Preliminary assessment of the effects of the discharge of fertiliser from the *Pacific Adventurer*

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A study commissioned by the *Pacific Adventurer* Marine Incident Scientific Advisory Panel

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PRELIMINARY REPORT

CSIRO and AIMS Joint Report

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1. EXECUTIVE SUMMARY

On Wednesday 11 March 2009 the vessel *Pacific Adventurer* reported it had lost 31 shipping containers of ammonium nitrate overboard seven nautical miles east of Cape Moreton, South East Queensland, during cyclonic conditions. Each container contained approximately 20 tonnes of ammonium nitrate.

The Queensland Government convened a panel of independent scientists to advise the Government of the likely and immediate impacts of the oil spill and the potential for the lost Ammonium Nitrate containers to affect the marine and coastal environment of South East Queensland. This panel requested that CSIRO and AIMS provide a report, in the limited time available, that used relevant available information to provide advice on the potential impacts of the discharge of fertiliser from the *Pacific Adventurer*.

A process of collecting and collating available information was undertaken and this information was used to underpin a set of calculations that aimed provide guidance on the likely mixing of the ammonium nitrate into the surrounding receiving waters and the likelihood of measurable biological consequences. The certainty of these calculations is heavily influenced by high uncertainty in the specific oceanographic conditions at the site and rate, depth and timing of discharge of the material from the containers. Nevertheless, given the total volume of material and the range of likely discharge and oceanographic conditions, it is plausible to argue that the majority of the material was mixed into the surrounding water-column sufficiently rapidly to ensure that any biological responses did not greatly exceed those due to other natural injections of nutrient into shelf waters e.g. due to floods or upwelling.

2. BACKGROUND

At 3:15 am on Wednesday 11 March 2009 the vessel *Pacific Adventurer* reported that while in transit from Newcastle to Brisbane it had lost 31 shipping containers of ammonium nitrate overboard seven nautical miles east of Cape Moreton. Each container contained approximately 20 tonnes of ammonium nitrate. While on the surface the containers ruptured the ship's hull, causing an amount of heavy fuel oil to be discharged into the sea. The cyclonic conditions at the time were gale force winds and four- to six-metre waves.

The Royal Australian Navy's minehunter ships HMAS *Yarra* and HMAS *Norman* were deployed to locate the containers. The Navy vessels positively identified 25 containers, with six probable targets yet to be confirmed at the time of writing. Closed-circuit TV pictures of sunken containers provided by the Navy on 27 March show some containers are damaged to the extent that seawater can enter the container, Whilst others appear relatively undamaged Coordinates of containers were provided by the Navy on 1 April (Appendix A).

As a result of the incident the Queensland Government convened a panel of independent scientists. This panel requested that CSIRO and AIMS provide a report, in the limited time available, that used relevant available information to provide advice on the potential impacts of the discharge of fertiliser from the *Pacific Adventurer*.

3. RELEVANT FACTS & ISSUES

We considered some relevant facts:

- Ammonium nitrate has a molecular weight of 80 and is commonly used in fertilizers and mining explosives (as ammonium nitrate fuel oil solution).

- Ammonium nitrate is very soluble in water.

- One tonne (10^6 grams) of ammonium nitrate contains 25,000 moles of nitrogen as equal amounts of NH_4^+ and NO_3^-.

- 600 tonnes of ammonium nitrate contain 210 tonnes of nitrogen [600 x (28/80)] or 15 x 10^6 moles (600 x 25,000) (1 tonne/km^3 = 1 mg/m^3).

- One tonne of ammonium nitrate dissolved in 1 km^3 of water (= 10^9 m^3 = 10^{12} L) gives a dissolved nitrogen concentration of 0.025 µM–N (0.35 µg N L^{-1}) split evenly between NH_4^+ and NO_3^- ions. The concentrations of the individual ions (0.012 µM) are close to the limits of detection by standard wet-chemical methods. They can be readily measured using high-sensitivity fluorometric (NH_4^+) or chemiluminescent (NO_3^-) methods, although this takes appropriate instrumentation and a well-trained analyst.

- Nitrate (NO_3^-) is the most common and stable form of inorganic fixed nitrogen in sub-thermocline waters throughout the ocean. It is produced naturally by oceanic bacteria and archea. Nitrate concentrations in deep waters of the Pacific Ocean can exceed 40 µM.

- Nitrate concentrations measured at 250-metre depths at stations on the continental slope bordering the central Great Barrier Reef range from 7 to 18 µM-N, with most values falling between 10 and 12 µM (140-170 µg N L^{-1}).

- Ammonium (NH_4^+) is the preferred nitrogen source for marine phytoplankton and bacteria.

- As a generalisation based on culture and microcosm studies, water containing 1 µmole (14 µg) of added nitrogen will support the production of marine phytoplankton biomass containing approximate 1 µg of chlorophyll a (Chla) if there are sufficient amounts of other nutrients to support this production.

There is a paucity of biological oceanographic measurements taken after the spill and at the location of the spill from which determinations of the impacts of the ammonium nitrate could be made. Historical data obtained from research cruises in the region are provided in Figure 1. Information on the surface conditions after the fertiliser spill is provided in remotely sensed images shown in Figures 2 and 3.

In the absence of comprehensive *in-situ* data of the receiving water parameters directly after the discharge, the only alternative is to consider some form of prediction based on either analytical, budget-type calculations or the predictions from a numerical ocean model, as discussed below. The accuracy of both of the approaches is largely dependent on the uncertainty regarding a number of key factors. Some of these factors have high certainty and these include the location and depth of the containers, and the quantities and composition of the fertiliser. By contrast, there is high uncertainty surrounding the values of a number of other key variables, as discussed in the next section of this report.

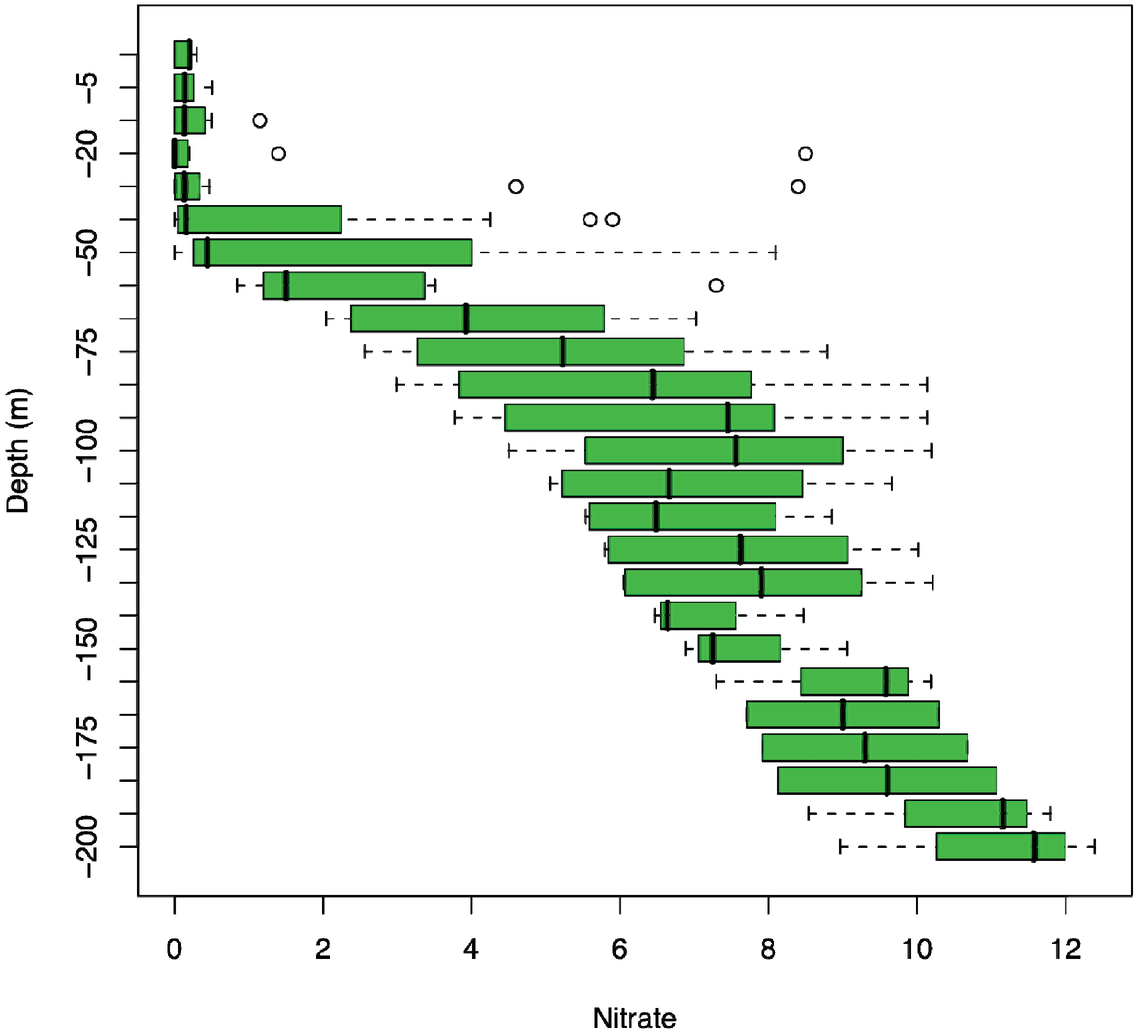

Figure 1: Historical nitrate profile from the site (latitude range: --27.63 to -26.45 degrees; longitude range: 153 to 153.8 degrees)

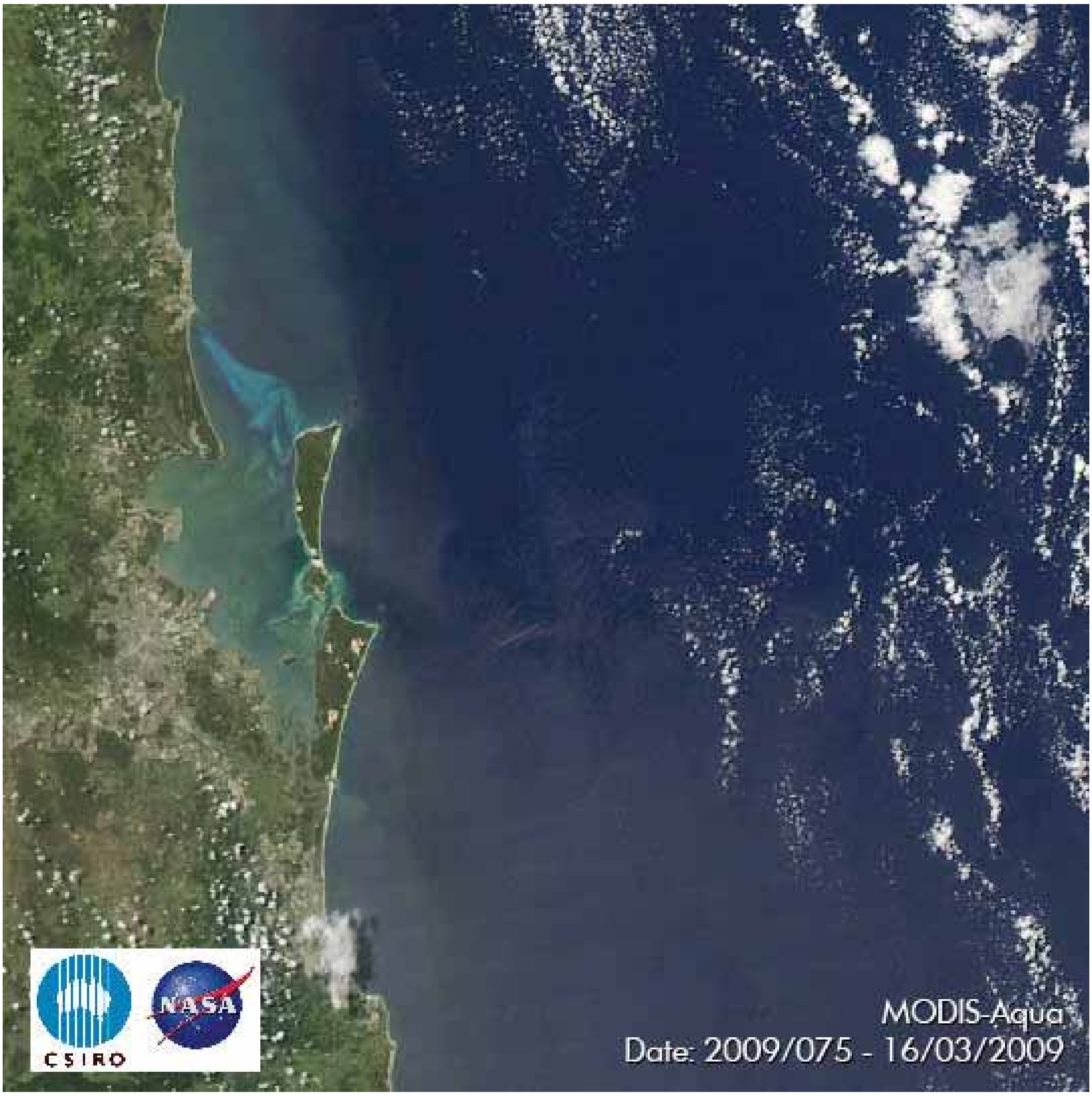

Figure 2: MODIS-Aqua image taken on Monday 16 March 2009 showing the Moreton Island region.

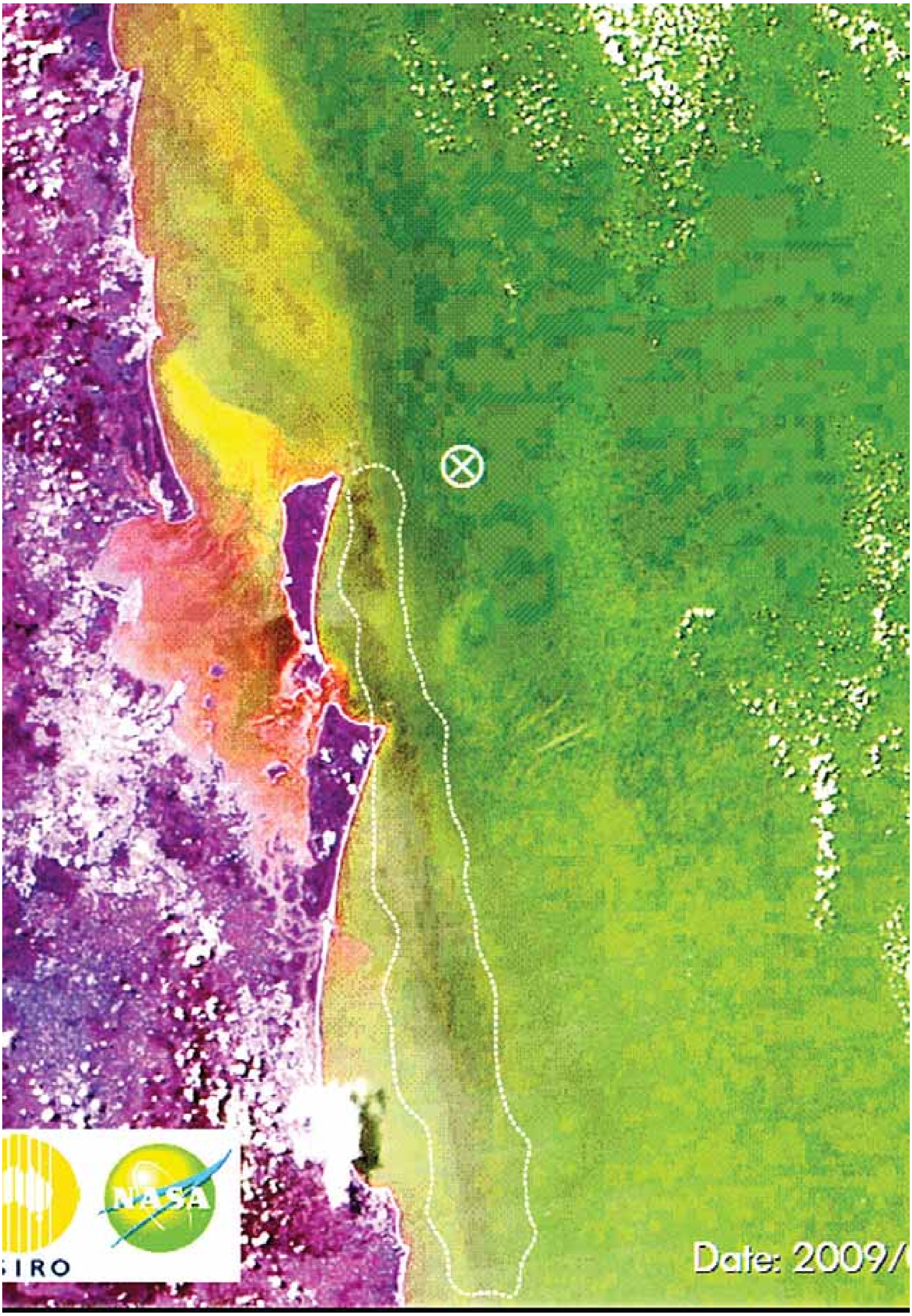

Figure 3: MODIS-Aqua ocean colour image taken on Monday 16 March 2009 showing the Moreton Island region. The cross represents the location that the incident occurred.

4. AREAS OF UNCERTAINTY

There are two key areas of uncertainty:

- the rate and depth of discharge of the material from the containers
- the specific oceanographic conditions at the time.

Consider firstly the rate of discharge of the material. Information provided by Maritime Safety Queensland (MSQ) demonstrates that the fertiliser was bulk-packed into the containers (Figure 4). However, it is unclear how much of the material was discharged during the containers' descent to the seafloor and how much and at what rate the material discharged after impact. These are critical parameters. If a large volume of the material was discharged in the upper depths of the ocean, namely in the surface-mixed layer, then a biological response is possibly more likely because of the higher levels of sunlight in these surface layers and the fact that these layers are often nutrient limited. By contrast, if most or all of the material was discharged into the layers beneath the mixed layer then conceivably little biological response will result and the material will be dispersed into receiving water of similar nutrient levels. Similarly, the attributes of any biological response may differ depending on whether all the material was discharged into the receiving waters in a short pulse or through a slow leak.

Figure 4: Photo showing the contents of one of the containers from the vessel showing the bulk packing of the fertilizer. Photo supplied by MSQ

Consider now the oceanographic conditions. We know the containers housing the material entered the water during strong wind conditions and a relatively high sea state. We also know the oil was transported in a north-westerly direction, but since the oil can move quite rapidly across the sea surface this does not provide much insight into the surface currents. We also know the average or mean current flow through the water-column at the incident's location runs to the south in a system known as the East Australian Current, which is part of the broader South Pacific circulation cell or gyre. The East Australian Current is known as a western boundary current. It can be considerably strong and is located close to the coastline. However, it is also clear that conditions at the time were not necessarily close to 'mean' conditions, given the region was experiencing the effects of cyclone Hamish that had the ability to change the depth of the mixed layer and potentially reverse at least the surface currents.

Unfortunately, the containers fell in a region of the continental shelf that can experience considerable variability in terms of both the distribution of currents across the continental shelf and down through the water column. A key uncertainty here, therefore, is whether the base of the mixed layer (often less than 50 metres deep at this location) was deep enough during the cyclonic conditions to entrain plumes of material coming out of containers that reached the bottom essentially intact. If this occurred then it is possible that some of the ammonium nitrate may have been able to mix upwards into the water column, which would enhance its ability to cause a biological response in the form of an algal bloom. By contrast if the plume of ammonium nitrate remained below the base of the mixed layer then it is more likely that it would simply mix into the background water as it was transported or advected southwards with the main flow of the East Australian Current. If this were the case biological implications would be considerably less as irradiance or sunlight levels are much reduced at these depths. However, if the current flow were weak then it is possible that much of the material may sit on the seafloor and impact benthic organisms over a small area around the discharge point.

The only available *in-situ* information of the currents at the time of the incident are derived from a surface drifter located about 10 km offshore of the site. The drifter showed near-surface (nominally 10 metre depth) currents moving rapidly to the south. Similarly, the Navy supplied information while it searched for the containers indicating strong southwards currents at the seafloor site (around 2 kts). The Navy's information is useful but not necessarily representative of conditions when the containers went overboard.

The lack of direct *in-situ* measurements of ocean conditions at the time and place of the discharge represents a source of high uncertainty for any analysis or predictions of the ultimate fate of the material in terms of biological uptake. This is because any biological response is dependent on the mixing of the material, which in itself is critically dependent on not only the location and rate of discharge, but also on the receiving water conditions.

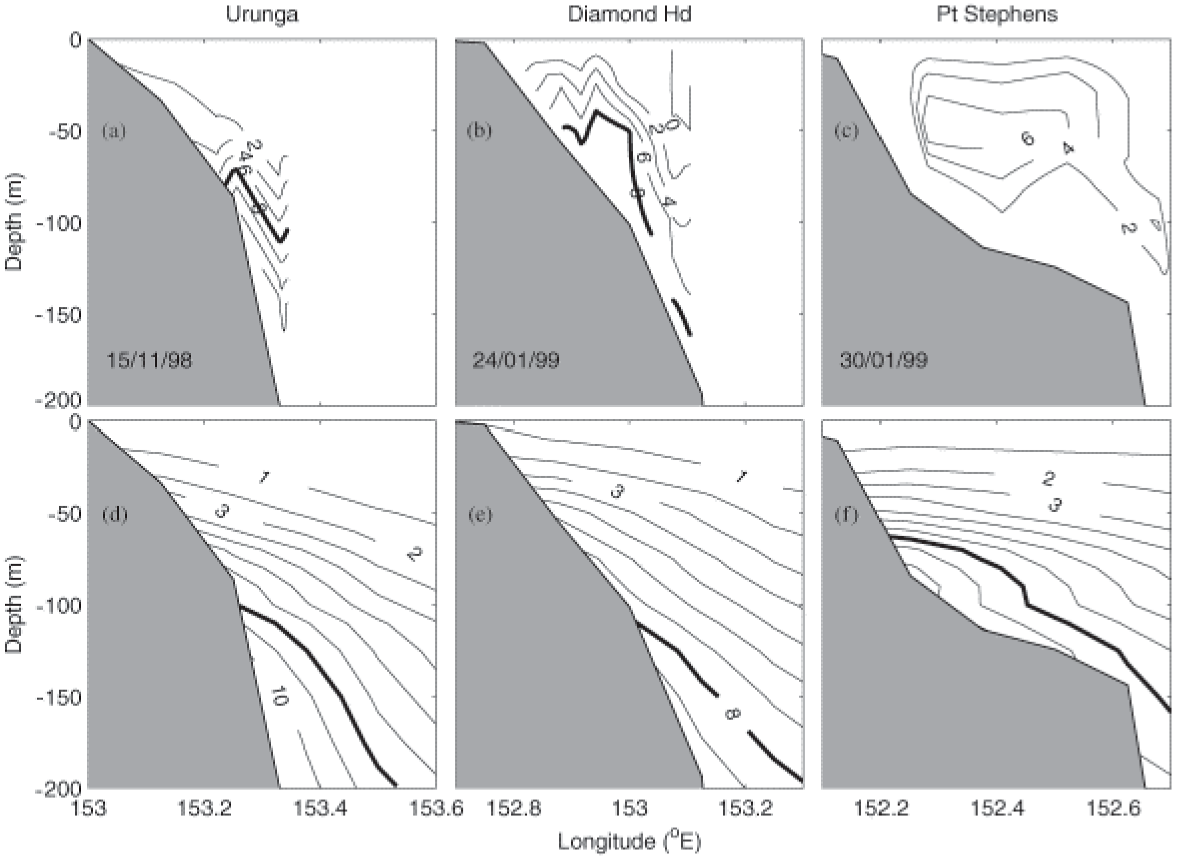

Figure 5: Observed nitrate concentrations during events at: (a) Urunga (wind-driven); (b) Diamond Head (encroachment driven); (c) Point Stephens (separation driven); (d–f) mean nitrate concentrations at each location, obtained from CSIRO Atlas of Regional Seas. Maximum concentration is 10 μmol l−1. The contour interval=2 μmol l−1 and the thick black line represents 8 μmol l−1.

5. CONCLUSIONS THAT CAN BE DRAWN

It is clear from the above discussion that there is high uncertainty surrounding some of the key parameters required to predict the fate of the plume with any high degree of confidence. Although numerical ocean models such as BLUElink can be run, in the absence of information on the specific characteristics of the discharge the results of any simulations will be feature a high degree of uncertainty. Despite these constraints, it is possible to do some calculations that may provide some insight into the key question of the possible biological consequences of the release of ammonium nitrate. Consider first some ‘budget’ type calculations that can provide insight into the likely scale of the response.

There are two ways to proceed. One is to determine a likely mixing volume and then compute the resulting concentration. Estimating this volume is best achieved by applying a hydrodynamic ocean model. However, given the time available to compile this report, such runs were not possible. Alternatively, we can propose a nitrogen concentration at which impacts could be judged significant, and calculate the corresponding mixing volume or area. We might say in an oligotrophic environment that 1 µM–N would be detectable as a significant increase in phytoplankton (roughly 1 mg/m^3 Chla).

The fertiliser, which is equivalent to 15 x 10^6 moles of N (nitrogen,) could produce an increase of 1 mg Chla/m^3 if mixed over a volume of 15 km^3 and converted to phytoplankton biomass.

Release in Surface Mixed Layer

If much of the material was released into and confined to the surface mixed layer, and this is assumed to be 50 to 100 m deep during the cyclone, a mixing volume of 15 km^3 would correspond to an area of 150 to 300 km^2. So if the fertiliser was released rapidly – which seems possible given the damage to many containers, loose packing and high solubility – it has the potential to ultimately increase chlorophyll-a measurably over a considerable area. Given the release point is on the edge of the East Australian Current, in an area of powerful long-shore currents, strong vertical and horizontal shear, and eddy activity, the volume of water containing fertiliser seems likely in practice to be advected southwards, and stretched and diluted through shear dispersion, potentially forming a long, narrow stream, possibly entrained into eddies. Of course this energetic surface activity would act to dilute the material and minimize a biological response. This is generally consistent with the results from satellite imagery (Figure 2 and 3) that show little evidence of a plume emanating form the site. Having said this however, such a conclusion could only be drawn following the analysis of similar images from previous years so that any new feature could be discriminated from features that regularly occur in the region.

Release beneath Surface Mixed Layer

If the fertiliser was mainly released beneath the mixed layer, it might be confined to a deeper thinner layer, where it could be subject to less mixing. On the other hand, if trapped below the mixing zone, it may not contribute much, if at all, to phytoplankton growth before it is dispersed to background concentrations. For example 600 tonnes of ammonium nitrate dissolved in 1 km^3 of water will raise the ambient concentration by 15 µM-N, which is of similar order to that observed at depths of 250-300 m in the East Australian Current.

Effects of Dispersal Time

The above analysis assumes the fertiliser is released and dispersed instantly. An alternative scenario is that it will leak slowly over time. If the ammonium nitrate were dissolving at 1 tonne per hour, it would take approximately 25 days for the cargo to dissolve and be dispersed. Dissolved nitrogen concentrations in the water flowing past the one-kilometre container patch would be increased by 1.4 µM (0.025 µM for 1 tonne in 1 km^3/0.018 km^3 hr^{-1}). If this was diluted ten-fold on being mixed into the surface layer where there is sufficient light for phytoplankton to grow, it would only add 0.14 µM of nitrogen. In the context of oceanic concentrations and volumes it is difficult to envisage that this addition would lead to a measurable biological response in the form of a bloom.

Slower release rates will give even smaller far-field effects, although there could be higher concentrations of nitrogen in the immediate vicinity of containers (tens of metres) or during periods of low or near-zero currents.

Free ammonia is toxic, and toxicity can occur in seawater at total ammonium concentrations in the order of 1 mg/L. So the total mass of ammonium could be toxic if confined to a volume of around 1 km^3. It is difficult to imagine ammonium persistence under any of the plausible scenarios. However, there could be toxic effects in the very near field (tens of metres) under a high rate of leakage from a single container.

Colour satellite images of the ocean could be used in principle to monitor the occurrence of any algal bloom resulting from the fertiliser release, if cloud cover permits. Inspection of the raw, true-colour MODIS image (Figure 2) reveals no obvious plumes or plume-like features in the surface waters. However, these images would need to be processed using appropriate algorithms to distinguish chlorophyll-a from other atmospheric and in-water effects. Robust CASE 2 algorithms are required given potential effects of runoff and turbidity plumes, which are visible in these images.

Comparison with other nutrient inflows

It is also worthwhile considering the discharge in the context of discharges and input of nutrients routinely occurring in the coastal zone. For example, the annual point source inputs of nitrogen into Moreton Bay or streams flowing into Moreton Bay (e.g. sewage plant) are estimated to be in the order of 1,000 -1,500 tonnes of nitrogen (Queensland Environmental Protection Agency website. The Luggage Point sewage plant accounts for about one-third of this load. Similarly, current terrestrial nitrogen inputs to the Great Barrier Reef from runoff out of drainage basins along the coast range from 230 (Mossman River) to 8,600 (Burdening River) tonnes of nitrogen per year for individual basins. Appendix B contains details of typical nutrient loads in coastal Queensland.

Finally, it is also worthwhile remembering that there are multiple processes by which nutrients for the deep ocean can be uplifted onto the continental shelf. Oceanographic studies from the region and the New South Wales (NSW) coast have demonstrated that, through the independent and interacting mechanisms of wind-driven and East Australian Current-driven upwelling, extremely large volumes of high-nutrient-concentration waters can be uplifted on to the continental shelf. The discharge of the fertiliser probably pales in comparison to these volumes associated with natural processes (see Figure 5 for an example of an upwelling event in the region). Similarly, the large flooding currently occurring in northern NSW is likely to inject far more nutrients into the coastal zone than the discharge from the *Pacific Adventurer's* containers.

6. SUMMARY AND RECOMMENDATIONS

In the short time available, we have made a preliminary assessment based on limited information of the fate of the ammonium nitrate discharged from the *Pacific Adventurer*. Major sources of uncertainty relate to the timing, rate, and depth range at which the material discharges from the containers. Furthermore, there is considerable uncertainty with respect to the specific oceanographic conditions at the time of the incident and shortly thereafter, which reduces the confidence of any predictions or analyses. Similarly, an almost complete lack of *in-situ* data of the seafloor and water-column area before and after the discharge also removes any opportunity to provide a robust assessment of possible biological effects. Nevertheless, given the total volume of material and the range of likely discharge and oceanographic conditions, it is plausible to argue that the majority of the material was mixed into the surrounding water-column sufficiently rapidly to ensure that any biological responses did not greatly exceed those due to other natural injections of nutrient into shelf waters e.g. due to floods or upwelling.

Collection of *insitu* data describing the discharge of material and local oceanographic conditions at the time would have helped reduce the uncertainty in any predictions, although running a serious of scenarios through the BLUELink ocean modelling system would provide insight into the range of possible behaviours of any plumes of material. A comprehensive analysis of satellite imagery would also provide more confidence in determining whether a biological response occurred in the surface waters. Similarly, direct evidence of the rate of discharge of the material remaining in the containers would be helpful in reducing uncertainly in any analyses of the fate of remaining material. Finally, direct observations of the seafloor and benthos surrounding the containers may help in the assessment of any possible impacts to the immediate benthic environment.

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APPENDIX A – LOCATION AND CONDITION OF THE CONTAINERS AS PROVIDED BY THE ROYAL AUSTRALIAN NAVY

Latitude	Longitude	ASSESSED	COUNT	RELATIVE POSITION	DESCRIPTION
27 01.719	153 36.063	VID CERT CONT	4	MAIN CLUSTER	BADLY CRUSHED
27 01.721	153 36.076	VID CERT CONT	3	MAIN CLUSTER	CRUSHED RIPPED
27 01.728	153 36.079	VID CERT CONT	3	MAIN CLUSTER	UNDAMAGED NOT BREACHED
27 01.735	153 36.075	VID CERT CONT	3	MAIN CLUSTER	1 OF 3 CRUSHED, 2 0F 3 NOT BREACHED
27 01.736	153 36.077	VID CERT CONT	2	MAIN CLUSTER	UNDAMAGED
27 01.737	153 36.082	VID CERT CONT	3	MAIN CLUSTER	ALL SLIGHTLY CRUSHED
27 01.723	153 36.095	VID CERT CONT	2	MAIN CLUSTER	CRUSHED MID
27 01.714	153 36.093	VID CERT CONT	2	MAIN CLUSTER	NOT BREACHED MOSTLY UNDAMAGED
27 00.513	153 35.294	VID CERT CONT	1	TO FAR NW ON MLA	RIPPED OPEN
27 00.778	153 35.338	VID CERT CONT	1	TO FAR NW ON MLA	CRUSHED FLAT
27 00.522	153 35.303	VID CERT CONT	1	TO NW ON MLA	DESTROYED
27 01.689	153 36.048	DSCL PROB	1	MAIN CLUSTER	SONAR CONTACT
27 01.664	153 36.070	DSCL PROB	1	MAIN CLUSTER	SONAR CONTACT
27 01.671	153 36.054	DSCL PROB	1	MAIN CLUSTER	SONAR CONTACT
27 01.770	153 36.025	DSCL PROB	1	MAIN CLUSTER	SONAR CONTACT
27 01.812	153 35.991	DSCL PROB	1	MAIN CLUSTER	SONAR CONTACT
27 02.214	153 35.696	DSCL PROB	1	1100YDS SW OF MAIN CLUSTER	SONAR CONTACT

APPENDIX B – NUTRIENT INPUTS INTO THE COASTAL ZONE IN QUEENSLAND

Basin Name	Area	Adjusted Runoff Volume	DIN Export	DON Export	PN Export	Total N Export
	(km2)	(km3)		Tonnes		Tonnes
Burdekin River	130,126	10.29	2,027	1,430	5,176	8,633
Fitzroy River	142,537	6.08	1,198	845	3,058	5,101
Mary River	9,440	2.72	536	378	1,368	2,282
Normanby River	24,408	4.95	846	394	720	1,960
Johnstone River	2,325	4.67	799	371	679	1,849
Herbert River	9,843	4.01	686	319	583	1,588
Shoalwater	3,605	1.83	360	254	919	1,533
Olive-Pascoe Rivers	4,179	3.71	634	295	539	1,469
Mulgrave-Russell Rivers	1,983	3.64	622	289	529	1,441
Styx River	3,012	1.58	312	220	796	1,327
Tully River	1,683	3.29	563	262	478	1,303
O’Connell River	2,387	1.54	303	214	775	1,292
Plane Creek	2,539	1.49	294	207	749	1,250
Burnett River	33,248	1.15	227	160	578	965
Waterpark Creek	1,835	1.11	219	154	558	931
Proserpine River	2,535	1.08	213	150	543	906
Lockhart River	2,883	1.94	332	154	282	769
Endeavour River	2,104	1.82	311	145	265	721
Baffle Creek	3,996	0.78	154	108	392	654
Don River	3,695	0.75	148	104	377	629
HaughtonRiver	4,044	0.74	146	103	372	621
Jacky-Jacky Creek	2,963	1.56	268	124	228	620
Jeannie River	3,637	1.54	263	122	224	610
Daintree River	2,192	1.26	215	100	183	499
Stewart River	2,743	1.21	207	96	176	479
Pioneer River	1,570	1.19	203	95	173	471
Burrum River	3,358	0.55	108	76	277	461
Murray River	1,107	1.06	181	84	154	420
Ross River	1,707	0.49	97	68	246	411
Kolan River	2,901	0.41	81	57	206	344
Barron River	2,902	0.81	139	64	118	321
Black River	1,057	0.38	75	53	191	319
Calliope River	2,236	0.30	59	42	151	252
Boyne River	2,590	0.29	57	40	146	243
Mossman River	466	0.59	101	47	86	234

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