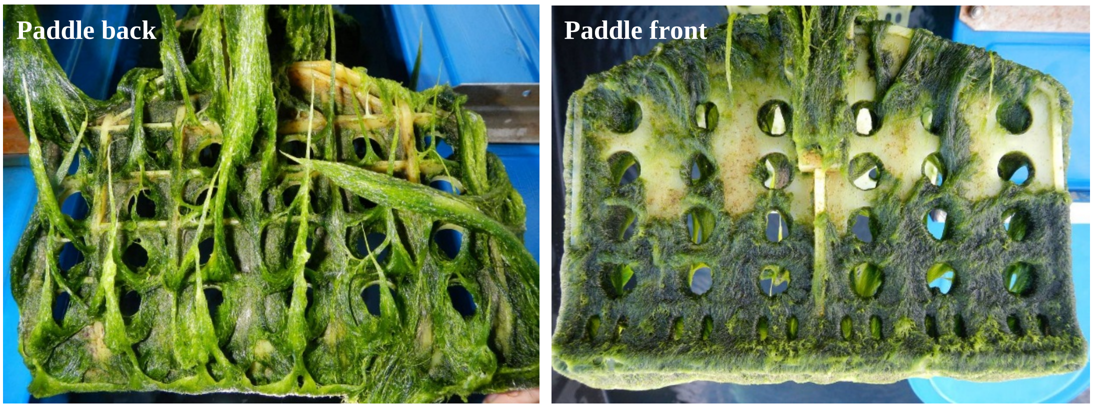

Figure 9. Blades of Futi 2hp paddlewheel tested. Paddles assembly removed from a fouled unit and placed on a clean one to provide data specifically for paddle fouling impact. Rotors combined wet weight of algae in air = 10.5kg.

(ii). Biofouling load simulation tests

The relationship between paddlewheel performance and additional loading rate was characterised using artificial weights in tests to simulate the wide range of fouling loads potentially experienced on farms. These tests determined a significant linear relationship between weight loading and five of the six measured parameters related to paddlewheel function (Table 10). Only the aeration efficiency (kg O_2 per kWh) was not affected by weight loading (Table 10).

Table 10. Performance characteristics of a 2hp 4 rotor paddlewheel in response to simulated biofouling weight loading. Within each parameter values with the same letter tag are not significantly different ($p<0.05$).

Parameter	Additional weight loading (kg)					
	0	10	20	30	40	50
Power (kW)	1.257 *a*	1.400 *b*	1.532 *c*	1.684 *d*	1.783 *e*	1.947 *f*
Current (A)	2.521 *a*	2.662 *b*	2.829 *c*	3.007 *d*	3.142 *e*	3.340 *f*
Power factor	0.697 *a*	0.736 *b*	0.754 *c*	0.778 *d*	0.794 *e*	0.812 *f*
SOTR (kgO2/h)	1.968 *a*	2.192 *b*	2.401 *c*	2.644 *d*	2.784 *e*	2.892 *f*
SAE (kgO2/kWh)	1.566 *a*	1.566 *a*	1.567 *a*	1.570 *a*	1.561 *a*	1.485 *a*
Rotation rate (rpm)	103.0 *a*	102.5 *a*	101.3 *b*	100.8 *b*	100.0 *c*	98.8 *d*
Pulling force (kg)	20.88 *a*	26.12 *b*	29.61 *bc*	33.23 *cd*	34.24 *d*	37.96 *e*

Consistent with the natural biofouled paddlewheel tests, results for the artificially fouled tests clearly show that increasing the total weight of a paddlewheel increases oxygen transfer rate (kg O_2 per hour) (Figure 10 A). The extra loading however causes a corresponding increase in power use (kW) (Figure 10 B) of similar proportions so there is a small to negligible decrease trend in the oxygen transfer efficiency (kg O_2 per kWh). Rising current draw (Figure 10 B) and reducing rotation speed (Figure 10 C), which means increasing motor slippage, indicate there is

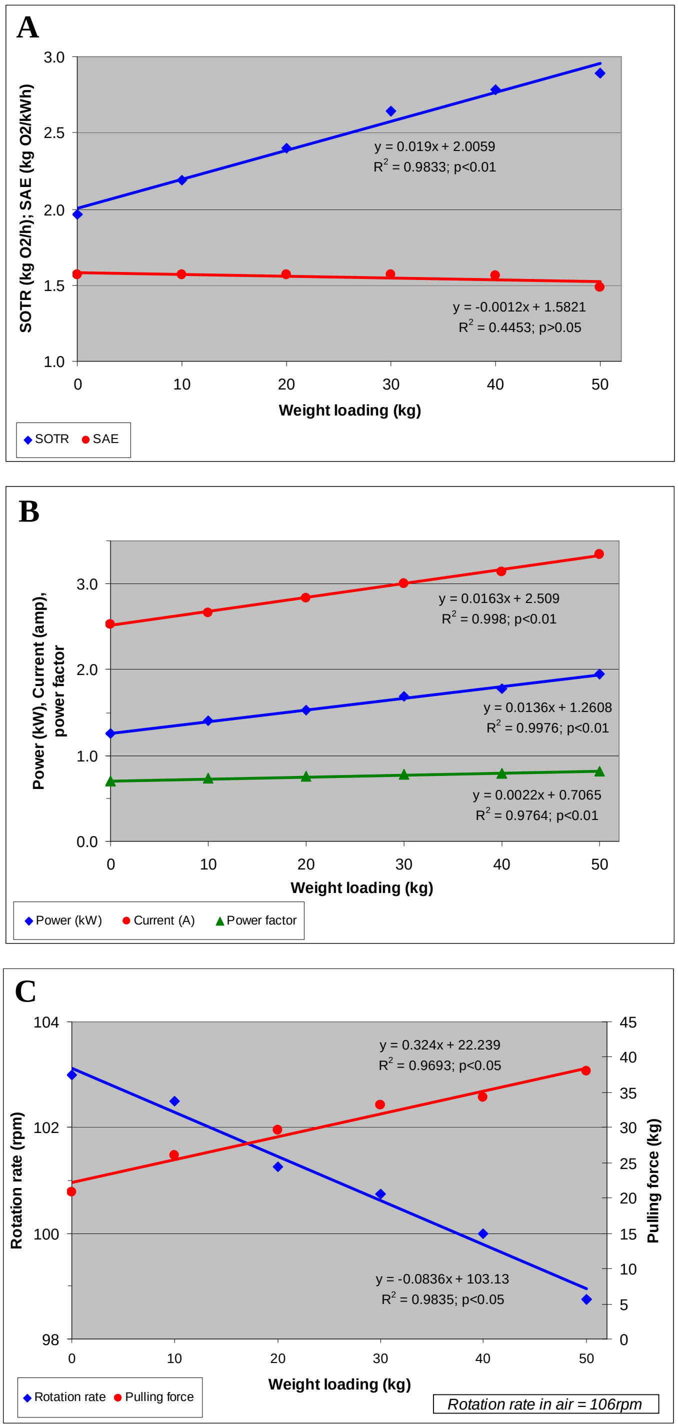

Figure 10. Performance of an industry standard 2hp 4 rotor paddlewheel in response to simulated biofouling weight loading. A. Oxygen transfer. B. Electrical measures. C. Rotation rate and lateral pulling force.

significant increases to load on the motor above the design specifications so wear and tear and unit maintenance costs become critical factors.

The lateral pulling force measured in these tests is considered to be directly related to the water current generating force of the paddlewheel. Higher pulling force means that the paddlewheel is pushing more water as it rotates and this increases linearly as paddlewheel loading increases. Additional weight on the paddlewheel affects the duration each rotating paddle is in the water and the depth of penetration and the outcome is an increase in the lateral force applied to the water and there is a 25, 42 and 59% increase for additional weight of 10, 20 and 30kg respectively (Figure 10 C). The consequence in a prawn pond is that a higher velocity water current when paddlewheels have significant biofouling loading. Depending on pond circumstances this could be a benefit or a disadvantage.

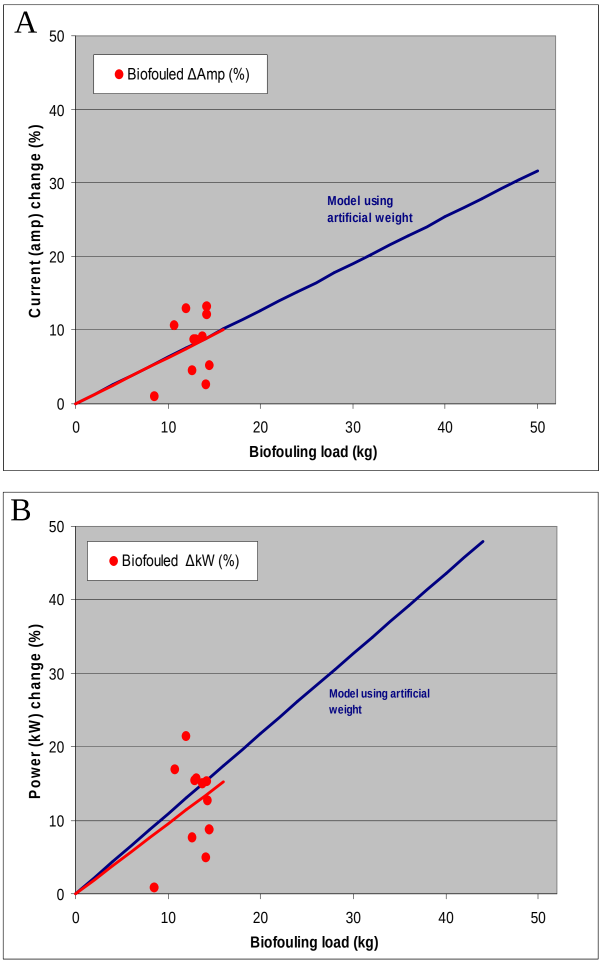

Figure 11. Change in current draw (A) and power use (B) of biofouled paddlewheels with estimated weight load compared with that for an artificially weighted paddlewheel.

The additional weight due to biofouling on a paddlewheel in operation is different to that measured with the device out of the water. It is not possible to measure weight with the paddlewheel operating and the high water turbulence surrounding the device means that relative floating height cannot be measured to calculate displacement weight. For this project an operating biofouling weight estimate was made using assumptions of barnacle density and algae water holding capacity, though this method has greater potential for error. The electrical performance of pond paddlewheels along with their estimated biofouling load was compared with that of the model derived from artificial weighting tests. The results show that there is a high variability in the electrical current and power use relationships with additional weight loading, however the average value for the pond biofouled paddlewheels is in reasonably close agreement to the modelling provided by artificial weighting of a standard paddlewheel (Figure 11). It can therefore be considered that the model has acceptable reliability when predicting performance of farm pond paddlewheels in situations where there is little or no paddle biofouling. Where there is obvious biofouling of the paddles, particularly filamentous algae, predicted values will likely stray from the model due to influences in addition to weight loading.

(iii). Energy cost of biofouling

Data on the effect of biofouling load on electrical performance of farm paddlewheels was used to estimate its affect on the operating cost of energy for the average paddlewheel. The additional cost attributable to biofouling was calculated as the biofouled paddlewheel operating cost minus the basal, clean operating cost of the same paddlewheel based on relative energy consumption. The maximum additional operating cost per day for operating an extremely fouled paddlewheel is around $3.50. However farm operators more typically defoul paddlewheels when they are in the 15 to 25kg loading range so maximal additional costs lie in the range $1.00 to $1.80 per day (Figure 12).

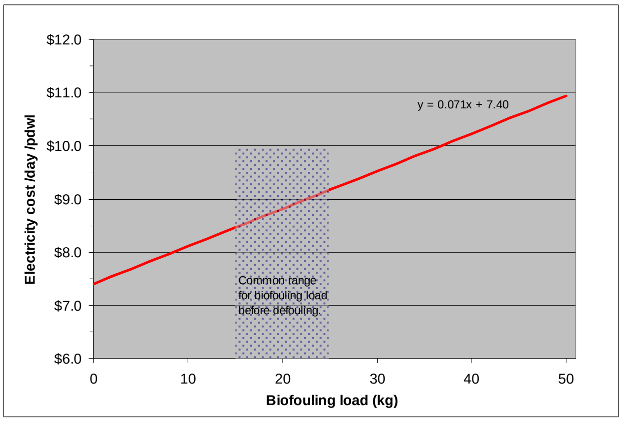

Figure 12. Cost of energy (kWh) to operate a standard paddlewheel for 24h over a range of biofouling loads. Basal power use in the clean condition is assumed to be 1.54kW and the energy cost $0.20/kWh.

3.3. Evaluation of selected biofouling control measures

Summary

Fouling release coatings were identified by the prawn farming industry as an appropriate option to control biofouling of aerators, particularly paddlewheels, since these products are non-toxic and are readily available. The potential for fouling release coatings to achieve an economically attractive biofouling control option for Australian prawn farms was investigated. Only two of the fouling release products on the market were suitable for the HDPE material used to construct the majority of paddlewheel surface area exposed to biofouling; a wax-based and a silicon-based product that differed markedly in cost and coating appearance.

The wax based fouling release product, AFwax®, has no merit for application to prawn farm aerators as it failed to inhibit barnacle colonisation or reduce attachment strength. This result indicates an apparent difference between barnacles and mussels in terms of inhibitory surfaces based on supplier tests conducted on a prawn farm in Thailand. The manufacturer of this product continues to work on new formulations appropriate for Australian prawn ponds.

The economic assessment of the silicon based product tested, Protecta-hull®, indicates that it is not an attractive proposition for a farm. Modelling using farm averages for paddlewheel and biofouling measures indicate that it reduces the total cost of biofouling per pond cycle, however its high initial investment cost as well as the ongoing coating maintenance costs, significantly detract from its viability. It was estimated that for an initial investment of $3,360 per ha, coating paddlewheel floats with Protecta-hull would reduce the cost of biofouling from $1,055 to $890 per ha.

In prawn pond tests Protecta-hull provided a highly significant reduction in barnacle settlement rate, averaging approximately 45% less barnacle cover on coated compared with untreated float submersed surfaces. High fouling release properties of the coating were also demonstrated. Barnacles and other fouling organisms did not achieve firm attachment and could be simply wiped free of the coating surface by hand or flexible implement. Any defouling considered necessary during the crop could be achieved by running a gloved hand over the Protecta-hull coated surface. Performance results of Protecta-hull were consistent with the supplier's prior experience with its application in open sea environments.

A critical problem identified was patches of coating integrity loss, possibly due to mechanical damage during paddlewheel handling and transfer to ponds or inconsistencies in coating application. These were experienced on almost all floats tested. Barnacles successfully exploited any patches of compromised coating and appeared able to undermine the coating as they grew, broadening the area of native float surface available for further colonisation. Coating disruption increases biofouling accumulation but also more critically complicates defouling and creates a maintenance need for regular repair. Thorough cleaning and patching at the end of each production cycle significantly reduces the economic attractiveness of the fouling release coating.

It is clear that paddlewheels with fouling release coated surfaces need to be handled very carefully to avoid damaging the coating. The need to transfer paddlewheels from pond to workshop for regular mechanical maintenance and the on-farm practicality of manipulating such cumbersome equipment however makes it difficult to avoid incidental damage. Additionally, paddlewheel floats present a relatively difficult surface to coat evenly due to their complex and curved shape. Applying two coats of the Protecta-hull would ensure that a suitable minimum depth of coat is achieved over the entire surface and the overall deeper coating, up to two times that achieved in this test, would possibly further improve the fouling release properties and its resistance to mechanical damage. Double coating the floats was not conducted in this test due to the significantly higher application cost, and this was considered to put the treatment further from economical viable.

The most cost effective way of using the Protecta-hull coating is to limit application to the submersed surfaces of the paddlewheel floats prone to high barnacle fouling. The upper constantly wetted surfaces susceptible to biofouling, particularly by filamentous macro-algae, can be controlled by regular dry-out days which is a cost effective method that works for all surfaces above the water line.

Each of the two fouling release products tested were assessed against key criteria relating to their suitability and economic viability for use on paddlewheels aerators (Table 11). The practical and economic attractiveness of Protecta-hull coating use on paddlewheel is low, however it is an inert silicon based impermeable layer that could be effectively used for surface protection and fouling attachment inhibition on smaller, critical surfaces that are in constant contact with pond water.

Table 11. Assessment summary for the two tested fouling release products against key criteria for application to reducing biofouling cost on prawn farm aerators.

	Initial cost	Effectiveness	Practicality	Durability	Maintenance requirement	Longevity	Economic attractiveness
Protecta-hull	high	mod-high	low-mod	low-mod	high	mod*	low
AFwax	mod	nil	low-mod	low-mod	mod	mod*	nil

** - not tested over multiple crops however where coating not disrupted following defouling after the first crop cycle the coating remained attached to the float and no changes to the surface appearance were observed.*

Fouling release coating test results

There were significant differences among the three farms in total biofouling cover on floats at the end of the test period ($p<0.05$; 69, 72 & 95% cover) but two organisms, barnacles and filamentous green algae dominated the cover on all farms. Apart from a colony of calcareous tubeworms on one float on one farm, barnacles strongly dominated the macrofouling cover on float bottoms (>95% cover) and filamentous algae was the only macrofouling organism associated with top surfaces. Float sides comprised a mix of barnacles and algae though dominated by barnacles (Table 12). Barnacles ranged from newly settled (<2mm) to 12mm base diameter. At the highest fouling rates observed barnacle colonies reached approximately 40mm deep by ‘stacked’ growth (Figure 13).

Table 12. Macrofouling cover as a proportion of total surface area for each fouling zone of paddlewheel floats coated with either a silicon (Protecta-hull) or wax (AFwax) based product or with no coating (control). Cover by each of the main macro-fouling organism groups presented both as total area covered by the group and as a proportion of the total biofouling cover.

	Mean % macrofouling cover			
Float zone / variate	*PtH*	*Afwax*	*Control*	*P value*
Bottom				
Total cover	51.9	93.0	91.0	<0.001
Barnacle cover	48.8	92.2	89.8	<0.001
Algae cover	3.1	0.8	0.0	0.144
Barnacle % of total cover	96.7	99.2	98.8	0.422
Algae % of total cover	3.3	0.8	0.0	0.13
Tubeworm % of total cover	only one occurrence			
Side				
Total cover	51.7	94.5	96.8	<0.001
Barnacle cover	39.8	86.7	87.8	<0.001
Algae cover	11.8	7.8	8.9	0.347
Barnacle % of total cover	83.3	90.0	90.2	0.147
Algae % of total cover	16.7	10.0	9.8	0.147
Tubeworm % of total cover	no occurrence			
Top				
Total cover	2.9	0.2	16.1	0.061
Algae % of total cover	only algae present			

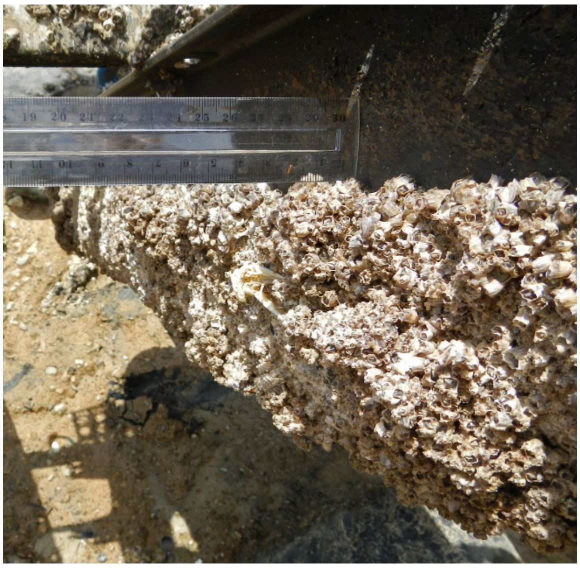

Figure 13. Multi-layered, stacked, barnacles on the side surface of a paddlewheel float. Colony depths up to 40mm were observed in this trial. Ruler included for scale.

(i). Wax based fouling release coating

The AFwax coating did not affect the settlement or growth of barnacles or algae on the submersed surfaces and cover rates were the same as the control floats (Table 12; Figure 13 and 15). Finger force tests indicated that the barnacles achieved a very high attachment strength equivalent to the control float and in many cases it was not possible to achieve dislodgement using this method. Close inspection revealed that the barnacles were able to grow into the coating to some extent, though still not attaching directly to the native float surface. Barnacles have the ability to penetrate soft coatings as they grow (Woods-Hole Oceanographic Institute 1952) and it is apparent that in the absence of settlement inhibition they were able to strongly attach to the AFwax coating.

There was some indication that AFwax may reduce the colonisation rate of filamentous algae on the top surface of the float with the probability approaching significance level (Table 12). The relatively low incidence of algal growth across the entire experiment reduced statistical power for this variate.

Barnacles required the full force of the high pressure water jet cleaner to be dislodged, ie with the nozzle around 10-15cm from the surface, and this was sufficient to also remove the wax coating.

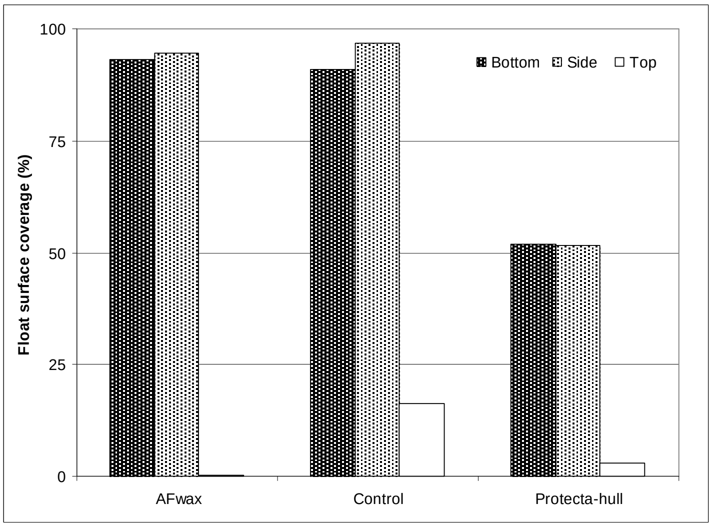

Figure 14. Colonisation rate for coated and non-coated surfaces for the three main colonisation zones of paddlewheel floats as a proportion of the total surface area; bottom (lower horizontal surface), side (submersed vertical surfaces) and top (upper horizontal surface)

The AFwax formulation trialled here had previously shown some promise in brief manufacturer's tests against mussel-fouling on prawn farms in Thailand. Test panels containing variants of the AFwax formulation were deployed in ponds at the same time as the paddlewheel tests and these identified particular formulations that were less susceptible to barnacle colonisation. The manufacturer advises that they will continue to develop the product to meet specific local biofouling needs.

Figure 15. Typical barnacle cover after 3 months operation, observed in the trial on each of the three float surface treatments. From left- uncoated, AFwax, Protecta-hull.

(ii). Silicon based coating

Total and barnacle specific coverage on the sides and bottom of Protecta-hull coated floats was significantly less than the control floats (Table 12; Figure 14 and 15). On average there was a 45% reduction in barnacle growth which appeared to be due to reduced settlement rather than dislodgement of established growth. Median size of barnacles on the coated and uncoated floats were not different. There were insufficient observations of algal growth on the top surface to statistically discern a potential reduction caused by the silicon coating.

There were two obvious groups of barnacle cover observed on the Protecta-hull coated floats, that occurring on the intact coating and that attached directly to the native float surface apparently exploiting areas of compromised coating integrity. In the latter case it appeared that barnacles may have been able to extend the boundary of the compromised coating area as they grew increased in size (Figure 16). Patches of lost coating integrity occurred on both the sides and the bottom of the floats.

Barnacles growing directly on the float surface and against, or in some cases partially under, the silicon coating could not be dislodged using the finger force test. In comparison the finger test determined that barnacles growing on the uncompromised coating had very weak attachment strength. Barnacles of approximately 10mm base diameter could be dislodged using light lateral force. In broad areas of the float where the coating remained intact it was possible to completely clear all fouling growth, including moderate sized barnacles, using a bare hand by sliding the hand held tight against the surface. In most circumstances sturdy gloves should be used however because it is not necessarily possible upon first inspection to ascertain whether the coating is compromised in some areas.

Figure 16. Barnacle growth in patches of ruptured Protecta-hull coating. Note that the barnacles are able to grow partially covered by the delaminated coating.

The amount of Protecta-hull applied to the floats, and therefore the final coating thickness, significantly affected barnacle fouling rate as indicated by a weak though significant relationship between coating weight per float and biofouling cover ($p=0.005$, $r^2=0.4$ for bottom surface) with less barnacles on floats with higher coating rate. Despite attempting to ensure a consistent coating application the final quantity of product ranged from 0.5 to 0.9kg per float. The approach taken was to apply the coating at a rate just below the point at which an unacceptable level of 'running' occurred. Ambient temperature may have affected the product viscosity and therefore its tendency to run. Applying a thick coating by brush over curved and angled surfaces may also contribute to wide variation. The actual coating thickness was estimated to range from 0.4 to 0.86mm.

The high pressure jet cleaner was effective in removing all biofouling from the intact Protecta-hull coating with the jet nozzle held at a greater distance from the surface than that required for the control float (15-25cm compared with 5-10cm), indicating that far lower pressure could be used. In areas of the coated float where the barnacles attached directly to the float surface the full force of pressure water was required and this force was also sufficient to remove the coating further. In areas of numerous breaches of the coating this meant that a considerable area of coating was removed during defouling. Extensive patching would then be required. Therefore if a water pressure jet is used to clean Protecta-hull coated surfaces low intensity should always be used to avoid disrupting the coating.

The cause of the localised coating loss of integrity may have been due to damage during handling and transport of the paddlewheels or inconsistencies in coating application. The former cause is indicated by coating breaches located on the raised points on the float bottoms that contact the ground when placed down during reattachment to the paddlewheel body. In this case the corrugated cardboard or fabric used may not have been sufficient protection and subtle damage to the coating was incurred. However other breaches of the coating are difficult to explain particularly given the care and attention applied during deployment of the aerators. It is also possible that variable adhesion to the HDPE surface causing patches of delamination may have been a contributing factor. Thickness of coating likely has an affect on its resistance to contact with abrasive or jagged surfaces. In this test a single application coat was used providing a coating thickness of around 0.5 to 0.75mm thick. Double coating the floats was not conducted in this test due to the significantly higher application cost, up to double, and would be less likely to be economically viable. Applying two coats of the Protecta-hull would reduce the likelihood of areas of sub-optimal coating depth and, as indicated in this trial, improve its fouling inhibitory properties. While costing more to initially apply, potentially the extra thickness could significantly improve its durability and reduce on-going coating maintenance requirement.

(iii). Economic analysis

The wax based coating, AFwax, was the cheapest option to apply at an estimated $91 per paddlewheel and $725 per ha (8x paddlewheels). However due to its infectiveness in controlling barnacle biofouling growth or inhibiting attachment strength it was not assessed for economic impact on farm aeration costs.

A previously conducted survey of Australian prawn farms had established a cost estimate breakdown for aerator biofouling per hectare per production cycle (Table 12). This was used as the basis for calculating the effect on total cost of Protecta-hull use on paddlewheel floats. It should be noted that the figures relate only to fouling release coatings applied to the floats and assume that no other biofouling control is undertaken. Therefore the cost impact calculated in this report refers solely to that due to Protecta-hull application to the floats. It is expected however that a farm using a fouling release coating on the floats would also practise scheduled paddlewheel off-duty days to control biofouling of the upper surfaces which can be highly effective and provide significant additional cost savings.

Electrical calculations are derived from a farm aerator monitoring program that was conducted in conjunction with the work reported here and which is reported elsewhere (Mann 2013). Average farm power use and current draw for 2hp paddlewheels were used in the calculations. Additionally data on the impact of weight loading and the impact of biofouling of paddlewheels on their electrical performance generated in a separate study (Mann 2012c) was used to calculate the impacts of biofouling load on energy use and cost and as an indicator of defouling demand.

Paddlewheel electricity use calculations show that over the course of a 20 week production cycle electricity cost savings by the Protecta-hull coating are modest (Figure 17), totalling $46.50 (at $0.20 per kWh), due to the fact that additional power use caused by biofouling accumulates slowly over the course of the cycle and that the fouling release coating is around 45% effective in reducing barnacle colonisation. The greatest economic benefit of the coating comes from reduction in the need to manually defoul the paddlewheels during the crop cycle. Farms typically undertake defouling of paddlewheels once the electrical current draw crosses a threshold of around 3 to 3.2 amp which represents a high increase in motor load. The modelling indicates that use of Protecta-hull on the floats could keep the current draw under a defouling trigger threshold of 3.0amp for the entire crop cycle, even under high barnacle fouling pressure (Figure 18). This assumes however that filamentous algae fouling of the upper surfaces is low to moderate or is controlled by other means.

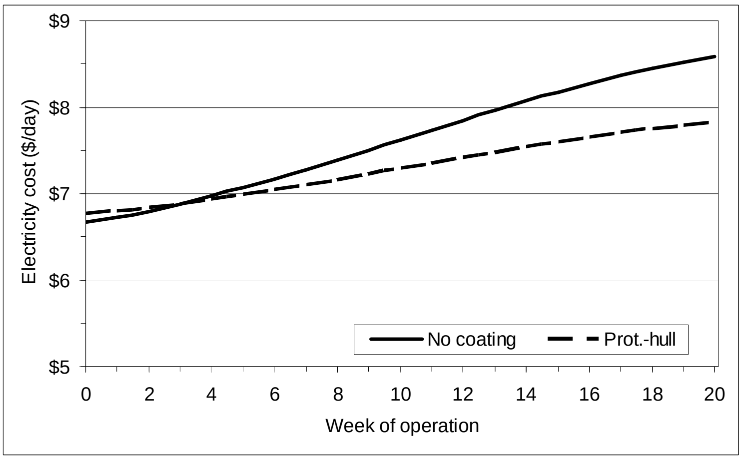

Figure 17. Modelling of the impact of a fouling release coating, Protecta-hull, application to the floats of a paddlewheel on the electricity cost per day. Figures for an industry average 2hp paddlewheel operated continuously except for scheduled off-duty days used to effectively control algal accumulation on the upper surfaces.

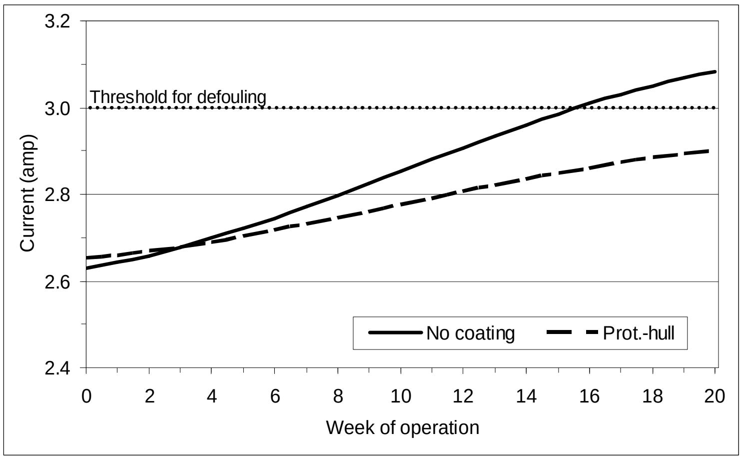

Figure 18. Modelling of the impact of a fouling release coating, Protecta-hull, application to the floats of a paddlewheel on time to reach the defouling current threshold of 3.0amp. Figures are for an industry average 2hp paddlewheel operated continuously.

The test floats used in the coating experiment were coated on all surface, however it is recognised that if the farm employs a procedure for inhibiting algal growth of the upper surfaces through regular off-duty days during daylight periods then coating of the top float surface is unnecessary. Not coating the top saves considerable costs of product and coating application labour ($3,360 compared with $4,940 for eight paddlewheels). It is also considered likely that a farm investing in coating of paddlewheel floats will also employ regular off-duty days to attain the highest level of biofouling control possible. The economic analysis of coating paddlewheel floats outlined in this report (Table 13) refers only to the impact of the coating on floats ignoring other biofouling controls farms may practise. Due to large number of factors that affect farm operation and the variability in aerator management practises among Australian farms figures presented here should be considered indicative but since calculations used real industry averages can be considered sufficient to make a valid assessment of the merits of potential biofouling controls.

Two aspects of coating floats with Protecta-hull have a large impact on the benefit attained. Firstly, the product is on average 45% effective in inhibiting barnacle settlement and colonisation under prawn production pond conditions. This result is consistent with the fact that fouling release coatings are not designed to prevent colonisation of organisms but rather reduce attachment strength so they are readily removed. Since barnacles and other macrofouling organisms will still accumulate paddlewheel weight loadings for electricity and mechanical maintenance accrue. Additionally manual defouling will still be required at the end of the crop cycle at least and during the crop cycle if algal growth on the upper surfaces of the appliance occurs at a moderate to high rate. Secondly, the resistance of the coating, as applied in this test, to mechanical damage is relatively low leading to areas of coating integrity loss, greater difficulty in defouling and cleaning and patching the coating. These factors create a relatively high on-going maintenance cost (Table 13).

The relatively high investment cost of applying Protecta-hull to a farm’s paddlewheel fleet and the extended payback period as well as the practical issues related to protecting coated surfaces makes it an unattractive proposition for a prawn farm. This outcome has little to do with the effectiveness of the product but rather its cost and low resistance to damage. The need for farms to regularly transfer aerators from ponds to workshop for maintenance means there is ample opportunity for surface knock or abrasion and it appears that barnacles are well able to exploit any loss of coating integrity. If such damage could be avoided the economic assessment is far more positive. It should be noted however that coating longevity would still need to be proved as this trial was only able to assess coating appearance after a single crop cycle as an indicator of longevity.

A practical outcome for farms from this trial is that the performance and effectiveness of a fouling release coating appropriate for use in aquaculture systems has been demonstrated. While the product identified is not considered a viable proposition for use on paddlewheels, however it is an inert silicon based impermeable layer that has a strong influence on the ability of biofouling organisms to colonise and firmly attach to coated surfaces as well as a surface sealant. It could therefore be effectively used for surface protection and fouling attachment inhibition on smaller, critical surfaces that are in constant contact with pond water.

Table 13. Economic benefit of applying Protecta-hull fouling release coating to the sides and bottom surfaces of paddlewheel floats. Cost estimates for items are the additional aeration operation and management costs due specifically to biofouling and are per hectare per crop cycle for 8 paddlewheels, each with 3 floats. Initial investment cost of $3,360 includes product and application costs.

	Current situation- no biofouling controls	Protecta-hull on float sides & bottom	Estimated saving using Protecta-hull
Defouling labour	$405	$210 [a]	$195
Electricity	$305	$200 [b]	$105
Mechanical maintenance. Labour	$250	$175 [c]	$75
Mechanical maintenance. Parts	$95	$65 [d]	$30
Ongoing coating maintenance	-	$240 [e]	-
Total cost of biofouling /ha /crop cycle	$1,055	$890	$165
Initial investment cost		$3,360	
Payback period (based on initial investment cost)		20.4 crop cycles	

[a] *Std defouling av. 1.7x during crop (range 0 to 4) + end of the crop. Cost reduction based on defouling only at end of crop and assumes moderate algae fouling of upper surfaces.*

[b] *Protecta-hull coating estimated to save 35% of electricity compared with non-coated.*

[c] *Estimated 30% reduction in paddlewheel breakdowns and parts replacement due to reduced load on motor and components.*

[d] *Estimated 30% reduction in paddlewheel breakdowns and parts replacement due to reduced load on motor and components.*

[e] *Labour and product for annual patching ($210) and additional handling time for coated paddlewheels.*

4. Conclusion

The impact of biofouling on aerator operation and management was quantified by this project and the average full cost of biofouling to Australian prawn farms was estimated at $1055 per hectare per crop cycle (**Error! Reference source not found.**). Biofouling increases mechanical wear and tear, contributing to higher maintenance costs, as well as demanding a high level of labour for regular defouling and increasing operating costs.

Paddlewheel type aerators have far higher biofouling costs compared with the other main aerator type used on pond farms, surface propeller aspirators, or ‘aeros’. Prawn farms need to defoul paddlewheels on average 1.7x during a single crop cycle though this can be up to 4x in heavy infestations. By comparison, ‘aeros’ are not as sensitive to biofouling weight accumulation and are typically not defouled during the production cycle.

Biofouling increases the cost of operating paddlewheels however it can also have a more dramatic impact due to the increased rate of unit breakdown. Partial loss of aeration capacity can quickly lead to critically low oxygen levels overnight, threatening stock health and survival. Conversely, the extra load on paddlewheels leads to an increased rate of oxygen transfer to the water though this comes at the expense of electricity consumption and aeration efficiency.

Biofouling control options for marine and brackish water pond farms are limited compared with most other marine industries due to their particular operational constraints and the characteristics of aerators. With individual ponds typically containing 10 aerators at peak production the prawn farming industry can have up to 6,000 aerators in operation simultaneously. No single, pond-friendly approach to completely preventing biofouling of paddlewheels or other aerators that is practical and cost-effective was identified. There are, however, options farms can implement that reduce the cost of biofouling.

Fouling release coatings are a logical approach to controlling biofouling of the submersed surfaces of pond aerators. These paint-on products physically restrict the attachment strength of biofouling organisms as well as deter organism settlement to some extent and do not release any toxic chemicals into the pond environment.

A silicon-based fouling release product, Protecta-hull® from Enviro Hull Solutions Pty Ltd was found to be suitable for the HDPE surfaces of paddlewheels though cost is an impediment to its extensive use on farms. In paddlewheel float tests on three prawn farms over ~90 days this coating decreased barnacle cover on average 45% and reduced barnacle attachment strength to the point where they could be simply wiped off by hand or flexible blade. Despite the effectiveness of the product an economic assessment indicates it is not an attractive investment for a farm (**Error! Reference source not found.**). Additionally such coatings are not resistant to the physical knocks and abrasion caused when moving coated paddlewheels around the farm imposing significant farm practicality issues and greatly reducing coating effectiveness.

All paddlewheel surfaces above the water line are constantly splashed during operation and are subject to biofouling, particularly green filamentous algae. Accumulation of biofouling above the waterline has a greater affect on paddlewheel function than that below the waterline because all accumulated mass contributes to weight loading, in contrast to the weight of submersed biofouling which is offset by the density of water. Additionally, a large amount of water can be trapped within upper surfaces algal growth while the paddlewheel is in operation, substantially contributing to the weight loading.

Regularly drying the upper surfaces of a paddlewheel by temporarily turning it off is a highly cost effective way to control development of all upper-surface biofouling (**Error! Reference source not found.**). A dry-out time of a single daytime period is usually enough to control biofouling if it is not allowed to develop beyond a thin layer prior to treatment. Following a scheduled off-duty day program will ensure paddlewheels are consistently treated at appropriate intervals.

Table 14. Economic benefit of applying two biofouling control options; fouling release coating (FR) to the sides and bottom surfaces of paddlewheel floats; and employing scheduled off-duty days for paddlewheels.

	Current situation - no biofouling controls	FR coating on submersed surfaces of floats	Scheduled off-duty days	Both FR coating on floats & scheduled off-duty days
Defouling labour	$405	$210	$210	$80
Electricity	$305	$200	$140	$55
Mechanical maintenance. Labour	$250	$175	$125	$50
Mechanical maintenance. Parts	$95	$65	$50	$20
Fouling release coating maintenance	-	$240	-	$250
Operating off-duty days program	-	-	$250	$240
Total cost of biofouling /ha	$1,055	$890	$775	$695

Switching off aerators can only be achieved manually at pond-side electrical distribution boards with current farm electrical systems. Labour required to undertake this task two times per day can accrue significant costs over a production season due to multiple distribution boards supplying each pond and large numbers of ponds. The advantage of manual switching over timers is however that the condition and operational status of the paddlewheel can be instantly checked each time.

Frequently switching aerators off and on can potentially increase wear and tear due to the high start up mechanical stresses and, more critically, lead to condensation of water inside the motor when it cools. Motors and drive gear that are in good condition however should be less susceptible to these problems. Additionally, reducing chronic mechanical loading by preventing biofouling accumulation will reduce unit wear & tear and labour and parts maintenance costs in the long run.

Biofouling most heavily impacts paddlewheel operating and maintenance costs compared with other aeration devices. A logical way to reduce the cost of aerator biofouling is therefore to replace paddlewheels with a less affected aerator. Surface propeller aspirators, or ‘aeros’ currently comprise a third of the aerator fleet across the prawn farming industry however extensive replacement of paddlewheels with these aerators would likely require a substantial change to pond management strategy. The high water flow generating capacity of paddlewheels is considered critical to achieving high stock health conditions under the standard pond management approach.

It is anticipated that prawn farms will use the information resource generated by this project to further refine efficient strategies to manage their aerator fleet, minimising labour for aerator maintenance and electricity use and maximising reliability. A range of information reports detailing project findings were provided to farms. These include a comprehensive outline of biofouling control methods potentially available and methods for implementing two leading approaches as well as their practical and economic assessment. Generating the project data on farms and using farm equipment ensured that prawn farms received information directly relevant to their circumstances and which can be confidently used in formulating aeration management strategies.

Project findings snapshot

- *The Australian prawn aquaculture industry has a pond aeration fleet of around 6,000 units in simultaneous operation at the peak of the production season.*
- *Across the industry the aeration fleet comprises approximately ⅔ Taiwanese-style paddlewheels and ⅓ propeller aspirators ('aeros').*
- *On average aerator motors operate at above their rated power use rating, likely contributing to reduced motor longevity. There is likely scope to improve this through upgrading of aeration equipment over time.*
- *Biofouling of aerators directly costs an estimated average $1,050 per ha per crop cycle.*
- *The cost of biofouling for paddlewheels is far greater than that for propeller aspirator aerators due largely to the need to defoul paddlewheels an average 1.7 times during a crop cycle.*
- *Labour required for regular defouling is the highest biofouling cost item, followed by the cost of conducting more frequent maintenance caused by increased wear-and-tear and increased electricity demand.*
- *Biofouling of paddlewheels increases the rate of oxygen transfer into the water but at the expense of electrical efficiency.*
- *Non-toxic, fouling release surface coatings can be applied to aerator surfaces that reduce both the rate of colonisation and organism attachment strength allowing defouling to be less frequent and quicker.*
- *Fouling release coating options are limited and one product found to be effective has practicality and cost issues that limit application for a farm's aeration fleet.*
- *The search for a viable method to control biofouling of constantly submersed surfaces should continue as ongoing developments in environmentally friendly antifouling solutions are expected to continue.*
- *Currently, regular 'off duty days' for paddlewheels is the most cost effective method for preventing accumulation of biofouling on all upper surfaces.*
- *Replacing paddlewheels with propeller aspirator type aerators will greatly reduce biofouling costs. Individual farms can optimise aerator fleet composition based on their own experience but total replacement is not considered a viable option.*

5. Benefits and Adoption

The prawn farming industry commissioned this project and are the primary beneficiary of the work. All research activities undertaken in the project were designed to directly relate to Australian prawn farms, however most elements are applicable to any marine pond farming situations. The non-prawn marine pond farm sector is comparatively small in Australia, comprising a few salt water barramundi farms and marine finfish grow-out operations.

The benefits expected to flow into the prawn farming sector as a result of this research will be derived from farm changes to aerator fleet management that improve efficiency. The project quantified parameters critical to assessing the impact of biofouling on aeration and its cost and this information is now available for farm self-assessment. It is clear from the findings that any reduction to biofouling load accumulation on paddlewheels in particular will immediately reduce energy use and defouling labour requirement and in the long run reduce maintenance costs. There are also additional benefits that will result from controlling aerator biofouling that were difficult to quantify during the project, including providing for increased farm productivity and reduced risk of pond oxygen depletion mediated stock losses.

With increasing productivity of prawn farms a new constraint to production has been experienced on some farms as they have reached the capacity of their electrical supply limiting further aeration. These farms therefore need to make as efficient use of the electrical energy they have while maximising farm production and, though relatively modest, reducing the electrical demand caused by biofouling will contribute to this.

It is known that periods of restricted aeration at the critical high biomass period of a pond production cycle can have a serious impact on pond production since even short periods of low dissolved oxygen will compromise prawn health, growth and potentially survival. This project was not able to estimate figures for the lost production attributable to biofouling induced breakdown of aerators as the detailed data required is not available. It is clear however from farm data that biofouling significantly increases the rate of wear and tear on paddlewheel drive gear and the maintenance and parts replacement required. The rate of unit breakdown is known to be increased by biofouling and with it the increased risk of reduced aeration capacity at least for short periods. For example, two paddlewheels in the same pond breaking down overnight is potentially sufficient to cause dissolved oxygen levels to drop below the critical threshold for prawns if not attended to quickly. Such occurrences will in the least retard growth for a period and at worst cause catastrophic stock loss. Towards the end of the crop the farm has made considerable investment in the stock, potential market value of the product is high and due to high pond total respiration rate oxygen depletion can occur rapidly. Reducing biofouling load on paddlewheels will not prevent this scenario but will reduce the risk.

In the course of this project there were no aerator modification solutions identified that presented an attractive investment proposition for farms. Such options that met the APFA criteria were restricted to fouling release coatings and the two identified products appropriate for paddlewheels and immediately implementable were either not effective or expensive. While real benefits were attributed to coating paddle-wheels with the silicon based coating, the high investment required and some practicality issues mean that it is unlikely to be adopted by farms. It would however be a cost-effective solution for smaller, critical surfaces in constant contact with pond water, such as auto-feeder and water quality monitoring equipment.

The other approach to biofouling control assessed in the project, implementation of off-duty days for paddlewheels, can be readily adopted by all farms with little investment and low running cost. This method can reduce aeration costs by $280 per ha per crop cycle. Reducing paddlewheel biofouling in this way will also reduce break-down rates, lowering the risk of night-time loss of aeration capacity leading to critical oxygen conditions and stock loss. It should be noted that at least three prawn farms have implemented an aerator off-duty program successfully prior to this projects outputs and will be continuing this practise. These farms provide direct evidence that this approach to biofouling control is an attractive and practical reality.

The figures generated by this project and the methodologies it used for examining cost effectiveness of modifications to aerators and their management provide a valuable reference for future assessments. Values for the various cost parameters associated with biofouling that were quantified by this project will enable ready assessment as new products or equipment considered for implementation. Additionally, individual farms can substitute those figures they may have for their own system for the industry average values used by this study to conduct an assessment more closely aligned to their particular circumstances.

6. Further Development

The aerator biofouling issue for prawn farms and the biofouling issue more broadly across the marine aquaculture industry has still not been controlled to what farms my consider an acceptable level. This project has highlighted a low cost practical method for effective biofouling reduction of the upper surfaces of splash aerators such as paddlewheels however a practical and cost effective solution to submersed surface biofouling appropriate for pond aquaculture has not been resolved. The search for appropriate products to meet this need should continue.

World-wide there continues to be fundamental research and product development directed to environmentally sustainable methods for controlling marine biofouling for a wide range of marine industries. The aquaculture industry stands to be a beneficiary of outcomes from this R&D investment. The critical part of exploiting this resource is monitoring world developments in the field and identifying those with potential for application to marine pond farming. This information then needs to be transferred to the aquaculture industry as new technologies arise. Individual farms can choose to explore this information further and conduct their own tests. This may not be the most efficient method of disseminating new technologies through-out the prawn or marine-pond industry however it is likely the most appropriate model following this project. Farms can make use of the figures generated in this project and follow the methods for assessment of candidate products as applied by this project. While the principal investigator of this project holds his current position at DAFF he will maintain information channels developed as part of the project and continue to monitor developments in biofouling control beyond this project. Any information of potential significance to the prawn farming industry will be passed on through the executive of the industry body and directly to farms.

Towards the end of the biofouling project two coating products come to the attention of the project investigator after completion of the on-farm testing program. Based on information from the suppliers with limited direct applicability to aquaculture ponds both products appear to meet the prawn industry conditions for a practical and readily implementable biofouling control option and have potential to be sufficiently effective to be an attractive proposition. The project has secured samples of these products and the project investigator has installed a test system on a prawn farm that will provide the necessary information regarding the effectiveness or otherwise under prawn pond conditions. The result of this test will not be available until 3 months after the termination of the project but DAFF Queensland will continue to support the work for the extended period. Cost effectiveness of the products will be evaluated following the previously applied method and results of significance will be reported to industry.

The aerator monitoring activities conducted during this project on a number of farms highlighted the general need for improved aeration systems, to both improve efficiency and reduce overall costs. This is supported by farm operators who consider paddlewheels in particular to be difficult to manage and costly to operate even if biofouling was less of an issue. They are resigned to the fact however that there is currently no aerator on the market that can fully replace the paddlewheel. New pond aerator designs are consistently being promoted by suppliers but typically reliable performance figures are not available for farms to make a decision and generally the designs do not address the water circulation function performed by paddlewheels. Improved aeration systems for pond based aquaculture is therefore an avenue that could contribute to industry sustainability into the future.

7. Planned Outcomes

The primary target outcome for the project was “Lower farmed prawn production costs due to reduced necessity for pond aerator defouling, improved aeration efficiency and optimised management of the aerator fleet”.

Achievement of this outcome requires farms to modify their current farm aeration fleet management. At the time of writing this report, favourable feedback had been received regarding farm interest in the information that had been provided to them. Generally farms review and evolve their methods on a continuous basis and the information outputs from this project will substantially contribute to the farm knowledge base used to formulate strategies appropriate to their particular circumstances. This is expected to occur over more than one production season. At least two farms had previously adopted the most cost-effective biofouling cost reduction measure assessed in this project. This combined with the data generated by this project further supports a more general move in this direction by industry.

The range of project generated information useful to prawn farms is contained in the following reports that were provided to farms:-

Survey of prawn farm aeration and biofouling. Report to industry.

Review of options for controlling biofouling of aerators on prawn farms.

Electrical performance of pond aerators on Australian prawn farms and the impact of biofouling. Industry report.

Performance of biofouled aerators measured under standard conditions. Report to industry.

Reducing the cost of aerator biofouling with fouling release coatings. Report to industry.

Biofouling cost and control for aerators in brackish and marine pond farms.

Private Benefit Outcomes

The project outputs were designed to provide key information to prawn farms relevant to biofouling and aeration management in a context and form that was directly applicable to their circumstances and could be readily utilised. Farms need to efficiently manage an aeration fleet of 100 to 600 units, so incremental improvements can accrue significant benefit over a farm. The aeration management related information generated by the project has not previously been available to farms and can be used to further refine the aerator fleet management strategy for efficiency and minimised cost. In particular the electricity use comparisons among different aerator types and with varying mechanical condition status will enable further optimisation of fleet composition and maintenance schedule. The biofouling information provided to farms clearly details biofouling impacts and costs and a reliable and directly applicable assessment of options available to mitigate those costs. As examples, figures for the cost per day of operating paddlewheels at different biofouling loads and information covering the pros and cons of a range of biofouling control options with a high level of detail for two approaches to reduce biofouling are valuable to optimising the maintenance program for the aeration fleet and implementation of a biofouling reduction scheme.

Public Benefit Outcomes

At the government and community level a priority is placed on restricting carbon emissions which dictates efficient use of electrical energy. Outcomes from this project contribute to the efficient use of the dominant electricity use sector on prawn farms. Pond aeration accounts for 70 to 80% of total farm electricity demand due to the large number of aerators typically in operation on farms.

Linkages with CRC Milestone Outcomes

The project aligns most closely with the following Seafood CRC stated Outcome and Output:-

Outcome 1 - Substantial increase in the production and profitability of selected wild-harvest and aquaculture species.

Output 1.3 - Removal or reduction of key production constraints in existing aquaculture systems.

The project was directly related to improving production efficiency and reducing production costs for an existing aquaculture system however this concept is not well captured by any stated Seafood CRC milestone connected to Output 1.3.

8. References

GenStat (2013). GenStat for Windows, Release 14.1., VSN International Ltd., Oxford.

Mann, D. (2012a). Review of options for controlling biofouling of aerators on prawn farms. Seafood CRC project 2011/734. Australian Prawn Farmers Association, Bribie Island Research Centre - Department of Agriculture, Fisheries and Forestry Queensland: pp 41.

Mann, D. (2012b). Survey of prawn farm aeration and biofouling 2012. Seafood CRC project 2011/734. Australian Prawn Farmers Association, Bribie Island Research Centre - Department of Agriculture, Fisheries and Forestry Queensland: pp 6.

Mann, D. (2012c). Measuring performance of biofouled aerators under standard conditions. Report to industry. Seafood CRC project 2011/734. Australian Prawn Farmers Association, Bribie Island Research Centre - Department of Agriculture, Fisheries and Forestry Queensland: pp 12.

Mann, D. (2013). Electrical performance of pond aerators on Australian prawn farms and the impact of biofouling. Report to industry. Seafood CRC project 2011/734. Australian Prawn Farmers Association, Bribie Island Research Centre - Department of Agriculture, Fisheries and Forestry Queensland: pp 3.

McCullagh, P. and J. A. Nelder (1989). Generalized Linear Models (2nd ed.), Chapman and Hall, London.

Woods-Hole Oceanographic Institute (1952). Marine fouling and its prevention. Ch1. The effects of fouling, U.S. Naval Institute, Annapolis, Maryland.

9. Appendices

Appendix 1. Intellectual Property

No valuable IP requiring commercial protection was generated in this project. Information of relevance to the prawn farming industry has been disseminated to farms.

Appendix 2. Staff and contributors to the project

Project staff	David Mann, DAFF Qld	Project investigator
Contributors to conduct of the project	Helen Jenkins, APFA Andrew Crole, Seafarm Tony Charles, APF Brian Paterson, DAFF Qld	Assisted with production of reports and industry liaison.
	No. of prawn farms, particularly APF, GCMA and Seafarm.	Assisted with on-farm testing and monitoring activities

Appendix 3. Farm aerator electrical monitoring results

All aerators were in normal operation in prawn production ponds.
Biofouling load score is calculated from observational assessment of the level of accumulated biofouling separately for the upper surfaces, submersed surfaces of the floats and paddle blades. Lower weighting in the score is given to the submersed surfaces load since contribution to the overall weight loading is reduced by the density of water.
"Pdwl, std" refers to paddlewheels of standard paddle and float configuration with four rotors and flat blades. "Aero" refers to the propeller aspirator type aerator.

Farm	Aerator type	Power (Hp)	Biofouling load score	Volts (V)	Current (amp)	Power (kW)	Power factor
1	pdwl, std rotor	2	6.3	424.8	2.917	1.947	0.902
1	pdwl, std rotor	2	0.3	423.9	2.724	1.402	0.697
1	pdwl, std rotor	2	0.3	422.8	2.656	1.309	0.670
1	pdwl, std rotor	2	0.3	423.3	2.509	1.620	0.877
1	pdwl, std rotor	2	2.4	423.8	2.718	1.793	0.895
1	pdwl, std rotor	2	3.3	425.0	3.100	1.757	0.766
1	pdwl, std rotor	2	1.9	428.4	2.808	1.857	0.889
2	pdwl, triangle blades	-	0.7	411.0	2.625	1.551	0.825
2	pdwl, triangle blades	-	0.7	411.1	1.879	1.053	0.786
2	pdwl, spiked rotor	-	0.7	408.4	2.284	1.121	0.691
2	pdwl, std rotor	3	0.7	410.2	2.268	1.356	0.836
2	pdwl, std rotor	3	0.7	411.8	2.181	1.351	0.859
2	pdwl, std rotor	3	0.7	410.6	2.235	1.384	0.866
2	pdwl, std rotor	2	0.0	405.8	2.298	1.439	0.878
2	pdwl, std rotor	2	0.0	405.5	2.808	1.464	0.740
2	pdwl, std rotor	2	0.0	405.9	2.677	1.397	0.738
2	pdwl, std rotor	2	0.0	409.6	2.305	1.441	0.876
3	pdwl, std rotor	3	5.5	405.9	4.046	2.541	0.897
3	pdwl, std rotor	3	8.1	407.4	3.240	1.916	0.833
3	pdwl, std rotor	2	0.3	407.7	2.808	1.687	0.847
4	pdwl, std rotor	3	0.0	430.3	3.199	1.763	0.735
4	pdwl, std rotor	3	0.0	429.2	3.162	1.741	0.736
4	pdwl, std rotor	3	2.8	428.7	3.376	1.966	0.780
4	pdwl, std rotor	3	0.0	428.8	3.293	1.876	0.761
4	pdwl, std rotor	3	2.8	423.7	3.549	2.114	0.806
4	pdwl, std rotor	3	0.0	423.6	3.251	1.837	0.763
4	pdwl, std rotor	2.5	0.0	433.7	3.659	2.259	0.819
4	pdwl, std rotor	2.5	2.8	425.4	3.167	1.872	0.796
4	pdwl, std rotor	2.5	0.0	428.3	3.013	1.721	0.760
4	pdwl, std rotor	2	0.0	427.4	3.110	1.915	0.824
5	pdwl, long-arm-11pdl	5	1.6	451.5	5.705	3.435	0.764
5	pdwl, long-arm-13pdl	4	0.7	452.2	4.593	2.322	0.642
5	pdwl, std rotor	2	2.4	453.7	3.294	1.719	0.660
5	pdwl, std rotor	2	4.6	452.4	3.284	2.034	0.786

5	pdwl, stainless pdls	2	1.6	453.9	2.967	1.568	0.668
5	pdwl, pipe rotor	2	3.3	451.7	2.704	1.363	0.641
5	pdwl, 2 rotor	2	3.7	452.4	1.290	0.868	0.859
5	pdwl, 2 rotor	2	4.6	453.8	1.925	1.126	0.741
6	pdwl, std rotor	2	0.3	418.3	2.463	1.328	0.741
6	pdwl, stainless pdls	2	0.3	417.9	1.589	0.790	0.688
6	pdwl, stainless pdls	2	0.3	420.6	2.134	1.000	0.640
7	pdwl, std rotor	2	6.7	397.3	3.069	1.809	0.850
7	pdwl, std rotor	2	5.8	398.7	3.155	1.800	0.821
7	pdwl, std rotor	2	6.7	402.1	3.931	2.364	0.861
7	pdwl, stainless pdls	2	2.8	398.1	2.332	1.079	0.665
8	pdwl, std rotor	2	0.0	409.9	2.690	1.616	0.846
8	pdwl, std rotor	2	2.1	405.9	2.590	1.566	0.860
8	pdwl, std rotor	2	0.0	430.7	2.714	1.411	0.693
8	pdwl, std rotor	2	0.0	416.0	2.423	1.172	0.669
8	pdwl, std rotor	2	0.0	430.3	2.665	1.473	0.738
8	pdwl, std rotor	2	0.0	416.9	2.632	1.342	0.704
8	pdwl, std rotor	2	0.0	432.4	2.822	1.528	0.719
8	pdwl, std rotor	2	0.0	427.7	2.357	1.223	0.699
8	pdwl, std rotor	2	0.0	423.3	3.765	2.383	0.864
8	pdwl, std rotor	2	1.0	409.5	2.569	1.573	0.863
9	pdwl, std rotor	2	5.7	414.2	3.339	1.997	0.830
2	aero, std	2	2.0	410.4	2.587	1.563	0.845
2	aero, std	2	2.0	408.0	2.842	1.717	0.852
2	aero, std	2	2.0	409.9	2.923	1.810	0.868
2	aero, std	2	2.0	411.3	2.787	1.721	0.858
2	aero, std	2	2.0	410.8	2.584	1.486	0.804
2	aero, std	2	2.0	410.6	2.596	1.483	0.799
3	aero, submersed motor	1.5	2.0	409.9	2.437	1.194	0.687
3	aero, submersed motor	1.5	2.0	408.9	2.490	1.234	0.696
5	aero, std	2	1.0	451.5	2.961	1.745	0.750
6	aero, std	3	1.0	416.5	3.092	1.541	0.687
6	aero, std	2	1.0	415.9	2.666	1.482	0.769
7	aero, std	2	2.0	403.2	2.836	1.863	0.936
7	aero, std	2	2.0	405.1	3.102	1.869	0.856
7	aero, std	2	2.0	404.0	2.979	1.766	0.843
8	aero, std	2	1.0	405.5	2.995	1.827	0.869
8	aero, std	2	1.0	405.4	2.845	1.703	0.852
8	aero, std	2	1.0	417.6	3.117	1.914	0.845
8	aero, std	2	1.0	427.8	3.408	2.027	0.798
8	aero, std	2	0.0	427.3	2.913	1.708	0.788
8	aero, std	2	1.0	427.3	2.723	1.883	0.928
8	aero, std	2	1.0	427.7	2.597	1.820	0.920

Appendix 4. Reports provided to industry.

In addition to this final report six further project reports, listed below, were generated. Reports 1 to 5 were provided to prawn farms during the project period and are currently accessible by the industry via the APFA members website. The primary intention of these reports was to disseminate project findings and information to the prawn farming industry in a timely manner. Report 6 was created at the end of the project and is a summary of project findings and recommendations.

1. Impact of aerator biofouling on farm management, production costs and aerator performance. *Mid-project report to farmers.* Comprising -
    - Part 1. Survey of prawn farm aeration and biofouling - July 2012.
    - Part 2. Performance of biofouled paddlewheels. Summary of results to June 12.
    - Part 3. Review of pond aeration and aerator performance.
2. Review of options for controlling biofouling of aerators on prawn farms.
3. Electrical performance of pond aerators on Australian prawn farms and the impact of biofouling. Industry report.
4. Performance of biofouled aerators measured under standard conditions. Report to industry.
5. Reducing the cost of aerator biofouling with fouling release coatings. Report to industry.
6. Biofouling cost and control for aerators in brackish and marine pond farms.

Report 2 ‘Review of options for controlling biofouling of aerators on prawn farms’ is included as a supplement in this final report.

Report Supplement

Review of options for controlling biofouling of aerators on prawn farms

David Mann

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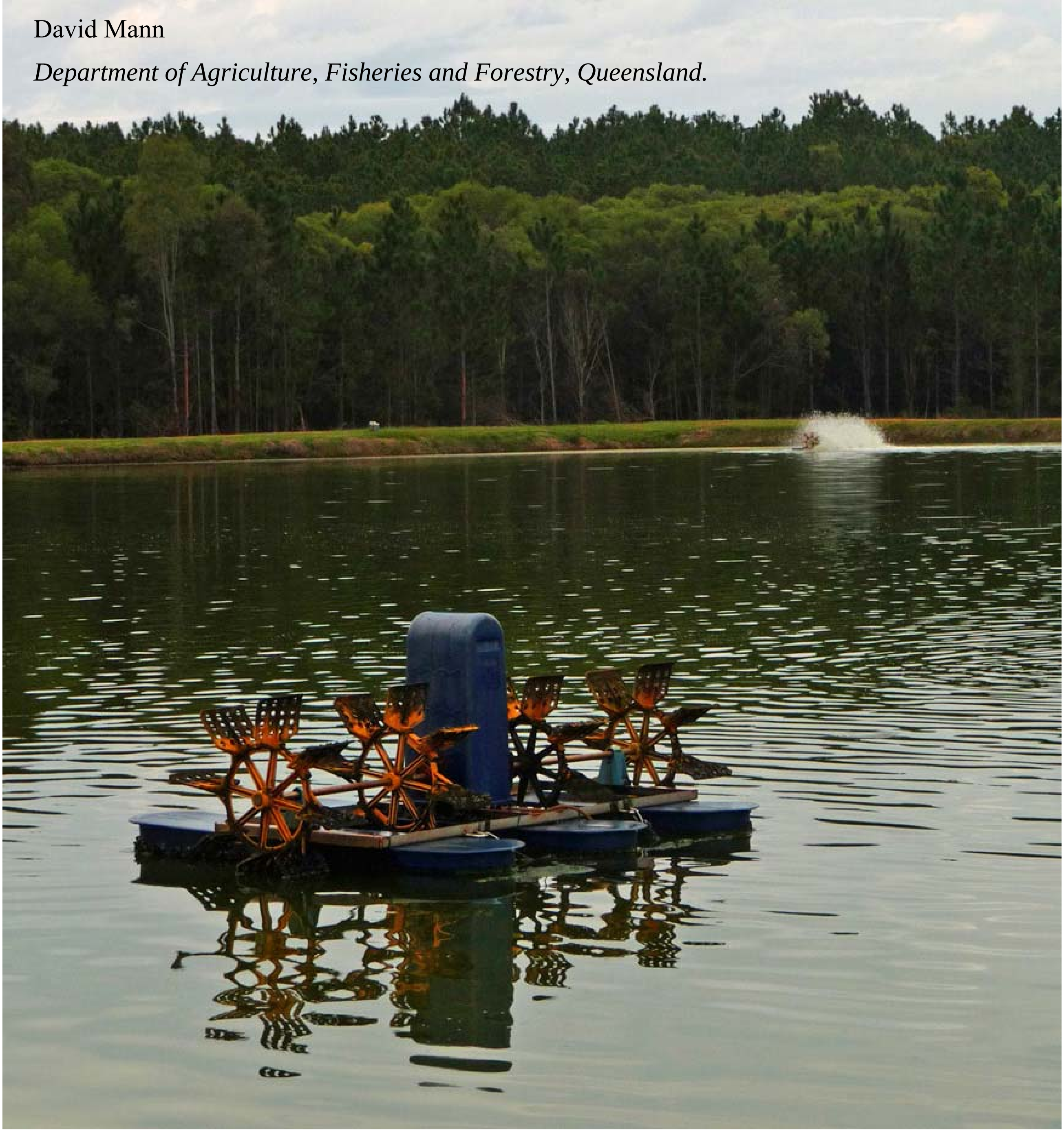

Review of options for controlling biofouling of aerators on prawn farms

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Summary

The term biofouling refers to the community of microscopic and macroscopic organisms that grow on surfaces submersed in water. For marine applications biofouling forms a major cost due to its adverse impact on operations and the costs associated with prevention and defouling. Biofouling of pond aeration devices raises the cost of production through increased electricity consumption, increased maintenance costs and extra labour demand for regular defouling. Despite this, the prawn farming issue has not been subjected to intense scrutiny, apparently because, in general, the long standing approach by farmers to controlling biofouling, manual defouling as required, has ensured that severe adverse outcomes arising from biofouling have remained limited in extent. Recent changes to the economics of prawn farming in Australia, relating to electricity and labour costs in particular, mean that it is now more critical than ever that the industry adopts a more practical and efficient approach.

This review is designed to provide a comprehensive evaluation of biofouling control options that may have potential application specifically to prawn farm aeration devices. The control options presented are drawn from those for which there are examples of successful application within a wide variety of marine applications and those that have demonstrated promise but may not yet be in commercial use. The list also includes pond and equipment management regimens as well as biocontrol measures that have potential to beneficially influence biofouling development.

The dominant form of biofouling control in use throughout the world is biocidal coatings containing primary biocides, commonly copper, and a suite of secondary organic booster biocides in a polymer matrix. These antifouling paints slowly release the biocides to inhibit settlement and attachment of organisms. This antifouling approach is undesirable for pond aquaculture and the prawn farming industry has indicated its preference to pursue non-toxic options.

In light of studies that have clearly determined significant adverse impacts on the environment by conventional antifouling paints, there has been a recent strong push world-wide to develop environmentally friendly antifouling systems. The two main directions taken for surface coatings are; replacement of the standard biocides in antifouling paints with natural chemical biocides which can have far less impact on the environment; and, benign surface coatings with particular surface physical properties that deter organism settlement and strong attachment. While there are several antifouling paints based on natural chemicals potentially available, it is the coatings with functional surface physical properties, termed fouling release coatings, that are the most immediate and viable option for pond aerators. Several available fouling release products are discussed in the review and unlike antifouling paints containing conventional or natural biocides, these fouling release coatings do not require Australian Pesticides and Veterinary Medicines Authority (APVMA) approval for use. Fouling release coatings will not however completely prevent biofouling. The best they can achieve is greatly restricting the attachment strength so that only minimal force, for example a gloved hand or low pressure water jet, is required to dislodge even the most tenacious biofouling organisms.

There are also non-coating measures that can reduce or prevent biofouling on at least some of the aerator surfaces exposed to fouling. For example, regularly turning a paddlewheel off during the day will stop biofouling growth on the paddles and upper surfaces of the appliance, though this approach will not solve biofouling of submersed surfaces. Similarly, a high level of filtration or disinfection of pond waters prior to use will remove the larval stages of barnacles and tubeworms that readily colonise all constantly wetted solid surfaces in ponds. Biocontrol options, such as using fish or snail species to clean surfaces, do not appear to be practical alternatives for prawn farmers.

The choice of biofouling control measure adopted by the prawn farming industry will be directed by the economic and practical benefit provided, that is, it needs to be cheaper and/or more practical to employ compared with the *status quo*, using manual labour to regularly defoul aeration devices.

Part A. **Introduction**

Biofouling of surfaces.

Biofouling refers to the community of organisms that attach to submersed surfaces. Typically, within hours of submergence in seawater a biofilm of bacteria and algae develops forming a mucous coating over the surface. This primary biofouling layer continues to develop in thickness and complexity over the following days and weeks. This biofilm in turn promotes settlement and attachment of larger secondary fouling macro-organisms, such as barnacles, tube worms and mussels, as it promotes larval settlement and attachment (Qian, et al. 2007; Steinberg, et al. 2002). Figure 1 depicts the typical progression of a biofouling community on solid surfaces.

Biofouling is a critical issue for many marine industries but is probably best known for its affect on shipping and boating. It has been estimated that the cumulative cost of marine biofouling world-wide is in the billions of dollars (Vladkova 2008). This high cost incentive has ensured that extensive resources have been directed to research and development of new coatings and improving the performance of currently used formulations (Dafforn, et al. 2011).

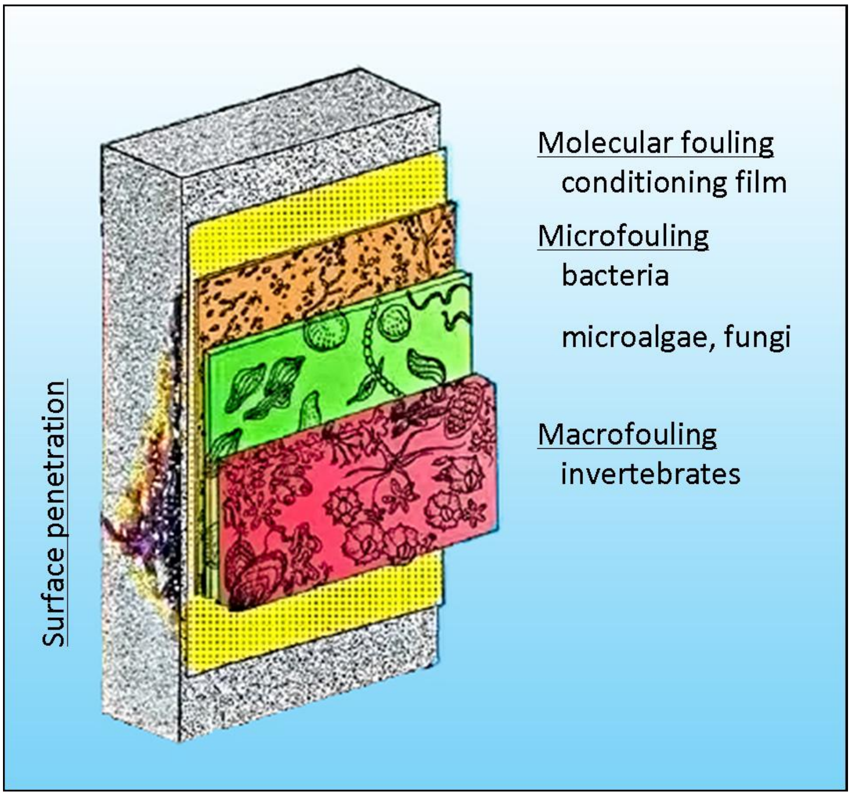

Figure 1. Fouling on marine structures proceeds in a sequence from a slime layer, to microfouling (bacteria, microalgae, fungi) to macrofouling (macroalgae, invertebrates) (Diagram from EcoSea 2010).

Antifouling methods

Early antifouling approaches for ships and other submersed structures in the marine environment involved coating at-risk surfaces with highly toxic paints that were designed to gradually release a biocide to provide biofouling inhibition over the life of the coating. A well known example of a very effective antifoulant compound, tributyltin (TBT), an organotin compound, has caused long term environmental damage as it remains highly toxic over long periods and is very persistent in the seawater and sediment particularly around marinas, harbours and bays. This highly toxic and persistent antifoulant was banned from some uses in the late 1980s and in 2003 was completely banned from use. The marine industry has largely turned to using copper and alternative organic biocides (Dafforn, et al. 2011; Konstantinou & Albanis 2004; Voulvoulis, et al. 2002) however while copper based antifouling paints are currently the most commonly used antifouling coating they are being subject to close scrutiny for environmental safety and use restrictions in some parts of the world (Dafforn, et al. 2011). Many of the currently registered organic biocides used to complement copper in antifouling paints are also being closely examined with respect to persistence in the environment and their impact on non-target organisms (Carbery, et al. 2006; Dafforn, et al. 2011; Thomas, et al. 2002; Voulvoulis 2006).

Environmental concerns are driving a general trend towards non-biocide releasing coatings and this has generated intensive effort into developing effective non-toxic systems. While it is generally considered that there is not yet an effective coating that completely replaces copper and organic biocide use in antifouling paints (Qian, et al. 2010; Raveendran & Limna Mol 2009) there are products that are similarly effective under particular circumstances (Dafforn, et al. 2011). It is these products that have potential application to prawn farms as they are not subject to the same restrictions as biocide releasing coatings and will not cause product quality or management issues for farms.

Biofouling control in aquaculture

Biofouling is a significant issue for all forms of aquaculture operating in the marine and brackish water environment (Forrest, et al. 2007a) but is particularly problematic for inshore and offshore aquaculture activities such as shellfish and finfish farming. The culture structures used for both and in the case of shellfish, the hard shell of the animals themselves, are severely impacted by biofouling and the industries need to employ a variety of approaches to control production-limiting affects (Keough 2011). A survey of shellfish culture operations in the USA put the cost of controlling biofouling at 14.7% of total operating costs (Adams, et al. 2011). Manual cleaning of fish cages and shellfish structures continues to be the most common control measure (Adams, et al. 2011; Durr & Watson 2006).

Copper based coatings or nets of copper alloy construction are commonly used on sea-cages and associated structures and are considered safe as fish are generally not sensitive to the potential elevated copper in their environment and do not bioaccumulate it (Borufsen Solberg, et al. 2002; Burridge, et al. 2010). Shellfish however are more sensitive to copper. Copper is known to bioaccumulate in scallops and oysters (Davies & Paul 1986) and copper based biofouling control applied to enclosures can under certain circumstances result in growth inhibition and mortality (Paul & Davies 1986). The pearl oyster culture industry which grow-out stock offshore, are heavily impacted by biofouling of the oyster’s shells. The industry typically deals with the problem through a labour intensive program of regular manual cleaning of all stock (Southgate & Lucas 2008) but shell fouling can still severely impact on growth and survival (Zhenxia, et al. 2007). The industry has investigated the development of a non-toxic shell fouling control coating however a product is yet to become a practical commercial reality (De Nys & Ison 2009).

The common use of antifouling paints, particularly copper based coatings, in the salmon aquaculture industry in Tasmania has been subject to close examination in the search for the most appropriate method to control fouling on nets and equipment (O'Brien, et al. 2011). To obtain Australian Pesticides and Veterinary Medicines Authority (APVMA) approval to use copper based antifouling paints the industry was required to undertake a pilot study to investigate the efficiency of copper oxide paints and provide data for the Environmental Risk Assessment. It is anticipated that other non-listed applications for copper, or other toxin, containing antifouling paints would require a similar approval process, including monitored pilot studies, to gain use certification.

In addition to biocide containing antifoulants there are also non-biocidal fouling release coating and physical barrier products that are designed to protect ropes and nets used for aquaculture that limit attachment of organisms. To date there appears to be limited use of such products despite a large amount of R&D in this field and there being some potentially useful products on the market. The primary reason for slow uptake of these technologies appears to be reduced effectiveness compared with biocidal products. Given the current state of antifouling technologies it is likely that for aquaculture and other marine activities biocidal antifouling strategies are still the most effective and economical solution if they seek and are given approval to use such products by the relevant authorities. In Australia, the APVMA strictly controls the use of bioactive compounds and there can be a long approval process.

While options for fouling control on marine fish and shellfish systems have been subject to extensive research and development there has apparently been little effort to proactively address biofouling of aerators or other submersed structures on marine pond farms. This is despite the conditions in such ponds being highly conducive to the growth of fouling organisms and farm operators continuously experiencing fouling over-growth. The nutrient rich waters of semi-intensive managed ponds can promote strong algal growth and high plankton and organic particulate loads favour rapid growth of filter feeding organisms such as barnacles and tubeworms.

Aerator biofouling

It is apparent that biofouling control of marine pond aerators has not previously been a wide-spread significant issue. Reports referring to the issue are scarce and there appears to be no studies detailing the issue or testing options for preventing biofouling. For example, a report summarising biofouling and antifouling approaches for aquaculture industries around the world compiled as part of an international project called the Collective Research on Aquaculture Biofouling gave only brief mention to paddlewheel fouling for shrimp culture ponds and biofouling issues were solved by air drying and cleaning (Willemsen 2006). Aerator biofouling has not been pursued as an issue by the marine pond aquaculture sector world-wide nor equipment manufacturers and there are several possible explanations for this:-

1. Biofouling does not occur to problematic levels elsewhere in the world, particularly major shrimp growing regions throughout tropical Asia to the extent that it does in Australia. There is some anecdotal evidence for this (pers. comm. Matthew Briggs).
2. Labour is relatively cheap in many shrimp and marine pond finfish growing regions so there is less economic imperative to reduce the demand for manual defouling.
3. Manufacturers of aeration devices have not rigorously pursued developing mechanical aerators that resist biofouling because the marine pond aquaculture industry has not indicated there is a significant demand.
4. There has not been an economic imperative to pursue a high level of energy efficiency.

Aerator surfaces that are typically subject to fouling are generally stainless steel and plastic. By far the greatest wetted surface area of paddlewheels and other aerators are plastics, particularly high density polyethylene (HDPE) which is used to construct the floats and the motor cover. HDPE has some inherent fouling control properties as a result of its surface characteristics but this does not prevent colonisation. Even under ideal conditions HDPE can only restrict the adhesive strength of foulants such as barnacles, tubeworms and algae.

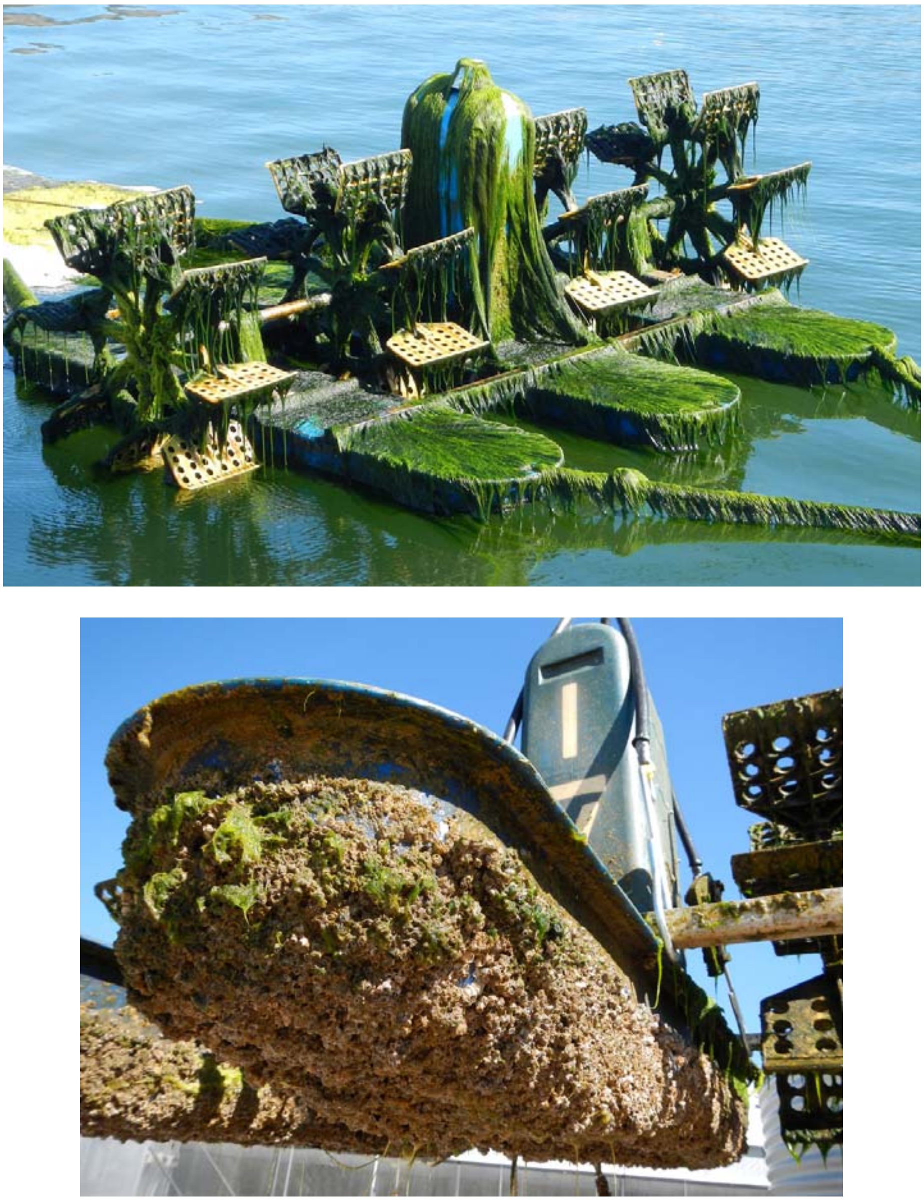

Figure 2. Algal fouling on upper surfaces and submersed surfaces of prawn farm paddlewheels. Photos D. Mann.

Biofouling of pond aerators has a number of unwanted impacts on their operation and farm management:-

- Increased electricity consumption
- Reduced efficiency of oxygen transfer
- Increased load on the drive system contributing to increased wear-and-tear, higher maintenance costs and reduction of the service life of the aerator
- Higher labour demand for regular defouling

In terms of direct cost, the increased labour requirement for defouling and maintenance is the most significant, though the real impact on electrical consumption is yet to be accurately measured. The Australian prawn farming industry has a combined aerator fleet, including electrical floating paddlewheels and propeller aspirators, of around 6,000 units (Mann 2010) and these consume 70-80% of the total farm energy use (Peterson & Patterson 2000). It is currently estimated that biofouling on prawn farms costs a minimum of AU$1,000 per hectare per crop cycle (Mann 2010), though this figure is likely to increase as more comprehensive farm figures are obtained. Additionally, in pond systems at peak biomass loading and little redundancy in the amount of aeration, reduced oxygenation efficiency or higher breakdown rates can have serious consequences for stock health and reduce pond productivity.

Implementing biofouling controls on marine prawn farms

The need to protect submersed surfaces in the marine environment spans a range of industries and applications and examples include shipping and fishing industries, seawater cooled power stations, oil industry, oceanic monitoring systems, marinas, aquaculture, navigation aids, public access ways. Most marine activities of this kind have implemented some form of biofouling control and it is the aim of this review to identify those products or systems currently used that may have direct application to marine aquaculture ponds, in particular, aeration devices.

The prawn farming industry has identified that there are economic and farm management benefits to implementing proactive methods of controlling the growth of fouling organisms on vital aeration equipment and have co-funded a study with the Australian and Queensland Governments to identify the most effective method (Controlling biofouling of pond aerators on marine prawn farms, Seafood CRC Project 2011/734). The objective is to implement a strategy that has significant benefits over the current defouling approach. The benefits of any proposed biofouling control option will be assessed on a range of criteria related to cost, practicality, reliability and durability as well as the overall impact on farm management and savings compared with manual defouling.

It is recognised that there are constraints on antifouling products that can be employed in prawn ponds as a result of characteristics inherent in this type of activity. Prawn culture ponds are enclosed water bodies that receive variable and limited water exchange and so any use of biocides is at elevated risk of accumulation to unsafe levels. Prawns are particularly sensitive to copper, the main active ingredient of most antifouling paints, and are also destined for human consumption, so residual biocide traces in the flesh must be avoided. The Australian Pesticides and Veterinary Medicines Authority (APVMA) stringently controls the use of biocidal antifouling chemicals and products and any proposed product containing bioactive compounds would need to satisfy a range of strict criteria and potentially incur significant registration costs. While approval requirements vary across products typically approval is still required for use of a commercially available product for an application other than what it is already registered for. For example, using a boating antifouling paint on fish cages would require a fish cage specific approval for use. These factors lead to the prawn farming industry's preference to pursue non-toxic, benign mechanical and physical options.

Part B. Biofouling control options

For the purposes of pond aquaculture potential biofouling control strategies can be placed into six general categories. Each category has pros and cons with respect to application to prawn farm aerators including practicality and cost effectiveness. As there is little collective knowledge and experience for marine pond systems it is through examining the outcomes for other applications that assessments can be made on the most appropriate strategies for prawn farms.

1. Biocidal surfaces – utilising standard and 'natural' biocides in coatings and construction materials. Eg antifouling paints as used for shipping and boating.
2. Non-biocidal coatings and surface micro-texture – surface physical properties that inhibit settlement, growth or attachment strength of fouling organisms. Eg super-hydrophobic surfaces.
3. Non-coating foulant disruption – non-chemical methods that do not require the fouling organisms to contact a treated surface. Eg ultrasound irradiation, electrical field.
4. Aerator design – aerator characteristics not related to surface chemical or physical properties. Eg surface configuration, colour, reduced contours and smoothness.
5. Aerator and pond management – farm practises that can minimise or prevent settlement or growth of problematic biofouling. Eg regular drying, exclusion of fouling organisms, manual defouling.
6. Biocontrol – organisms specifically added that reduce biofouling. Eg bacteria, planktivores, grazers.

1. Biocidal surfaces

Antifouling paints containing biocides are the most common type of antifouling coating used around the world as they are the most effective and versatile coating. The standard biocides used are toxic to a broad range of organisms and are relatively stable compounds. The effectiveness of the paints is due to their capacity to release biocidal agents at a consistent, slow rate so that settling organisms come into contact with the chemical.

Copper is a very effective biocide with broad toxicity so it is a common component of antifouling paints and in structures as copper alloy construction material or metallic copper surface coating.

While the standard antifouling paints as described above dominate the antifouling coating market there are newly emerging products promoted as being more environment friendly which are based on compounds mimicked from nature and are therefore termed 'natural biocides'. Compounds in this category tend to have more specific biocidal activity than standard biocides and may be effective at very low concentrations. The other critical characteristic that supports the environmentally sustainable claim is that they are less likely to persist or accumulate in the environment or the food chain and therefore at lower risk of incidental adverse affect on the environment.

The Australian Prawn Farming Industry has expressed a preference to not pursue biocidal options to combat the problem of aerator biofouling. However this section outlining aspects of the various biocidal coating options for antifouling is included as these coatings are by far the most common antifouling approach taken for marine applications and are currently used for off-shore aquaculture applications. It was also considered important to outline the known issues for the commonly used biocidal coatings and identify antifouling coatings based on natural compounds, with improved environmental credentials that may be of some interest in the future.

1.1 Antifouling paints

The typical antifouling paint used in the shipping and boating industry contains a primary biocide, usually copper and/or zinc, and one or more booster biocides which are typically organic compounds. Booster biocides are included to improve the effectiveness of the paint as copper does not have effectiveness against all fouling organisms, particularly some green macroalgae species.

There are two main types of biocidal paints, self polishing copolymer (SPC), and controlled depletion polymers (CDP). The copolymers of SPC paints hydrolyse in seawater and constantly erode from the surface slowly, maintaining a clean smooth surface free of attaching organisms as well as exposing new surface for release of biocides. SPC paints are the most effective for application to shipping and can last for up to 5 years. CDP paints constantly release biocides through the gradual hydration of the polymer matrix. They have an effective life of up to 2 years but are cheaper than SPC antifouling paints.

Both SPC and CDP antifouling paints can be formulated with or without a suite of organic booster biocides in addition to the primary trace metal biocide. SPC paints in general have a much longer effective life than conventional coatings, though each type has its pros and cons in relation to use in the shipping and boating industry. Both coatings are designed to slowly release the biocides into the water to ensure the settling fouling organisms are exposed to them. Therefore for all biocidal antifouling paints release broadly toxic chemicals into the environment where depending on local conditions can impact on non-target animals and algae in the water and sediments. A list of commonly used biocides and details of their mode of action are given in Appendix 1.

Theoretically biocidal paints could effectively reduce biofouling if applied to the plastic and metal surfaces of pond aeration devices just as they are for boat hulls however several critical factors need to be considered:-

- Biocides in the coating are released into the surrounding environment through normal leaching as well as chips and flakes that will fall to the bottom sediments.
- The primary biocides are persistent and cumulative in the environment and can concentrate in the sediments.
- At least some of the organic booster biocides can have persistent activity in the surrounding environment and strong doubts are being raised as to their environmental sustainability (Konstantinou & Albanis 2004).
- Ponds are enclosed water bodies receiving limited water exchange so persistent biocides are of particular concern. The APVMA would need to be satisfied that biocidal antifoulant use does not pose unacceptable risk to the animals, the environment or to consumers.
- Harvested animals from the ponds are processed for direct marketing and consumption so residual chemicals in the flesh could be an issue.

1.1.1 Copper

Copper is the most commonly used antifouling biocide and can be used in metallic, alloy or ionic form as in organo-copper compounds. Its biocidal activity stems mainly from the cupric ion form dissolved in the water (Omae 2003). Copper based antifouling coatings are designed to slowly release Cu^{2+} ions into the surrounding water. Leaching rates of copper from typical copper based antifouling paints have been estimated to be 16 to 25 ug/cm^2/day (Boxall, et al. 2000).

Copper alloys are being employed by the marine fish cage industries as the physical and chemical properties are attractive for net construction. Such cages elevate the total amount of dissolved copper in the vicinity of the cages (Lewis & Metaxas 1991), though the elevated available copper shows little tendency to bioaccumulate in fish within the cage or shellfish and algae in the close vicinity to the cages (Borufsen Solberg, et al. 2002). It has also been shown that the uptake of copper by mussels exposed to elevated environmental levels is extremely variable (Phillips 1976).

Copper is a natural element that has a role in the physiology of plants and animals. Shrimp species have approximately 83ug Cu g^{-1} dry weight and that is largely located in the haemolymph (40-50%) and midgut gland (25%) (Depledge 1989). It has been estimated that the optimum dietary copper requirement for juvenile *P monodon* is around 10-30mg/kg, though several times more than this 9in the diet is not acutely toxic (Lee & Shiau 2002).

Copper is toxic to crustaceans, particularly those species with low regulation capability, which includes groups more primitive than Decapods (Rainbow 1985). Copper is therefore an effective control agent for barnacles but is also considered highly effective against tubeworms and most algae species (Omae 2003). It is known that some algae species are relatively tolerant of elevated copper concentrations and in particular this group includes *Ulva* spp. (*Enteromorpha* spp.) which is one of the dominant algae groups colonising aerators on Australia's prawn farms and other on-shore marine facilities.

Decapod crustaceans, including Penaeid species, are able to regulate tissue levels of copper, manganese and zinc (Valavanidis & Vlachogianni 2010) and can therefore tolerate a relatively wide range of concentrations. Other species, including fish, polychaete worms and bivalve molluscs are also able to regulate the concentrations of essential metals in their tissues to some extent (Bryan 1968). In shrimps the internal levels can remain relatively constant despite variability in the environmental concentrations up to around 100 μgL^{-1} (White & Rainbow 1982) though the natural range for seawater copper concentration is typically less than 3 μgL^{-1} (Dafforn, et al. 2011) but can reach 10 μgL^{-1}. Beyond a species' threshold environmental concentration of bioavailable copper growth and health can be severely impacted.

The bioavailability and therefore the toxicity of copper can be difficult to predict as it is affected by the form it is in and whether it is bound to other compounds, as well as the pH and salinity of the water. Copper is typically rapidly and tightly bound to organic compounds and accumulates in sediments where it has restricted bioavailability(Valkirs, et al. 1994). Copper therefore tends to be cumulative in the local environment, particularly persisting in the sediments where potential remains for it to become bioavailable to the overlying waters again (Teasdale, et al. 1996). Copper bound in the sediments can also continue to have a strong impact on the benthic infauna for long periods (Hall & Frid 1995). Use of copper in earthen ponds could therefore lead to significantly elevated levels in bottom sediments over repeated uses unless sediment removal is practised.

It should also be noted that conventional commercial copper based antifouling coatings typically have one or more additional 'organic booster biocides' to improve the efficiency and control organisms tolerant of copper (Voulvoulis 2006). Some of these chemicals are persistent and accumulate in marine systems and would therefore also be problematic for earthen pond culture systems.

Copper is released into the environment from treated surfaces by leaching from the metallic copper or antifouling paint surfaces and by paint particles being shed from coated surfaces or being dislodged during cleaning. Due to the chemistry of cupric ion in seawater however the proportion of bioavailable copper in the water column is many times lower (<0.1%) than the total amount of copper released from antifouling paints (Hall Jr & Anderson 1999). Most leached copper is rapidly bound to organic material in the water column and eventually accumulates in bottom sediments (Valkirs, et al. 1994).

In a prawn pond it is unlikely that copper levels in the water column could become toxic if copper based antifouling paints were used on aeration equipment and other structures as almost all the copper would not be bioavailable to the prawns. The main risk for toxicity is therefore exposure to copper via consumption of copper enriched organic materials directly or consuming organisms that have elevated copper levels due to their feeding on copper rich organic material. Filter feeding organisms, eg oysters, are known to bioaccumulate copper (Davies & Paul 1986) so it is likely that a range of organisms either directly feeding upon organic material or living within the sediments can become enriched in copper. These in turn are potential prey for the cultured prawn species. Risk of toxicity would increase if pond sediments are retained in the ponds over multiple cycles.

There is also a copper based product on the market that operates differently to standard antifouling coatings. The product is called Cop-R-Bote and it contains a very high level of metallic copper particles. The manufacturers promote it as long lasting (5-10 years) and non-polluting due to the fact that it is non-ablative nor designed to constantly release copper in the way that standard antifouling paints do (BoatCraft Pacific Pty Ltd). This coating does however release copper into the environment. Despite the fact the coating lasts for an extended period regular maintenance in the form of sanding of the surface with a fine sandpaper is required to ensure that the copper particles remain exposed at the surface/water interface. Rates for release of copper into the water is by this product are not available.

1.1.2 Zinc

Zinc in several forms can be added to standard antifouling paints as a biocide or as zinc oxide for the purpose of adjusting the paint physical and chemical properties or as a pigment . Zinc pyrithione is a good bactericide, fungicide and algaecide and is commonly used as a booster biocide in antifouling paints (Thomas 1999).

Zinc is generally less toxic to crustaceans than copper (Ahsanullah, et al. 1981) and marine algae are considered particularly sensitive to zinc (Burridge, et al. 2010). As for copper its bioavailability and toxicity is influenced by environmental factors and can be strongly bound in organic rich sediments where it has low bio-availability. Various toxicity investigations have determined that elevated zinc levels in the water produce sub-lethal and lethal effects on crustaceans and other invertebrates (Burridge, et al. 2010). Accumulation in sediments can result in toxicity to invertebrate infauna as well as development of resistance in organisms including disease causing bacteria (Akinbowale, et al. 2007).

1.2 Natural biocide coatings

Many marine organisms, including micro-organisms, plants and animals, prevent biofouling of their surface through chemical inhibition and such natural chemicals are potentially useful for antifouling products (Omae 2003). Similarly, bioactive compounds with antifouling properties have also been isolated from terrestrial plants and animals. Significant R&D effort in this field has isolated a large number of chemicals from a diverse range of organisms and assessed their potential use in antifouling coatings (Qian, et al. 2010; Raveendran & Limna Mol 2009). Appendix 2 contains a list of naturally occurring chemicals identified from organism that exhibit antifouling properties. For example, a compound called bufalin, a steroid from toad poison, is over 100 times more toxic to barnacles than TBT (Konstantinou 2006). The full extent of known compounds with antifouling activity covers a broad range of chemical groups (Appendix 2) and their various modes of action include settlement, attachment and growth inhibition, bactericidal, repellent, metamorphosis inhibition and anaesthetic affects (Omae 2003).

It should be noted however that ‘natural’ biocides are compounds that can have unwanted impact beyond the coated surface on non-target organisms. For example, barnacles are crustaceans so prawns are potentially impacted by chemicals that control barnacles. Natural, low environmental impact, biocides however should not accumulate in the environment, whether in the sediments or fauna, as standard antifouling paint biocides are known to do, because they are more readily degraded into benign components.

As natural biocides are bioactive compounds their use in aquaculture requires approval by the APVMA for use in any application. The process of gaining full certification can be long and involved for products that have not already been through the process for other applications. As none of these antifouling products have been assessed for use in pond based aquaculture a period of experimental use and assessment of environmental and product health and safety would likely be required before full commercial use could be approved. This could potentially be prohibitively expensive in relation to the volume of product ultimately used by the industry.

There are currently very few products incorporating natural antifoulant compounds available on the market. A major limitation on producing natural antifouling coatings is that the natural antifouling chemicals discovered are typically very difficult to produce or extract in sufficient quantities at a reasonable price to make commercialisation of the final antifouling coating viable (Qian, et al. 2010; Raveendran & Limna Mol 2009). Another constraint is the critical step of formulating a surface coating that ensures the compound is effectively exposed at the surface/water interface to exert control over foulant settlement or growth for a practical duration. Generally, to be useful the active compound must be stabilised and leech from the coating to come in contact with settling organisms and this imposes a limitation on the effective life of the coating.

A small number of low environmental impact natural antifouling products have been developed and one recently released product is Selektope with the active constituent, medetomidine. The chemical is highly specific to the settling stage of barnacles in particular and can be used in antifouling paints in the same way as conventional biocides. The barnacle cyprid larva stage cannot settle on the coated surface when it detects medetomidine as it causes its legs to start kicking and it swims away (Lind, et al. 2010). According to the explanation of the manufacturers barnacle larvae are not harmed by contact with the chemical and can go on to settle elsewhere. This product is therefore best described as a bio-deterrent rather than a biocide. While medetomidine has a strong effect on barnacle larvae it also has some influence on settlement of tubeworms and to a lesser extent mussels and bryozoans (Lena Lindblad, I-Tech AB, pers. comm.). It has no affect on algae so an algaecide may still need to be incorporated into the coating for this purpose. It is not approved for use in Australia however it is currently being evaluated for approval for use as an antifouling biocide in the EU and has approvals for Japan and Korea.

Other compounds that have been progressed into commercially available natural antifouling coatings included a product marketed under the name of Sea-Nine 211®. The active constituent belongs to the isothiazolone group of compounds and is most noted as a settlement inhibitor for a wide range of marine organisms including algae, barnacles and tubeworms. Its chemical properties are conducive to long duration antifouling coatings and as it rapidly biodegrades, less than 1 day in seawater (Dafforn, et al. 2011), its impact on the environment under normal applications is expected to be minimal. It can be incorporated into most antifouling coatings.

Furanone is a natural metabolic product of a red seaweed found in Australia and antifouling coatings use an analogue halogenated furanone that even at low concentrations has significant settlement inhibition effects on barnacles and algae as well as having antibacterial activity (De Nys, et al. 1995). It was extensively investigated as part of the Australian Aquaculture CRC R&D program in early 2000. Even though it has been identified as a strong candidate biocide for eco-friendly antifouling coatings there is apparently some way to go before its application is fully understood and is widely approved for use.

1.3 Construction materials containing biocides

The best current example for aquaculture systems constructed from inherently antifouling materials is copper alloy mesh being used for offshore fish cages, including the salmon industry in Tasmania. These nets are effective because they release copper ions and therefore lead to elevated copper concentrations in the vicinity of the cages though for many sea cage applications the levels are not considered to pose an unacceptably high risk for the environment. The fish are not affected by the copper and it is not bioaccumulated so there is no affect on product quality.

A recent novel approach to creating antifouling construction materials is the development of a method for post-manufacture embedding of plastics with metal particles such as copper. This method, referred to as ‘cold spray antifouling’ was developed in Australia and involves the firing of metal particles at the plastic polymer surface so that they embed and form a layer at or slightly below the polymer surface, remaining in contact with the water via their entry pore (Vucko, et al. 2012) (Figure 3). Small scale trials have been conducted which have shown promising results with copper particles. Other naturally antifouling metals such as zinc or alloys such as bronze may also be used (Poole 2012).

It would be feasible to use this cold spray antifouling process to treat the HDPE and nylon plastic surfaces of aerators though special equipment is required to undertake the process. It should be noted that so far only copper has been tested and it is known that algae, such as *Ulva* spp. can be relatively resistant to copper based antifouling coatings.

Figure 3. Copper coating on polyurethane at two densites.
Photo from (King, et al. 2010).

It is possible to incorporate biocides, including novel natural compounds, into the plastic polymer matrix used to construct ropes and nets or solid structures such as pontoons. One such example arose out of research conducted as part of the Australian CRC for Aquaculture program 1993 to 2000. A formulation and production method was developed which provided for a range of extruded plastic polymers, such as HDPE, nylon, polypropylene or EVA, to incorporate the synthetic antifouling compounds furanone and isothiazolone into the matrix to effect significant biofouling inhibition over more than 100 days (Christie, et al. 2003). There is strong interest in such developments by aquaculture applications such as oyster and offshore fish culture, however there does not currently appear to be any commercial application of this or similar technology by these industries.

2. Non-biocidal coatings and surface modification

Fouling release surfaces

The term fouling release refers to the characteristic of a solid surface to restrict the ability of fouling organisms to strongly attach to it without the use of toxic chemicals. Even though organisms can settle and attach the attachment remains weak and they are relatively easily released. In the case of boat hulls, fouling organisms such as barnacles, tubeworms and algae can be sloughed from the surface when the boat is run at high speed. For other surfaces these organisms may be simply wiped from the surface with a glove protected hand.

From a chemicals science perspective, two of the critical properties that correlate with biofouling attachment ability are water contact angle and surface free energy (Vladkova 2008). For surfaces this is measured by the water droplet contact angle with the surface. On high surface energy surfaces the water droplets spread out and on low surface energy surfaces droplets bead-up. In general, biofouling organisms do not attach as readily and cannot form a strong attachment to surfaces with low surface energy (Singer, et al. 2000). There are exceptions to this rule as some organisms show preference for surfaces with low surface energy but less so for very high surface energy surfaces. Appendix 3 lists the surface free energy value of a range of plastics. The science gets a little complicated in relation to the affect of very low surface energy on the attachment strength of organisms. Ultra-low surface energy on its own does not necessarily confer reduced attachment strength. Early works indicated that below a moderately low surface energy of 20 mN/m attachment strength can increase (Webster & Chisholm 2010). Other factors, both chemical and physical, play an important role in influencing the interaction between attaching organisms and the surface.

One critical coating property for fouling release is the ‘elastic modulus’, which refers to the force required to fracture an adhesive from the surface. In general it is the elastic modulus and the surface energy combined that explain most of the variation in attachment strength among polymer coatings (Brady & Singer 2000). Surface topography is also an important property that influences the interaction of water with the solid surface (Sun, et al. 2005) and has a strong influence on the ability of fouling organisms to strongly attach (Brady & Singer 2000). This aspect is quite complex as at different degrees and characteristics surface topography can enhance or inhibit the attachment of fouling organisms.

The interaction of fouling organisms with a surface is an extremely complex science as the attachment strength of organisms to a surface can be affected by a range of factors including “surface reconstruction, surface roughness, the chemical nature of cell exopolymers, mechanical properties of the surface, the nature of the adhering cell and the extracellular matrix, duration of contact of cells with the surface and presence of conditioning film on the surface” (Krishnan, et al. 2006). The most effective fouling release coatings will employ as many fouling inhibitory mechanisms as possible.

The above summary of fouling release surfaces provides an indication that the science is complicated and in combination with the practical issues associated with development of novel polymers and the difficulties in bringing a new product to market explains why development of highly effective fouling release coatings is occurring slowly. It is predicted that new developments of increasingly effective coatings will continue for many years (Rittschof 2010). Currently there are several fouling release coatings available that can, under certain conditions, reduce, but not prevent, foulant attachment but do allow fouling organisms to be readily removed with relatively light force. For example adhering barnacles are able to be wiped off with a gloved hand or removed with low water pressure jet.

2.1 Fouling release construction materials

Aerators are made principally from plastics (floats, motor cover, paddles), stainless steel (axle, brackets, bolts) and cast iron (gear box and motor housing). Plastics comprise the majority of the surface area exposed to water and create the main biofouling issue. Typically high density polyethylene (HDPE) is used to construct the floats and motor cover and polyamide (nylon) for the impeller assembly.

Due to its relatively low surface energy characteristics HDPE (see Appendix 3) has some inherent fouling release properties. This means that even though it will be susceptible to fouling settlement the attachment strength will be poor and defouling should be accomplished with little force needing to be applied. Theoretically it could be possible to wipe algae, barnacles and other foulants from the surface with a gloved hand or application of a light water pressure spray. In practice however this is not possible due to the modification to the plastic surface properties. Both heat and UV exposure cause the surface energy of HDPE to increase. Additionally, surface abrasion causing roughing of the surface, also allows for much greater adhesive strength of the foulants. The practical outcome for aerators used on farms is that HDPE surfaces have not provided any practical fouling release advantages over metals or other commonly used plastic construction materials.

Reducing the amount of mechanical damage inflicted on the plastic parts of aerators could however go some way towards improving the removal of foulants. This would include not using a scraper to remove biofouling where possible and not dragging the floats across hard surfaces. Design of the floats and motor cover may also assist in the removal of biofouling. Contoured surfaces and corners promote settlement and strong adhesion by fouling organisms. Therefore forming the plastic surfaces to be smooth and flat would assist defouling.

Plastics used in all forms of equipment manufacture range widely in surface energy values (Appendix 3) and this has relevance to biofouling control. A study investigating the attachment strength of foulants to different commonly used construction plastics determined that the relative ease of removing attached *Ulva*, a common green macroalga, were in the following order from easiest to hardest to remove: polypropylene, high density polyethylene, polypropylene-polyethylene copolymer, ethylene vinyl acetate. This order closely correlated with a hydrophobicity measure called contact angle hysteresis (Ucar, et al. 2010). Teflon® (PTFE) is considered to have an extremely low surface energy and is recognised as having useful antifouling properties. It is not technically feasible however to construct the plastic components of paddlewheels from Teflon as it is difficult to work with using standard plastics manufacturing equipment. However a plastics raw material producer contacted on this topic indicated that they had pursued incorporating teflon and similar low surface energy plastics into a copolymer product for the purpose of reducing surface adhering properties. However they advised that currently this does not seem to be technically possible (Bloys Rijkmans pers. comm.). Other investigators have sought to develop similar complex polymer materials for enhancing fouling release properties (Wang, et al. 2011) however such novel materials do not yet seem to be available.

It is however possible to post-manufacture apply a coating of a low surface energy compound to provide the fouling-release surface properties sought after. This topic is covered in the 'Fouling-release coatings' section.

2.2 Fouling release coatings

Strongly hydrophobic coating formulations, that is with very low surface energies of 10-20m Nm^{-1}, (Webster & Chisholm 2010) can be highly effective for fouling release purposes. Such coatings when applied form a smooth, low surface energy surface that inhibits the strong attachment of organisms. Such surfaces still foul but as the attachment is weak biofouling is more readily removed. (Singer, et al. 2000).

Silicon based, PDMS (polydimethylsiloxane), is the most common fouling release compound in use (Sommer, et al. 2010) and as listed in Appendix 3 has a surface energy similar to that of Teflon™ polytetrafluoroethylene - PTFE), a well known 'non-stick' fluoropolymer used in a variety of industrial and household applications. PDMS also has a low elastic modulus value which means that adhering organisms are highly susceptible to fracture of their bond and therefore require low removal forces (Marabotti, et al. 2009). The effectiveness of fouling release coatings are further enhanced by incorporation of additional benign compounds such as waxes and oils that contribute to settlement inhibition and reduced attachment strength. The fouling release properties of these coatings can be sufficiently effective to release macro-fouling organisms such as barnacles, tubeworms and algae when the ships or boats reach speeds of 15 to 20 knots. Investigations of the use of fouling release coatings on sea cage nets have demonstrated that the coating changes the fouling community structure and reduces overall biofouling and the netting is relatively easily defouled (Hodson, et al. 2000).

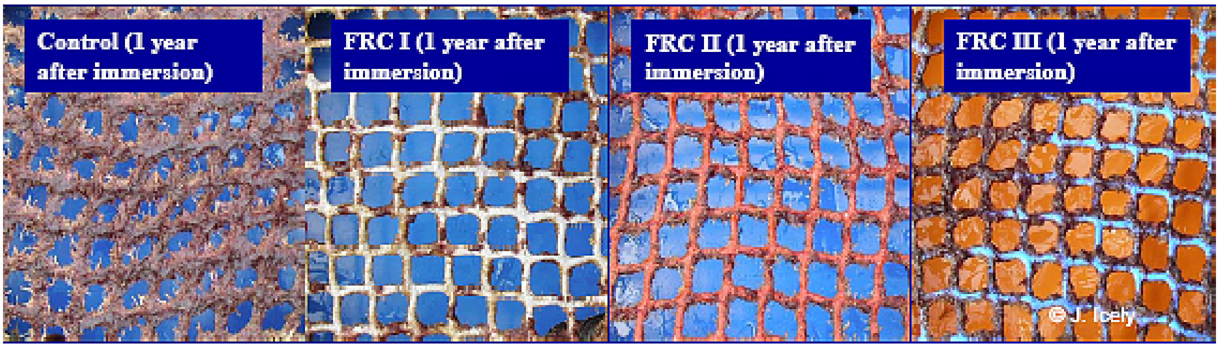

Figure 4. Comparison of biofouling load for fish cage nets treated with three different fouling release coatings (FRC) and a non-treated control. Photo from Willemsen (2006).

There are several commercially available products in the fouling release coating market including those which are a combination of polymers. Blends of PDMS with fluorinated polymers like Teflon have been shown to have even greater fouling release properties as tested on the macroalgae *Ulva* and barnacles (Marabotti, et al. 2009), both organisms that are primary culprits on prawn farms. One such product is called Intersleek®970 (Interlux 2011) which is a 3-part coating incorporating a fluoropolymer which according to the manufacturer offers high foul release characteristics, resistance to mechanical damage and good longevity, up to 10 years. This product can be applied to HDPE however requires prepping the surface with another product coating.

Protecta-Hull is a silicon based product designed for use on boats as well as off-shore aquaculture structures such as ropes, buoys and cages and a similar product has been trialled for use on pearl oysters (Jeff Hamilton pers. comm.). It can be applied by brush to form a strong coating on most surfaces, including HDPE. Removing foulants can be achieved by using a plastic scraper or low water pressure jet.

A product that has recently been developed by Ecozean Pty Ltd in Australia is called AFwax and as the name suggests is based on a waxy compound. It is applied by brush or as a dip when hot and it cools to form a sealing antifouling coating. The product was recently trialled on prawn farms in Thailand and showed significant ability to resist mussel, barnacle and filamentous algae fouling (Charlton 2012). Due to the waxy nature of this coating, high temperature, such as that experienced by black surfaces under the tropical sun, can affect its durability (Charlton pers. comm.).

Figure 5. Floats from a paddlewheel that was installed in a prawn pond in Thailand. Weight of mussels on untreated float was approximately 10kg. Photo from Charlton 2012.

There is some anecdotal evidence that a Teflon polish designed to lower the friction of sailboat hulls (Hullkote, Harken McLube) has significant fouling release capability however the manufacturer recommends that the longevity of the product is too short to be of practical antifouling use.

An important point regarding the use of fouling control coatings applied to aerators is that to maintain the peak effectiveness of the coating farms may have to modify their aerator handling and management practises. The coating, particularly silicon based fouling release coatings, have relatively low resistance to mechanical disruption, such the abrasion that can occur as the floats are dragged across a solid surface. Handling and transporting the aerators would therefore need to ensure that the coating is not scratched or peeled off due to mechanical knocking or abrasion. A supplier advised that damage to the coating can be fixed easily by cleaning and drying the area and then painting the coating over the damaged area.

Waxy compounds can be used for fouling release coatings just as plastic polymers are used and are similarly considered chemically benign and environmentally safe. One of the benefits of waxes compared with other antifouling coatings is that they are chemically safer to apply as they do not contain chemicals such as solvents that are harmful to human health. They are also biodegradable.

The biofouling control characteristics of several basic petroleum waxes, such as paraffin, were found to have useful antifouling and fouling release properties that could be utilised in a practical coating under marine conditions (Afsar 2008).

There are several wax based fouling release coatings that have been designed for boats, including Seawax® and Lanolene®. The manufacturer of Seawax® advices that it is not appropriate for HDPE surfaces. Clear boat waxes, such as VS721® Bottom Wax, marketed primarily as glossy coatings that reduce drag also have fouling release properties due to the smooth, glossy, low energy surface they create. An important aspect not known about these products is their effective fouling release life.

2.3 Surface microtopography

Research has been conducted in Australia and elsewhere investigating the potential for micro structure at the 'nanoscale' on surfaces to prevent settlement and colonisation of submersed surfaces by biofoulants, including bacteria, algae and barnacles (Aldred, et al. 2010; Scardino, et al. 2008). There is strong evidence that this concept greatly reduces the likelihood of algae spores and fouling organism larvae permanently settling on the surface particularly when combined with hydrophobic surface materials (Scardino, et al. 2009a). The impetus for this line of investigation comes from examples in the natural world, such as shark skin. Shark skin has a very high degree of nanoscale roughness created by overlapping hard plates producing parallel ridges at a spacing that discourages spore or larval settlement. While a fine topographic surface can be created in an objects surface or on a film applied to the surface, there are significant practical difficulties in applying this novel technology to products that can be used over large surfaces in the marine environment. Consequently there are currently no manufacturing process or coatings that are available that are relevant to boat hulls or similar surfaces, such as aeration devices.

There is one known example where a nano-scale topography antifouling surface has been commercially produced for sale which acts at the primary fouling level by preventing colonisation by bacteria. This product is an adhesive film that can be applied to bacteria contamination risk surfaces such as medical equipment and consumer items. The manufacturer advises that it is continuing to develop a product that can be applied to marine surfaces (Sharklet^{TM}Technologies 2010) (figure 6).

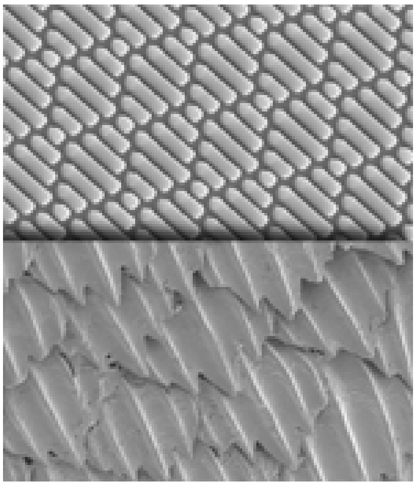

Figure 6. Close up image of shark skin (below) and Sharklet antifouling surface (above). Image from (Sharklet_Technologies 2010).

Combining nano-surface structure with very low surface energy materials has been shown to be extremely effective in inhibiting settlement and attachment of a broad range of fouling organisms (Scardino, et al. 2009a). However there is not yet a practical, cost effective product on the market that could be used for any marine biofouling control application.

At a size scale above the micron level there is a novel technology that has been demonstrated to reduce settlement of macro-fouling organisms and involves covering the surface with fine, short fibres (figure 7). According to the manufacturer’s description, “the surface becomes prickly and unattractive for fouling organisms to settle” (Micanti 2012). The Thorn-D® product is applied to netting and ropes by glue or to solid surfaces as a stick on foil. The foil product is designed for boat hulls but may be appropriate for the surfaces of aerator floats and motor cover.

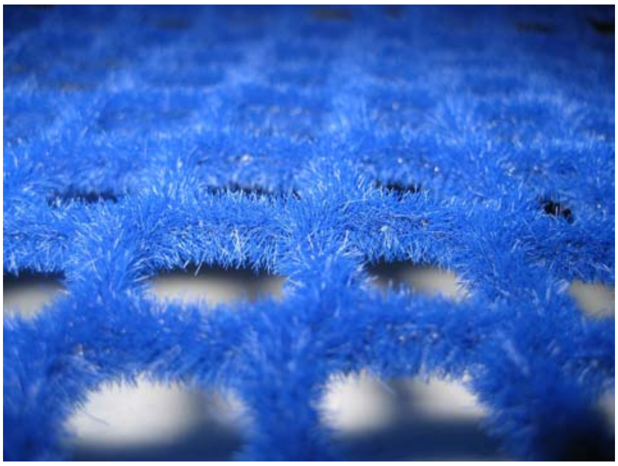

Figure 7. Thorn-D physical biofouling deterrent as applied to fish cage netting (Micanti 2012).

2.4 Sacrificial covering

The idea of using a sacrificial, removable layer surrounding submersed surfaces prone to biofouling has been around for a long time. “The heavy biological growth over the plastic film can be removed more rapidly by stripping away the plastic film than by conventional methods such as scraping and sandblasting” (Muraoka 1969). In practice it may be possible to apply this theory to the floats and motor cover however it is difficult to see how it could be applied to the paddles without compromising operation.

For this approach to be viable the plastic film would need to be cheap and quickly applied, removed and replaced. Also the plastic film would need to be relatively UV resistant and tear resistant. It could remain flexible, thereby covering the aerator components like a sock or be heat-shrinked to form a close fitting semi-rigid layer. With respect to the later, materials are available that are used for manually shrink-wrapping boats and other large items so it is conceivable that aerator floats and motor cover could be effectively covered. However some modification to the design of the floats and frame and brackets would facilitate this approach. It would be an advantage to be able to complete a cover change without moving the aerator from its position in the pond which then prevents using the shrink-wrap approach.

One pitfall could be that if any plastic coverings detached from the aerator it could damage aerators or pumps, so attachment would need to be very secure.

3. Aerator design and construction

3.1 Fouling resistant construction

Aerator construction materials that are typically subject to fouling include stainless steel (brackets, bolts, shaft) and plastic. By far the greatest wetted surface area of paddlewheels and other aerators are plastics, particularly high density polyethylene (HDPE) which is used to construct the floats and motor cover and polyamide (nylon) used to make the impeller of paddlewheels. In terms of fouling release characteristics HDPE has low surface free energy (high hydrophobicity) compared with other plastics and therefore significant inherent ability to restrict foulant adhesion. However the surface energy is modified by agents acting on the plastic. Heating and exposure to UV light and mechanical abrasion drastically raise the surface energy (Bhowmik, et al. 2001) rendering it more susceptible to strongly adhering biofouling. Though probably the greatest affect on the ability of the paddlewheel plastic surfaces to resist biofouling is mechanical damage to the surfaces that can occur during transport and cleaning. Brand new paddlewheels with highly polished plastic surfaces on the motor housing, floats and paddles will restrict the adhesive strength of foulants greater than older ones.

The potential for producing a range of plastic equipment from novel materials to reduce all sorts of fouling has had some consideration by the plastics industry. One large international supplier of plastics raw material that supplies equipment manufacturers advised that they have investigated copolymer blends designed to enhance the fouling release characteristics inherent in the final product but so far have not achieved a workable formulation with the characteristics they desire (Bloys Rijkmans, pers. comm.).

3.2 Design

Paddlewheel surfaces above water foul due to the constant splash they receive which particularly promotes the growth of macro-algae. This is in contrast to the above water surfaces of propeller aspirator above water surfaces that remain clear. Creation of a large splash zone is one of the main ways paddlewheels affect oxygen transfer to the water. With the standard 3 float 2Hp paddlewheel it is difficult to envisage a design that could create the necessary splash without wetting a substantial above water surface area.

3.2.1 Long arm paddlewheels

Certain long arm paddlewheel designs used in shrimp farms do minimise the surface area of floats and motor cover that are subject to biofouling since one long axle with impellers replaces a number of individual 2hp standard paddlewheels and the single driving motor is housed on the bank away from splash (figure 8). Such designs are not commonly used in Australia.

Figure 8. Long arm paddlewheel driven from the bank.

3.2.2 Opaque cover over aerator

Macro-algae, such as the green filamentous alga *Ulva* sp, is one of the significant fouling groups for pond aerators in Australia. It grows well in the nutrient rich waters of ponds where it can attach to solid objects at or near the surface of the water. On paddlewheels this includes the above water surfaces that are constantly wetted by splash. Removing light from the paddlewheel surfaces can theoretically prevent algae from growing and therefore be a highly effective control method. It can be relatively cheap an easy to retrofit an aerator with a black HDPE cover (figure 9). The impact of such a cover on the aeration performance of the aerator is however unknown and would need to be tested. Additionally, the cover would potentially provide a large surface for barnacle attachment, particularly if the aerator is never turned off to allow the inside of the cover to dry and heat under the sun.

Figure 9. Black HDPE sheet cover over paddlewheel.

3.2.3 Air curtain

A curtain of fine air bubbles produced from an air–diffuser can be used to create a continuous flow of bubbles over the submersed surface that will disrupt macrofouling organism settlement (Scardino, et al. 2009b). The effect can potentially be enhanced by first coating the surface to be protected with a hydrophobic layer that will tend to attract air bubbles to the surface, further excluding water contact.

For the aeration equipment currently used on prawn farms producing an air-curtain would require an additional source of compressed air, a diffuser mounted underneath each of the 2 to 4 floats per aerator and a means to reticulate the air to the diffusers. The practicality of this approach is therefore doubtful. If compressed air was being used to aerate and create flow in the culture ponds then air curtain biofouling control may be a little more realistic. Though it would still suffer from the problem of air diffuser fouling which can quickly reduce air flow and itself become overgrown with macrofouling organisms.

3.2.4 Alternative aerator types

Paddlewheels and propeller aspirators are almost exclusively the only types of aerators used on commercial prawn farms in Australia. However simple aerator designs developed by shrimp farmers overseas are also being used effectively though their applicability under Australian pond conditions is uncertain. One example, found in Thailand is based on the airlift principle and may due to the construction materials have some fouling limiting characteristics (M. Briggs, pers. comm.) Any solid surface that is constantly wetted is a high risk for fouling. Air diffusers, such as air stones or perforated rubber hose, can foul and suffer greatly reduced performance within days of installation. The air diffusers used in the Thai example above were made from flexible material that was very cheap and replaceable.

3.2.5 Simplified surfaces

Current paddlewheel designs from a range of suppliers have float and motor cover surface contours, edges and corners that are more complicated than is perhaps absolutely necessary (figure 10). Reducing the number of protected corners and surface patterned profile may have some affect on reducing biofoulant attachment through removing protected corners as well as reducing the areas where water can accumulate. However simplifying and smoothing the design would have the benefit of making them easier to clean, either by scraping or high pressure water jet. Manufactures would need to be convinced that there is sufficient demand to warrant changing their design and production system.

It has been shown that the orientation of surfaces relative to the sun and water-flow patterns influences the biofouling community that develops (Glasby 2000; Glasby & Connell 2001). There are also observations of non-uniform biofouling distribution on paddlewheel floats that suggests the settlement rate is influenced by highly localised physical conditions. However based on current understanding it is not immediately clear how the settlement of problem fouling organisms could be manipulated to achieve a significant reduction for the floats of paddlewheels and propeller aspirators.

Figure 10. Front profile of a standard Taiwanese style paddlewheel showing numerous corners and curves and profiles on larger surfaces. Photo D. Mann.

4. Aerator and pond management

4.1 Regular sun drying

If paddlewheels can be turned off at regular intervals, particularly every day, then establishment of a thick biofilm on the air-exposed surfaces can be prevented. The limitations on taking this approach are that it is only applicable to paddlewheels as other aeration devices do not have a significant above water surface susceptible to biofouling. Also, the drying will need to be conducted regularly as once a thick aggregation of foulants has established, for example, clumps of filamentous algae, a day of exposure may not be enough to kill it. Long periods of wet weather will also greatly reduce the effectiveness of turning the paddlewheel off.

4.2 Regular cleaning

Controlling growth of the primary biofilm

Many of the surface fouling macro-invertebrates, particularly barnacles and tube worms, are very difficult to remove once the settled larvae have metamorphosed, and commenced cementing themselves to the surface. Therefore even from very early in the development of the fouling organisms removal will require the laborious task of pressure blasting or scraping to get complete cleaning of the surface. It is known that the primary fouling micro-organisms promote the settlement and adhesion of biofouling macro-organisms (Qian, et al. 2007; Steinberg, et al. 2002) so regular removal of the primary biofilm will greatly reduce the incidence of secondary fouling as well as remove pre-attachment macro-organisms. In marine waters the biofilm can become sufficiently mature to attract settling macro-organisms within 3 to 6 days of submergence. Therefore to maintain a biofilm at the immature stage the surface may need to be cleaned every 3 days (Caron & Sieburth 1981).

Given the impracticality of manually cleaning most marine exposed surfaces at this regularity it would be necessary to devise a system that automatically or passively wiped the surface with sufficient force to dislodge the primary biofilm. One mechanism that may achieve this is the installation of filaments in a configuration that through random movement in agitated water would continually brush over the surface to be protected. One issue is however that it is extremely likely that these filaments themselves would have zones that are not periodically abraded by other filaments or the surface being cleaned and would become heavily loaded with fouling organisms and end up making the problem worse.

Aerator surfaces above the water could be disinfected of early stage fouling organisms in a low manually intensive manner through the application of ‘safe’ chemical solutions regularly. Chemicals such as acetic acid (vinegar), hydrated lime and sodium hypochlorite are considered to be ecologically safe for use on comparatively small surface areas in aquatic systems because of their low toxicity, particularly given massive dilution, and short life in the environment (Forrest, et al. 2007b; Piola, et al. 2010). Yet these chemicals have been shown to strongly control primary biofouling and algal and invertebrate fouling even when used at 5 to 10% solution strengths with contact times of 1 to 30 minutes (Piola, et al. 2010).

The practicality of adopting the practice of the spraying of each aerator on a regular basis on a prawn farm is questionable given the large number of paddlewheels in use. In each pond the aerators would need to be turned off and working from a boat would be sprayed on all exposed surfaces. The regularity of treatment would be influenced by the farms prevailing conditions but even at fortnightly treatment intervals would represent a significant labour requirement.

4.3. Fouling organism exclusion

Macro-invertebrate fouling organisms such as barnacles and tubeworms can be excluded from entering a pond if the water is filtered down to a level which retains their egg and larval stages. Almost all invertebrate larvae are larger than 50µm and 100µm should retain all barnacle larval stages. While this sounds simple in theory the task becomes technically demanding when the highly variable water conditions and large volumes typically flowing onto prawn farms is taken into consideration. Large scale filtration units, such as drum filters or disc filters, that automatically flush and maintain a high level of performance are available that can do the job, but for whole of farm application there is expected to be significant investment costs and on-going monitoring and maintenance. Additionally such filtration does not remove macroalgae, particularly the filamentous green algae, *Ulva* spp., which have spores which are very small, ~5µm wide.

In addition to restricting invertebrate larvae of problematic fouling species from entering the pond it will also be necessary to ensure that the ponds and other sites of potential colonisation, such as the intake canal, are free of adult stages that can liberate large numbers of eggs and larvae into the system in a short period of time. The disinfection necessary can be achieved by a suitable period of drying or by the addition of a disinfectant such as sodium hypochlorite. The disinfection step should also ensure that colonies and spores of macroalgae are killed. It is not possible to stop the introduction of algal spores into the pond but removable of viable seed from the pond at the start should delay the onset of problems.

Due to the complexities and cost of treating large amounts of water it is likely that to be cost effective water exchange rates with new seawater would need to be limited. Ponds will need to be managed such that the requirement for water exchange is reduced. Alternatively, if the farm was set up to recirculate through a remediation system, then potentially biofouling invertebrate-free water could be circulated within the farm.

5. Non-coating foulant disruption

5.1 Ultrasound

Ultrasound treatment refers to the irradiation of a medium at sound frequencies above the threshold of human hearing (~20kHz) and is utilised by a diverse range of applications, from imaging internal organs for medical purposes to cleaning and sterilising equipment. The successful application of ultrasound irradiation to controlling biofouling in marine systems is a relatively new development and there is likely still much progress to be made to achieve desired control rates in many applications. Currently an acceptable level of success is being claimed for the application of ultrasound systems on small water craft. There is two ways in which this is being achieved; using the boat hull to conduct the sound waves to disrupt settlement and growth of organisms on the surface, appropriate only for certain hull materials; and, irradiating the treated surface using water as the conducting medium. In both cases the applied sound frequency and intensity needs to be in the range that will affect the cells of the organism. Unicellular and microscopic organisms are most affected. Ultrasound is known to control aquatic algae, both filamentous and planktonic types and one application gaining greater acceptance is its use in eutrophic pond waters to reduce algal scum formation. Its use to remove zooplankton, including biofouling species, is not currently effective as these types of organisms are more tolerant of ultrasound than algae. There is no evidence that ultrasound adversely affects fish or other macrofauna so it is expected that it could be safely used in prawn culture ponds.

The juvenile and adult forms of biofoulants such as barnacles and tubeworms are far more resistant to ultrasound than earlier larval forms so to be effective the surface should be treated soon upon submergence and regular doses maintained. Ultrasound has the ability to smash apart barnacle larvae (Seth, et al. 2010) though the power levels required to achieve this level of destruction are likely unrealistic for grow-out ponds. There is recent anecdotal evidence however that practical levels of ultrasound irradiation has successfully killed juvenile zebra mussels and barnacles in a marina setting (Shiks 2012). Further developments in this field will be monitored.

In the case of paddlewheels and other floating aerators the greatest surface area prone to biofouling is made of plastic which is not a good material for transferring sound waves so that propagating the sound waves through the structure is unlikely to be effective. Additionally the cost of such units would be prohibitively expensive if each aerator needed to have one. Using the other treatment method, with the ultrasound transmitted to surfaces through the water then only submersed surfaces will be treated. Another complication to treating the surfaces directly is the complicated configuration of the underwater surfaces creating unexposed regions and the curtains of bubbles produced by aerators also act as a shield against sound wave penetration. These factors indicate that the most likely mode of action to achieve effective biofouling control through ultrasound irradiation is by irradiating the pond generally in order to reduce the larval and spore stages prior to settlement.

Ultrasound is used to control the growth of algae and other organisms in the aquatic environment. It is therefore feasible that it could control the population of algae, barnacles and tubeworms through inhibition of growth in the case of algae, or destruction of the spores and larvae of other fouling organisms. There are few reports available on this aspect however the author has had some experience with application of ultrasound to marine pond water and has not observed a clear impact on microscopic fauna, larval stages or adults. However there is good evidence that inhibition of filamentous algae has occurred in outside marine tank treatments.

5.2 Electrical antifouling system

This category includes two main types, direct electrical disruption of surface organisms and electrically generated biocides.

In the first method the primary fouling organisms are killed directly by the application of an alternating electrical potential through a conductive surface coating of around 1.2V (Omae 2003). Such methods have been successfully applied to fishing nets soaked in a urethane based conductive paint (Matsunaga, et al. 1998). Such conductive polymer formulations are commercially available however there are likely to be complications in taking this approach on the various components of aerators. An electro-chemist consulted on the application of this method considered that “using a conductive coating and applying a potential between it and a series of electrodes around the aerator could possibly be effective however recommended that some tests should be conducted first before estimates of potential effectiveness can be made (Mike Horne, pers.comm).

The other form of electrical antifouling is using an electrical potential in electrodes to generate a biocide. In one method a copper electrode upstream of the surface to be protected is used to generate copper ions when an electrical potential is applied. The waters enriched in copper then flow around the surface and inhibit biofouling. As such, this approach is more similar to biocidal coatings based on copper and therefore is subject to the same issues of affect on non-target organisms and the environment.

In another electrically generated biocide approach a higher potential is applied to a conductive surface which generates free chlorine from the chloride in the seawater which then acts as a disinfectant (Huang, et al. 2010). This method greatly depends on a conductive coating covering all surfaces to be protected so that the chlorine can be fully effective. The chlorine generated is very unlikely to affect non-target organisms away from the treated surface as there is little produced and it quickly gets reduced to a non-harmful state. Such systems however appear to be very restricted in commercial application and suffer problems of effective life (Huang, et al. 2010).

6. Biocontrol

With the general shift away from biocide approaches to biofouling control the use of grazing and predatory species to naturally remove fouling organisms has received more attention and there are examples which demonstrate that this approach can be effective. Grazing snails or urchins have been effectively deployed in shellfish cages to control biofouling, particularly macroalgae, on both the shells and the cage structure (Roma, et al. 2009). Similarly fish species can control biofouling of seacages as well as sea lice in salmon farms (Newman 2003). The biocontrol approach however does not appear to be common practise in the finfish and shellfish industries and appears even less common in marine pond aquaculture.

Scientific literature also indicates there is some future potential for application of selected bacterial strains that could be used to create a natural protective biofilm on the solid surface. Isolates have been tested and shown to inhibit both micro and macro fouling organisms from settling. It has also been demonstrated that certain useful bacteria can be imbedded in gels to create a living antifouling coating (Holmström, et al. 2000). There is also interest in the use of bacteriophages to inhibit the development of biofilms, particularly with application to water treatment membranes (Xiong & Liu 2010).

Given the nature of biofouling on pond aerators a species of surface grazing fish would be the most applicable due to their mobility and likely ability to subsist on other food sources when biofouled surfaces are in limited supply. Selection of species and size at stocking are critical considerations to ensure effective biofouling control without impact on the prawn population. Grazing omnivores will potentially predate on juvenile prawns or compete for the pelleted diets. They would also create complications at harvest. It is clear that substantial investigation and development would need to be done before any potential biocontrol agent such as fish is realised.

Part C. Summary table of biofouling control options.

Method	Pros	Cons
1. Biocidal surfaces **1.1. Biocide releasing coatings**		
Standard antifouling paints containing copper, zinc and organic biocides.	Most commonly used antifouling coatings and readily available. Most effective settlement and growth inhibiting coating. Potential long service life – up to 5 years. Damage resistant coating. Bioavailable copper and zinc likely to remain within environmental tolerance levels for prawns (however sediment accumulation is greater concern.)	Biocides are released into the environment. Primary and organic booster biocides toxic to prawns. APVMA approval required for application to prawn culture ponds.
Metallic copper and alloys	Effective in preventing settlement and growth of fouling organisms. Releases less copper into the environment than most biocidal antifouling paints. Bioavailable copper likely to remain within environmental tolerance levels for prawns (however sediment accumulation is an issue)	Releases copper into the environment. Requires regular sanding of surface to maintain effectiveness. Copper persistent in the environment and accumulates in sediments. APVMA approval required for application to prawn culture ponds.
1.2. Natural biocide releasing coatings		
Sea-Nine 211®	Effective at low release rates. Biodegrades rapidly and not persistent in the environment. Effective against the major foulants of prawn ponds. Commercially available for incorporation into a range of antifouling paints (effective life is affected by type of paint used).	Biocide is released into the environment. APVMA approval required for application to prawn culture ponds.
Furanones	Preliminary investigation indicates strong potential to control problematic biofouling groups. Should be safe for prawns and pond health when used only for aerators.	There are currently no products approved for use though some are in development. Biocide is released into the environment. Effective life unknown however maybe less than 1 year. APVMA approval likely required for application to prawn culture ponds.
Selektope® (medetomidine)	Highly specific activity – primarily barnacles but also tube worms and mussels affected. Not biocidal, ie does not kill or affect organism health. Affect localised to close to the coated surface. Can be incorporated into a range of antifouling paints.	Not effective for algae. APVMA approval required for application to prawn culture ponds. Not currently approved for general antifouling use in Australia.

Method	Pros	Cons
1.3. Biocidal construction materials		
Biocide release from plastic polymer	Appropriate construction plastics (eg HDPE) with eco-friendly biocides (eg furanone, Sea-Nine 211) have been developed.	Biocide is released into the environment. Effective life unknown however maybe less than 1 year. APVMA approval required for application to prawn culture ponds.
Cold spray embedment of metallic copper or other metal particles	Metal particles are embedded in the plastic polymer and is therefore more durable. Copper and zinc are well known effective antifouling agents. The process can be used on most plastic surfaces and can be performed repeatedly.	Requires specialised equipment and unlikely to be possible on-farm by the farm. Effectiveness and longevity, particularly under prawn farm conditions, requires further assessment as it is a relatively new product. Releases copper, or other metal ion biocide into the environment.
2. Non-biocidal coatings and surfaces **2.1. Fouling release construction materials**		
Settlement and attachment inhibitory physical surface properties	Chemically benign and completely safe for prawns. Does not require APVMA approval – can be implemented immediately. Simple for on-farm operations, ie no coating required (though greater care to avoid surface damage is required). Fouling organisms more easily and quickly removed, eg low pressure water jet or wiping with gloved hand. Potentially reduces rate of macrofouling accumulation (affected by conditions).	Products not currently available. Aerator manufacturers not currently using this technology. Manufacture may not be economically viable. Surfaces likely to reduce effectiveness after exposure to UV and high temperature. Does not prevent fouling. Mechanical damage will greatly reduce effectiveness – extra care required. Surfaces will still need cleaning (though should be simpler and quicker).
2.2. Fouling release coatings		
Settlement and attachment inhibitory coating physical properties	Chemically benign and completely safe for prawns. Does not require APVMA approval – can be implemented immediately. Fouling organisms more easily and quickly removed, eg low pressure water jet or wiping with gloved hand. Potentially reduces rate of macrofouling accumulation (affected by conditions). Effective life 2-5 years depending on conditions. Several products are commercially available (see following).	On-farm coating to be undertaken. Does not prevent fouling. Surfaces will still need cleaning (though should be simpler and quicker). Coating not highly resistant to mechanical damage (can be patched).

Method	Pros	Cons
2.2. Fouling release coatings *con't*		
Ecozean AFwax	Fouling release coating with no toxins. Applied by brush or dipped. Preliminary evidence that it can be effective in prawn ponds. Can be readily patched.	Fouling release rather than prevention. Yet to be comprehensively tested to determine longevity and durability Very high temperatures can weaken it. Susceptible to mechanical damage (eg scraping along the ground).
Protecta-Hull	Fouling release coating with no toxins. Applied by brush. Can be readily patched. Relatively robust.	Fouling release rather than prevention. Susceptible to mechanical damage (eg scraping along the ground).
2.3. Surface microtopography		
Surface microtopography Nanoscale contours Sharklet®	Chemically benign and completely safe for prawns. Does not require APVMA approval – can be implemented immediately. Fouling organisms more easily and quickly removed, eg low pressure water jet or wiping with gloved hand. Potentially reduces rate of macrofouling accumulation (affected by conditions). Can be combined with low surface energy compounds to greatly improve effectiveness. One product found that can be retrofitted as an adhesive film to the larger exposed aerator surfaces.	Number of products with potential application to pond aerators very restricted. Suitable only for the larger surfaces of the floats and motor cover of paddlewheels. Not applicable to the spindle and blades of paddlewheels. Effectiveness under high organic loading conditions of prawn ponds is questionable. Effective life highly dependant on use and management.
Surface texture covering Thorn-D®	Chemically benign and completely safe for prawns. Does not require APVMA approval – can be implemented immediately. Fouling organisms more easily and quickly removed, eg low pressure water jet or wiping with gloved hand. Reduces rate of macrofouling. Can be retrofitted as an adhesive film to the larger exposed aerator surfaces.	Effectiveness under high suspended solids and organic loading conditions of prawn ponds is unknown. Suitable only for the larger surfaces of the floats and motor cover of paddlewheels. Not applicable to the spindle and blades of paddlewheels.

Method	Pros	Cons
2.4. Sacrificial covering		
Replaceable film covering	Simplifies defouling of the larger exposed surfaces. Can be flexible plastic with inherent fouling release properties and UV stabilisers to extend deployed life. Sock style coverings could be reusable and biofouling easily removed.	No products currently available. (though likely not difficult to organise custom fabrication). Applicable to floats and motor cover of paddlewheels. Aerator may need some modification to facilitate cover ease of use and effectiveness. Requires manual replacement throughout operation (though could be relatively quick and simple). May lead to high temperature of paddlewheel motor. Dislodged covers can foul aerators and pumps.
3. Aerator design		
Long arm paddlewheels	Reduces the total surface area subject to biofouling.	Not a favoured aeration configuration in Australia. Only reduces the amount of surface fouled.
Opaque cover over aerator	Prevents algal growth on aerators. Relatively simple retrofit to aerators.	Does not affect non-algal biofouling organisms. May affect oxygen transfer efficiency (can be easily tested using existing test system). Could create extra surface area for barnacle and tubeworm colonisation (unless managed to stop this).
Alternative aerator types	Potentially can reduce extent of biofouling and/or reduce its impact on performance, eg less solid wetted surface area. Cheaper construction design and materials may allow for regular replacement rather than defouling and redeployment, eg use of recycled packaging materials in airlift systems.	No alternative aerators designed to limit biofouling on the market. Oxygen transfer efficiency and water flow characteristics cannot be compromised. All aerators require a solid surface in contact with water so alternative designs will only reduce extent or impact of biofouling.
Simplified surfaces (less ridges and contours)	Potentially reduce rate of biofouling accumulation. Quicker manual defouling.	No products specifically designed with this in mind are available from aerator manufacturers. Potential benefit is not accurately known.
Air curtain over submersed surfaces	Simple in concept and non-toxic.	Benefit limited to submersed surfaces only. Requires additional systems attached to aerators and a source of compressed air. Fouling of the air diffusers. Does not prevent microfouling organism.

Method	Pros	Cons
4. Aerator and pond management		
Regular sun drying – paddlewheel on/off cycle or removal from water	Does not involve direct removal of organisms by hand (different from 'manual defouling') On/off cycle easily achieved – potentially automatically or centrally.	Involves manipulation of the aerator in some way Labour involved in replacing aerators. On/Off cycle ramifications for motor and condensation. On/off cycling could lead to lower oxygen and process failure can be catastrophic. On/Off cycling only clears upper surfaces, submerged biofouling remains. Removal of aerator requires replacement – therefore extra labour for handling and transport.
Regular cleaning – application of safe disinfectant	Potentially simple process of spraying the exposed surfaces. Can use environmentally safe quantities of relatively low toxicity chemicals.	Paddlewheels need to be turned off for short period. Likely needs to be done regularly (Interval duration would be influenced by local conditions)
Biofouling organism exclusion by filtration and disinfection	Aerators would likely last entire crop cycle without cleaning without macrofouling organisms.	High infrastructure costs for filtration and potential water reuse. May require change to standard pond management regimens. Disinfection may require use of a chemical disinfectant though other methods such as UV or ultrasound may be appropriate. Filtration only will not exclude algal spores. Possibility of other vectors for spores and larvae, eg birds, wind.
5. Non-coating foulant disruption		
Ultrasound	Potentially could reduce biofouling organism spore and larval survival or settlement through-out a pond, thereby reduce aerator colonisation rates. No chemicals used or toxins generated.	Application in aquaculture ponds is not well understood though use on boat hulls is becoming more common. The complicated surfaces of aerators and bubble fields create treatment protection zones. Plastics do not conduct ultrasound well enough. If ultrasound devices are required for each aerator then cost is prohibitive. Impact of ultrasound on zooplankton is not well understood, though current devices do not appear to affect rotifers or copepods. Will only be effective on submersed surfaces.

Method	Pros	Cons
5. Non-coating foulant disruption con't		
Electrically generated biocide	Copper ion generation method may just require replacement of electrodes.	Copper ion generation method has same risk to non-target organisms and environment as biocidal coatings. Chlorine generation method requires application and maintenance of an electrically conductive coating on all surfaces at risk of biofouling. A period of design and testing would be required to assess potential application to ponds.
Direct electrical disruption	No biocide release. Very low electrical potentials required.	Requires application and maintenance of an electrically conductive coating on all surfaces at risk of biofouling. A period of design and testing would be required to assess potential application to ponds.
6. Biocontrol		
Micro-organisms	Could be simple addition of a commercial preparation.	No product available to achieve this (and unlikely to be one that could be broadly effective).
Planktivores and grazers	Removes nutrient rich waste (though amount would likely be very small)	Added level of complexity since requires production and management of another animal. Would only be effective for submersed surfaces.

References

Adams, C.M., Shumway, S.E., Whitlatch, R.B. and Getchis, T., 2011. Biofouling in Marine Molluscan Shellfish Aquaculture: A Survey Assessing the Business and Economic Implications of Mitigation. Journal of the World Aquaculture Society. 42, 242-252.

Afsar, A., 2008. Settlement of marine fouling organisms in response to novel antifouling coatings, Biological, Earth and Environmental Sciences. University of New South Wales, Sydney, pp. 230.

Ahsanullah, M., Negilski, D.S. and Mobley, M.C., 1981. Toxicity of zinc, cadmium and copper to the shrimp <i>Callianassa australiensis</i>. I. Effects of individual metals. Marine biology. 64, 299-304.

Akinbowale, O.L., Peng, H., Grant, P. and Barton, M.D., 2007. Antibiotic and heavy metal resistance in motile aeromonads and pseudomonads from rainbow trout (Oncorhynchus mykiss) farms in Australia. International Journal of Antimicrobial Agents. 30, 177-182.

Aldred, N., Scardino, A., Cavaco, A., de Nys, R. and Clare, A.S., 2010. Attachment strength is a key factor in the selection of surfaces by barnacle cyprids (Balanus amphitrite) during settlement. Biofouling. 26, 287-299.

Bhowmik, S., Ghosh, P.K. and Ray, S., 2001. Surface modification of HDPE and PP by mechanical polishing and DC glow discharge and their adhesive joining to steel. Journal of Applied Polymer Science. 80, 1140-1149.

Borufsen Solberg, C., Saethre, L. and Julshamn, K., 2002. The effect of copper-treated net pens on farmed salmon (Salmo salar) and other marine organisms and sediments. Marine Pollution Bulletin. 45, 126-132.

Boxall, A.B.A., Comber, S.D., Conrad, A.U., Howcroft, J. and Zaman, N., 2000. Inputs, Monitoring and Fate Modelling of Antifouling Biocides in UK Estuaries. Marine Pollution Bulletin. 40, 898-905.

Brady, R.F. and Singer, I.L., 2000. Mechanical factors favoring release from fouling release coatings. Biofouling. 15, 73-81.

Bryan, G.W., 1968. Concentrations of zinc and copper in the tissues of decapod crustaceans. Journal of the Marine Biological Association of the United Kingdom. 48, 303-321.

Burridge, L., Weis, J.S., Cabello, F., Pizarro, J. and Bostick, K., 2010. Chemical use in salmon aquaculture: A review of current practices and possible environmental effects. Aquaculture. 306, 7-23.

Carbery, K., Owen, R., Frickers, T., Otero, E. and Readman, J., 2006. Contamination of Caribbean coastal waters by the antifouling herbicide Irgarol 1051. Marine Pollution Bulletin. 52, 635-644.

Caron, D.A. and Sieburth, J.M., 1981. Disruption of the primary fouling sequence on fiber glass-reinforced plastic submerged in the marine environment. Appl. Environ. Microbiol. 41, 268-273.

Charlton, T., 2012. Trial of AFwax coating on aerators for a shrimp farm. Report for Ecozean Pty Ltd.

Christie, G.B.Y., Christov, V., De Nys, P.C., Hodson, S. and Steinberg, P., 2003. Antifouling polymers Aquaculture CRC Limited (Sydney, AU).

Dafforn, K.A., Lewis, J.A. and Johnston, E.L., 2011. Antifouling strategies: History and regulation, ecological impacts and mitigation. Marine Pollution Bulletin. 62, 453-465.

Dataphysics, 2007. Solid surface energy data (SFE) for common polymers. www.surface-tension.de pp. Table.

Davies, I.M. and Paul, J.D., 1986. Accumulation of copper and nickel from anti-fouling compounds during cultivation of scallops (Pecten maximus L.) and Pacific oysters (Crassostrea gigas Thun.). Aquaculture. 55, 93-102.

De Nys, R. and Ison, O., 2009. Evaluation of antifouling products developed for the Australian pearl industry. FRDC project 2000/254

De Nys, R., Steinberg, P.D., Willemsen, P., Dworjanyn, S.A., Gabelish, C.L. and King, R.J., 1995. Broad spectrum effects of secondary metabolites from the red alga *delisea pulchra* in antifouling assays Biofouling. 8, 259-271.

Depledge, M.H., 1989. Re-evaluation of metabolic requirements for copper and zinc in decapod crustaceans. Marine Environmental Research. 27, 115-126.

Durr, S. and Watson, D., 2006. Fouling and antifouling in aquaculture. A review, pp. 15.

Forrest, B., Keeley, N., Gillespie, P., Hopkins, G., Knight, B. and Govier, D., 2007a. Review of the ecological effects of marine finfish aquaculture: final report. , Prepared for Ministry of Fisheries. Cawthron Report No. 1285., pp. 71.

Forrest, B.M., Hopkins, G.A., Dodgshun, T.J. and Gardner, J.P.A., 2007b. Efficacy of acetic acid treatments in the management of marine biofouling. Aquaculture. 262, 319-332.

Glasby, T.M., 2000. Surface composition and orientation interact to affect subtidal epibiota. Journal of Experimental Marine Biology and Ecology. 248, 177-190.

Glasby, T.M. and Connell, S.D., 2001. Orientation and position of substrata have large effects on epibiotic assemblages. Marine Ecology Progress Series. 214, 127-135.

Hall, J.A. and Frid, C.L.J., 1995. Responses of estuarine benthic macrofauna in copper-contaminated sediments to remediation of sediment quality. Marine Pollution Bulletin. 30, 694-700.

Hall Jr, L.W. and Anderson, R.D., 1999. A Deterministic Ecological Risk Assessment for Copper in European Saltwater Environments. Marine Pollution Bulletin. 38, 207-218.

Hodson, S.L., Burke, C.M. and Bissett, A.P., 2000. Biofouling of fish-cage netting: the efficacy of a silicone coating and the effect of netting colour. Aquaculture. 184, 277-290.

Holmström, C., Steinberg, P., Christov, V., Christie, G. and Kjelleberg, S., 2000. Bacteria immobilised in gel: improved methodologies for antifouling and biocontrol applications. Biofouling. 15, 109-117.

Huang, J.R., Lin, W.T., Huang, R., Lin, C.Y. and Wu, J.K., 2010. Marine biofouling inhibition by polyurethane conductive coatings used for fishing net. Journal of Coatings Technology and Research. 7, 111-117.

Interlux, 2011. Intersleek 970. Patented fluropolymer foul release coating.

Keough, M., 2011. Tackling a critical industry bottleneck: developing methods to avoid, prevent and treat biofouling on mussel farms, Active project 2010/202 as at Sept 2011. FRDC, Uni of Melbourne.

King, P.C., Poole, A.J., Gulizia, S., Jahedi, M.Z., Vucko, M.J. and Nys, R.d., 2010. Embedment of copper for fouling protection of polymers using cold spray, 15th International Conference on Marine Corrosion and Biofouling, Newcastle.

Konstantinou, I.K., 2006. Antifouling Paint Biocides. Springer, 275 pp.

Konstantinou, I.K. and Albanis, T.A., 2004. Worldwide occurrence and effects of antifouling paint booster biocides in the aquatic environment: a review. Environment International. 30, 235-248.

Krishnan, S., Wang, N., Ober, C.K., Finlay, J.A., Callow, M.E., Callow, J.A., Hexemer, A., Sohn, K.E., Kramer, E.J. and Fischer, D.A., 2006. Comparison of the Fouling Release Properties of Hydrophobic Fluorinated and Hydrophilic PEGylated Block Copolymer Surfaces: Attachment Strength of the Diatom Navicula and the Green Alga Ulva. Biomacromolecules, 13.

Lee, M.-H. and Shiau, S.-Y., 2002. Dietary copper requirement of juvenile grass shrimp, Penaeus monodon, and effects on non-specific immune responses. Fish & Shellfish Immunology. 13, 259-270.

Lewis, A.G. and Metaxas, A., 1991. Concentrations of total dissolved copper in and near a copper-treated salmon net pen. Aquaculture. 99, 269-276.

Lind, U., Alm Rosenblad, M., Hasselberg Frank, L., Falkbring, S., Brive, L., Laurila, J.M., Pohjanoksa, K., Vuorenpää, A., Kukkonen, J.P., Gunnarsson, L., Scheinin, M., Mårtensson Lindblad, L.G.E. and Blomberg, A., 2010. Octopamine Receptors from the Barnacle Balanus improvisus Are Activated by the α2-Adrenoceptor Agonist Medetomidine. Molecular Pharmacology. 78, 237.

Mann, D., 2010. Preliminary report to industry on prawn farm aerator biofouling. Australian Prawn Farmers Association and Department of Agriculture, Fisheries and Forestry Queensland, pp. 6.

Marabotti, I., Morelli, A., Orsini, L., Martinelli, E., Galli, G., Chiellini, E., Lien, E., Pettitt, M., Callow, M., Callow, J., Conlan, S., Mutton, R., Clare, A., Kocijan, A., Donik, C. and Jenko, M., 2009. Fluorinated/siloxane copolymer blends for fouling release: chemical characterisation and biological evaluation with algae and barnacles. Biofouling. 25, 481-493.

Matsunaga, T., Nakayama, T., Wake, H., Takahashi, M., Okochi, M. and Nakamura, N., 1998. Prevention of marine biofouling using a conductive paint electrode. Biotechnology and Bioengineering. 59, 374-378.

Micanti, 2012. Thorn-D. Non-toxic fouling defence technology.

Muraoka, J.S., 1969. Plastic film coatings for protection from marine fouling and corrosion, Technical Report Naval Facilities Engineering Command, Naval Civil Engineering Laboratory, Port Hueneme, California

Newman, J., 2003. 'Biocontrol' of aquaculture biofouling. CRAB Collective research on Aquaculture Biofouling.

O'Brien, D., Simpson, S. and Spadaro, D., 2011. Final Report - 2009/218 - Ecological effects due to contamination of sediments with copper-based antifoulants (Part 2). FRDC.

Omae, I., 2003. General Aspects of Tin-Free Antifouling Paints. Chemical Reviews. 103, 3431-3448.

Paul, J.D. and Davies, I.M., 1986. Effects of copper- and tin-based anti-fouling compounds on the growth of scallops (Pecten maximus) and oysters (Crassostrea gigas). Aquaculture. 54, 191-203.

Peterson, E.L. and Patterson, J.C., 2000. Energy Auditing Aquaculture Facilities, 3rd Queensland Environmental Conference, Brisbane, Australia.

Phillips, D.J.H., 1976. The common mussel Mytilus edulis as an indicator of pollution by zinc, cadmium, lead and copper. I. Effects of environmental variables on uptake of metals. Marine biology. 38, 59-69.

Piola, R.F., Dunmore, R.A. and Forrest, B.M., 2010. Assessing the efficacy of spray-delivered 'eco-friendly' chemicals for the control and eradication of marine fouling pests. Biofouling. 26, 187-U145.

Poole, A., 2012. Fouling control materials. Materials Science Researcher at CSIRO.

Qian, P.Y., Xu, Y. and Fusetani, N., 2010. Natural products as antifouling compounds: recent progress and future perspectives. Biofouling. 26, 223-234.

Qian, P.Y., Lau, S., Dahms, H.U., Dobretsov, S. and Harder, T., 2007. Marine Biofilms as Mediators of Colonization by Marine Macroorganisms: Implications for Antifouling and Aquaculture. Marine Biotechnology. 9, 399-410-410.

Rainbow, P.S., 1985. Accumulation of Zn, Cu and Cd by crabs and barnacles. Estuarine, Coastal and Shelf Science. 21, 669-686.

Raveendran, T.V. and Limna Mol, V.P., 2009. Natural product antifoulants. Current Science. 97, 508-520.

Rittschof, D., 2010. Research on practical environmentally benign antifouling coatings. in: Durr, S., Thomason, J.C. (Eds.), Biofouling. Wiley-Blackwell, pp. 396-409.

Roma, R.P.C.R., Marques, H.L.d.A. and Bueno, R.S., 2009. Biological control of fouling incrustation on the scallop Nodipecten nodosus (Linnaeus, 1758) cultured in Ubatuba, SP, Brazil. Biotemas. 22, 107.

Scardino, A., Zhang, H., Cookson, D., Lamb, R. and De Nys, R., 2009a. The role of surface roughness in antifouling. Biofouling. 25, 757-767.

Scardino, A.J., Guenther, J. and de Nys, R., 2008. Attachment point theory revisited: the fouling response to a microtextured matrix. Biofouling. 24, 45-53.

Scardino, A.J., Fletcher, L.E. and Lewis, J.A., 2009b. Fouling control using air bubble curtains: protection for stationary vessels. Proceedings of IMarEST - Part A - Journal of Marine Engineering and Technology. 2009, 3-10.

Seth, N., Chakravarty, P., Khandeparker, L., Anil, A.C. and Pandit, A.B., 2010. Quantification of the energy required for the destruction of Balanus amphitrite larva by ultrasonic treatment. J. Mar. Biol. Assoc. UK. 90, 1475-1482.

Sharklet_Technologies, 2010. Sharklet™ Surface Protection.

Sharklet^{TM}Technologies, 2010. Sharklet™ Surface Protection.

Shiks, G., 2012. Use of ultrasound to control fouling invertebrates. in: Mann, D. (Ed.). Aqua Sonic Management, Moores Pocket Qld.

Singer, I.L., Kohl, J.G. and Patterson, M., 2000. Mechanical aspects of silicone coatings for hard foulant control. Biofouling. 16, 301-309.

Sommer, S., Ekin, A., Webster, D., Stafslien, S., Daniels, J., VanderWal, L., Thompson, S., Callow, M. and Callow, J., 2010. A preliminary study on the properties and fouling-release performance of siloxane-polyurethane coatings prepared from poly(dimethylsiloxane) (PDMS) macromers. Biofouling. 26, 961-972.

Southgate, P.C. and Lucas, J.S., 2008. The pearl oyster. Elsevier.

Steinberg, P.D., De Nys, R. and Kjelleberg, S., 2002. Chemical cues for surface colonization. Journal of Chemical Ecology. 28, 1935-1951.

Sun, T., Feng, L., Gao, X. and Jiang, L., 2005. Bioinspired Surfaces with Special Wettability. Accounts of Chemical Research. 38, 644-652.

Teasdale, P., Apte, S., Batley, G. and Ford, P., 1996. The bahaviour of copper in sediments and waters of Macquarie Habour, western Tasmania.

Thomas, K.V., 1999. Determination of the antifouling agent zinc pyrithione in water samples by copper chelate formation and high-performance liquid chromatography atmospheric pressure chemical ionisation mass spectrometry. Journal of Chromatography A. 833, 105-109.

Thomas, K.V., McHugh, M. and Waldock, M., 2002. Antifouling paint booster biocides in UK coastal waters: inputs, occurrence and environmental fate. Sci. Total. Environ. 293, 117-127.

Ucar, I.O., Cansoy, C.E., Erbil, H.Y., Pettitt, M.E., Callow, M.E. and Callow, J.A., 2010. Effect of contact angle hysteresis on the removal of the sporelings of the green alga Ulva from the fouling-release coatings synthesized from polyolefin polymers Biointerphases. 5, 75-84.

Valavanidis, A. and Vlachogianni, T., 2010. Metal pollution in ecosystems. Ecotoxicology studies and risk assessment in the marine environment. www.chem-tox-ecotox.

Valkirs, A.O., Davidson, B.M., Kear, L.L. and Fransham, R.L., 1994. Environmental effects from in-water hull cleaning of ablative copper antifouling coatings. Naval Command, Control and Ocean Surveillance Center.

Vladkova, T., 2008. Surface Modification Approach to Control Biofouling, Springer Series on Biofilms. Springer-Verlag, pp. 1-29.

Voulvoulis, N., 2006. Antifouling paint booster biocides: Occurrence and partitioning in water and sediments. Antifouling Paint Biocides. 50, 155-170.

Voulvoulis, N., Scrimshaw, M.D. and Lester, J.N., 2002. Comparative environmental assessment of biocides used in antifouling paints. Chemosphere. 47, 789-795.

Vucko, M.J., King, P.C., Poole, A.J., Carl, C., Jahedi, M.Z. and Nys, R.d., 2012. Cold spray metal embedment: an innovative antifouling technology Biofouling.

Wang, Y., Betts, D.E., Finlay, J.A., Brewer, L., Callow, M.E., Callow, J.A., Wendt, D.E. and DeSimone, J.M., 2011. Photocurable Amphiphilic Perfluoropolyether/Poly(ethylene glycol) Networks for Fouling-Release Coatings. Macromolecules. 44, 878-885.

Webster, D.C. and Chisholm, B.J., 2010. New directions in antifouling technology. in: Durr, S., Thomason, J.C. (Eds.), Biofouling. Wiley-Blackwell, pp. 366-387.

White, S.L. and Rainbow, P.S., 1982. Regulation and Accumulation of Copper, Zinc and Cadmium by the Shrimp Palaemon elegans. Marine Ecology - Progress Series. 8, 95-101.

Willemsen, P., 2006. Towards European Best Practice in Aquaculture Biofouling A workshop organised by the EU-funded Collective Research on Aquaculture Biofouling and held during AQUA 2006, in Firenze, Italy

Xiong, Y. and Liu, Y., 2010. Biological control of microbial attachment: a promising alternative for mitigating membrane biofouling. Applied Microbiology and Biotechnology. 86, 825-837.

Zhenxia, S., Yan, Y. and Huang, L., 2007. Effect of fouling on feeding, oxygen consumption and wate excretion of peral oyster Pinctada martensii in Daya Bay cultivation. Marine Science Bulletin. 9.

Appendix 1.

Biocidal components currently used in antifouling coatings (Dafforn, et al. 2011; Voulvoulis, et al. 2002).

Category	*Chemical name*	*Toxicity/risks*
Primary biocide	Copper (elemental, chelated or organo-complex)	Broadly toxic, particularly to crustaceans. Not persistent in the water column but accumulates in sediments. Bioavailability and toxicity depends on pH, salinity and dissolved organic matter and other environmental factors.
Primary / secondary biocide	Zinc (elemental, chelated or organo-complex)	Broadly toxic. Bioavailability and toxicity depends on pH, salinity and dissolved organic matter and other environmental factors. Marine algae are particularly sensitive to zinc .
Organic booster biocides	Chlorothalonil (2,4,5,6-tetrachloro-isophthalonitrile) Copper pyrithione (copper 2-pyridinethiol-1-oxide) Dichlofluanid (N0-dimethyl-N-phenylsulphamide) DCOIT (Sea-Nine 211®) (4,5-Dichloro-2-n-octyl-4-isothiazolin-3-one) Diuron (3-(3,4-dichlorophenyl)-1,1-dimethylurea) Irgarol 1051®; (2-methylthio-4-tertbutylamino-6-cyclopropylamino-s-triazine) Kathon 5287 (4,5-dichloro-2-n-octyl-4-isothazolin-3-one), TCMS pyridine; thiocyanatomethylthio-benzothiazole TCMTB (2-thiocyano methylthio benzothiazole) Zinc pyrithione (Zinc 2-pyridinethiol-1-oxide) Zineb (Zinc ethylene bisdithiocarbamate)	List includes microbiocides, fungicides and herbicides Affect a broad range of non-target species. Persistence in seawater ranges from < 1 day (DCOIT, dichlofluanid) to > 1 year (diuron, Igarol 1051).

Appendix 2.

Chemical groups of known naturally occurring antifouling compounds. Information derived from Omae 2003 and Qian 2010.

These compounds were discovered in organisms from a diverse range of groups including bacteria, coral, marine algae, marine sponges, molluscs, starfish, terrestrial plants.

General chemical group	*Chemical group*
Terpenes	monoterpenes susquiterpens isocyanosesquiterepene alcohol diterpenes sesterterpene terpene
Acetylenes	polyacetylenes
Polycyclic compounds	solenoide
Steroids	epidioxy sterol seco-steroids steroid lycosides
Phenols	tannins phloroglucinols kaempferol glucopyranosides stilben glucoside monophenols (capsaicin, pepper)
Furanones	halogenated furanones
Isothiocyanates	alkyl isothiocyanates
Nitrogen-containing compounds	pyrroles indoles amides carbamates primary amides
Glycerol derivatives	glycoylglycerolipids
Higher fatty acids	arachidonic acid palmitoleic acid
Enzymes	phenoloxidase

Appendix 3.

Surface free-energy values of a range of plastics. Modified from (Dataphysics 2007).

Polymer	*Surface free energy (SFE) at 20°C in mN/m*
Polydimethylsiloxane PDMS	19.8
Polytetrafluoroethylene PTFE (Teflon™)	20
Polytrifluoroethylene P3FEt/PTrFE	23.9
Polyhexylmethacrylate PHMA	30
Polypropylene-isotactic PP	30.1
Polyvinylidene fluoride PVDF	30.3
Poly(t-butylmethacrylate) PtBMA	30.4
Polychlorotrifluoroethylene PCTrFE	30.9
Polyisobutylmethacrylate PIBMA	30.9
Polybutylmethacrylate PBMA	31.2
Polytetramethylene oxide PTME (Polytetrahydrofurane PTHF)	31.9
Polyisobutylene PIB	33.6
Polycarbonate PC	34.2
Polyethylene-branched PE	35.3
Polyethylene-linear PE	35.7
Polyethylmethacrylate PEMA	35.9
Polyvinylacetate PVA	36.5
Polyvinyl fluoride PVF	36.7
Polyethylacrylate PEA	37
Poly-α-methyl styrene PMS (Polyvinyltoluene PVT)	39
Polyamide-12 PA-12	40.7
Polystyrene PS	40.7
Polymethylacrylate (Polymethacrylic acid) PMAA	41
Polymethylmethacrylate PMMA	41.1
Polyvinylchloride PVC	41.5
Polyetheretherketone PEEK	42.1
Polyethyleneoxide PEO	42.9
Polyethyleneterephthalate PET	44.6
Polyvinylidene chloride PVDC	45
Polyamide-6,6 PA-66 (also known as nylon)	46.5