Water Quality Targets for the Burdekin Water Quality Improvement Plan

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Prepared for the Burdekin Dry Tropics NRM Water Quality Improvement Plan

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1. INTRODUCTION

The Great Barrier Reef World Heritage Area (GBRWHA) lies along the north-eastern Australian coast and consists of a diverse range of ecosystems including coral reefs, seagrass meadows, mangrove forests and open water communities. On the western boundary of the GBRWHA a number of rivers and streams discharge into the Area over the approximately 2000 km of coast. Loads of pollutants discharging from these rivers have increased greatly with the development of the river catchments for agriculture over the past 150 years (Furnas, 2003; McKergow et al., 2005a; 2005b), with up to five times as much suspended sediment discharging from some rivers, twenty times as much nitrate in others and considerable quantities of pesticides in rivers which would have had no pesticides before 1950 (Mitchell et al., 2005). Impacts of this increased pollutant loading on coral reefs in the central part of the GBRWHA has resulted in reef degradation in the Wet Tropics coastal area (Fabricius et al., 2005) and overall reduced coral biodiversity between Townsville and Cooktown (DeVantier et al., 2006). In Figure 1, adapted from DeVantier et al. (2006), the sag in coral biodiversity in the Wet Tropics coastal area compared to expected biodiversity can be seen.

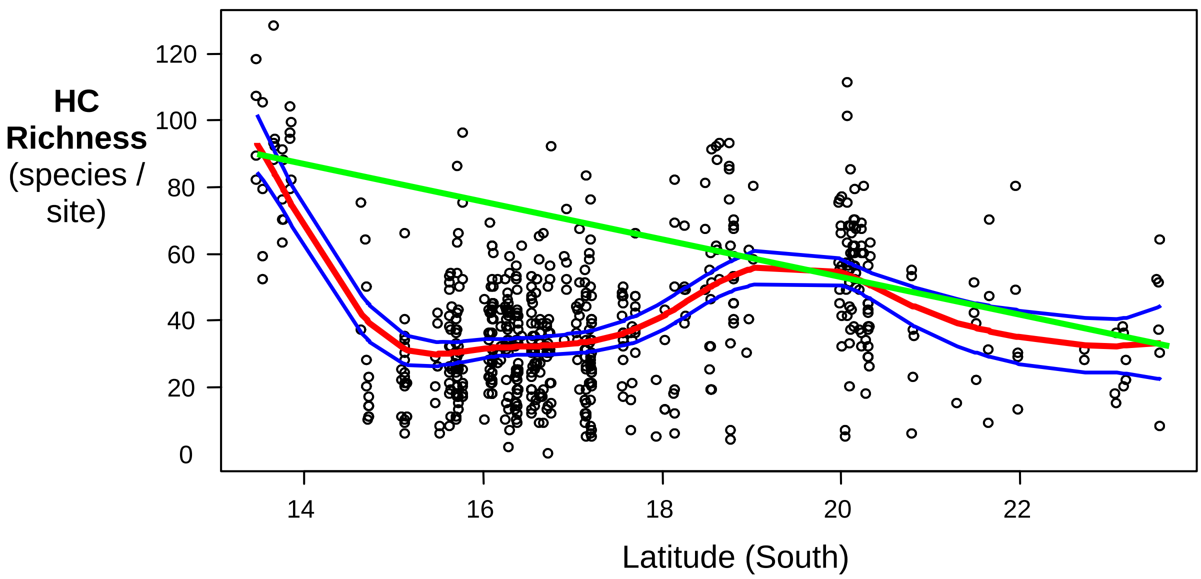

Figure 1. Hard coral species richness with latitude in the central GBR. Red line is actual richness, green line is expected richness. (From DeVantier et al., 2006).

A reduction of richness of 40 species compared to the expected value is evident in the area adjacent to the area of influence of discharge from the Burdekin and Wet Tropics rivers (between 15-20° latitude). Reefs in the central GBR are also subject to damage from crown of thorns starfish outbreaks, most likely associated with nutrient enrichment issues (Brodie et al., 2005), bleaching and ocean acidification effects associated with increased atmospheric carbon dioxide and other greenhouse gases (Lough, 2008) and fishing pressures. The combination of these impacts has resulted in reef degradation similar to that seen in other parts of the world (Bruno and Selig, 2007) although the levels of degradation are considered less than in many other reef systems (Pandolfi et al., 2003).

In response to the threats posed to the GBR from land-based pollution (Brodie et al., 2001a) a joint Australian and Queensland State Government GBR Water Quality Protection Plan (Reef Plan) was developed (Anon, 2003). As part of the implementation of this plan regional Water Quality Improvement Plans (WQIPs) were developed for priority regions of the Great Barrier Reef Catchment Area (GBRCA). Currently WQIPs are developed or in the process of being developed for Douglas Shire, the Tully/Murray Basin, the Black Ross Basin, the Burdekin Basin, the Mackay Whitsunday Region and the Burnett Baffle Basin. During the development of WQIPs a series of linked targets are attempted to be developed such that the targets for levels of agricultural best management practice in the catchment are linked to the end of system (generally a GBR ecosystem) target. The current study describes how this was attempted for one set of targets in the Burdekin WQIP. Some attempt, albeit qualitatively (on a high, medium, low scale), is made to assess the levels of uncertainty in each step of the model chain which links the marine ecosystem end point target to the land use management target.

2. NEED FOR TARGETS

Targets in the WQIP process are required to justify the level of investment based on a known 'required' level of pollutant reduction to meet the ecosystem requirements of GBR ecosystems such as coral reefs. Historically, although targets were set (e.g. Brodie et al., 2001b), the process was quite ad hoc and lacked scientific transparency. The current target setting process using linked models from paddock to reef also allows analysis of management options by running scenarios and can assess potential progress towards scientifically valid targets for various management options.

The implementation of best management practices under the WQIP will reduce pollutant runoff to the Great Barrier Reef lagoon. However, this improvement needs to be quantified to ensure that ecosystem health is maintained or enhanced. Therefore, water quality targets over the short-term (5 years), medium-term (20 years) and long-term are required to achieve the key aim of the reef water quality protection plan '*To halt and reverse the decline of water quality entering the reef within 10 years*'.

This report compiles the best available information to set both short-term and total maximum pollutant load (TMPL) targets for the Burdekin Region of the GBRCA. The report will be divided into two sections which focus on the water quality issues identified in both the Burdekin River catchment (rangelands) and the lower Burdekin area (primarily sugarcane).

3. PROJECT OBJECTIVES

For the receiving water body, within the accuracy limits of available tools and information:

A. Estimate total maximum pollutant loads of key pollutants to achieve and maintain water quality objectives.
B. Determine how the total maximum pollutant load differs from the current estimated pollutant loads.
C. Demonstrate that seasonal variations in pollutant loads have been applied to account for uncertainty in estimating the total maximum pollutant loads.
D. Estimate constituent point and diffuse source allocations of the total maximum pollutant loads.
E. Identify the specific locations of sources that could be targeted for the most cost effective options for reducing key pollutants through improvement activity and describe which ones would be most effective in achieving pollutant load targets.
F. Estimate interim WQIP targets for: nitrogen, phosphorus, TSS and pesticides to the receiving water body; to be applied during the period of this WQIP, for the purpose of achieving the water quality objectives and total maximum loads objectives. Explain the basis to those estimates.

4. TARGET SETTING FOR THE BURDEKIN RANGELANDS (COMPONENT A)

The Burdekin River flows from a large catchment (130,000 km^2) where the dominant land use is rangeland beef grazing. Since the introduction of beef cattle 150 years ago erosion rates in the catchment have risen greatly (McCulloch et al., 2003; Lewis et al., 2007) and suspended sediment (SS) loads are now estimated to be five times the loads before beef grazing commenced (Furnas, 2003; McKergow et al., 2005b).

In the Burdekin rangelands, where the cattle grazing industry is the dominant land use, the key water quality pollutants of concern include suspended sediment, particulate nitrogen (PN) and particulate phosphorus (PP) (Mitchell et al., 2007). Based on our current understanding of loads from the Burdekin River catchment, our best estimate of the average annual sediment load lies between 3.6 million tonnes (Kinsey-Henderson et al., 2007: SedNet model with 59% dam trapping scenario) to 3.7 million tonnes (Mitchell et al., 2006; adjusted mean SS load from monitoring over 5 wet seasons between 1995-2000). However, the annual flow statistics of the Burdekin River demonstrate the highly variable nature of this catchment which would considerably influence sediment and particulate nutrient loads. The annual discharge for the Burdekin River has ranged from 0.25 (1930/31) to 54.0 (1973/74) million ML, with a mean of 8.4 million ML over the period 1922 to 2005 (Lewis et al., 2006). Therefore the sediment and nutrient loads exported from the catchment would also reflect this extreme variability. Assuming the event mean concentration (EMC) is consistent across flood events, our current best estimates of 'average' loads suggest an EMC for suspended sediments lies between 420-550 mg/L. This equates to a range in the Burdekin River sediment load from 0.10 to 30 million tonnes per year in the period 1922 to 2005. The extreme range highlights the difficulty of applying 'averages' to the Burdekin catchment and the significant challenge of setting water quality targets for this catchment. The average annual sediment loads estimated by modelling and monitoring data are both based on long-term averages (models: 30 years; monitoring: 5 years) and are also based on mean annual discharge. Therefore, these estimates account for intra and inter-annual variations as well as rainfall variability within the Burdekin River catchment.

The influence of drought-breaking floods on Burdekin River runoff is another difficult consideration in setting end of river targets. The monitoring data identified four drought-breaking floods (1993/94, 1995/96, 1996/97 and 2004/05) which considerably influenced end of catchment loads of suspended sediments and particulate nutrients. While 1995/96 was a drought-breaking year, its low discharge of 2.2 x 10^6 ML also made this year a relative drought for the 1996/97 wet season to break. Flow-weighted loadings for DIN, PN, PP and SS are plotted against annual discharge for the two sampled periods, 1990/91 to 1999/00 and 2004/05 to 2005/06 (Figure 2). The six aberrant years are denoted by red symbols while the five ordinary years are indicated by black symbols. Suspended sediments (SS) show a flattish pattern, with about a 100% increase in loadings during the three drought-breaking years (average 0.70, range 0.63-0.79 Mt/ML^6) that were sampled. By contrast, loading in normal years were considerably lower (average 0.29, range 0.23-0.39 Mt/ML^6). A similar increase in SS exports appears to have occurred in 2006/07 following the low discharge year of 2005/06. These data support the findings of McCulloch et al. (2003) who found elevated Ba/Ca ratios in the coral record coinciding with runoff following extended dry periods in the Burdekin River catchment.

For particulate nutrient forms, the level of exports is also clearly raised in drought-breaking flood years (upper red symbols) above the level in normal years (Figure 2). In the case of PN, during ‘normal’ years (represented by the black symbols) the flow-weighted PN loadings are flat across the annual discharge range (average 500, range from 479-569 t/ML^6), while in three of the drought-breaking years the PN loadings are 100-200% higher (range 1092-1574 t/ML^6). During 2004/05 however, the PN loading was much lower (465 t/ML^6). The relationship between PP loadings and annual discharge is of a rising nature, though this flattens out if the large 1990/91 year (with small sample numbers) is included (lower PP graph; Figure 2). Unfortunately, data for PP in 1999/00 were lost (Mitchell et al., 2006). Again, an increase is seen in the PP loading of around 100-200% for the drought-breaking flood years (average 234, range 191-312 t/ML^6), compared to normal years (average 82, range 48-134 t/ML^6).

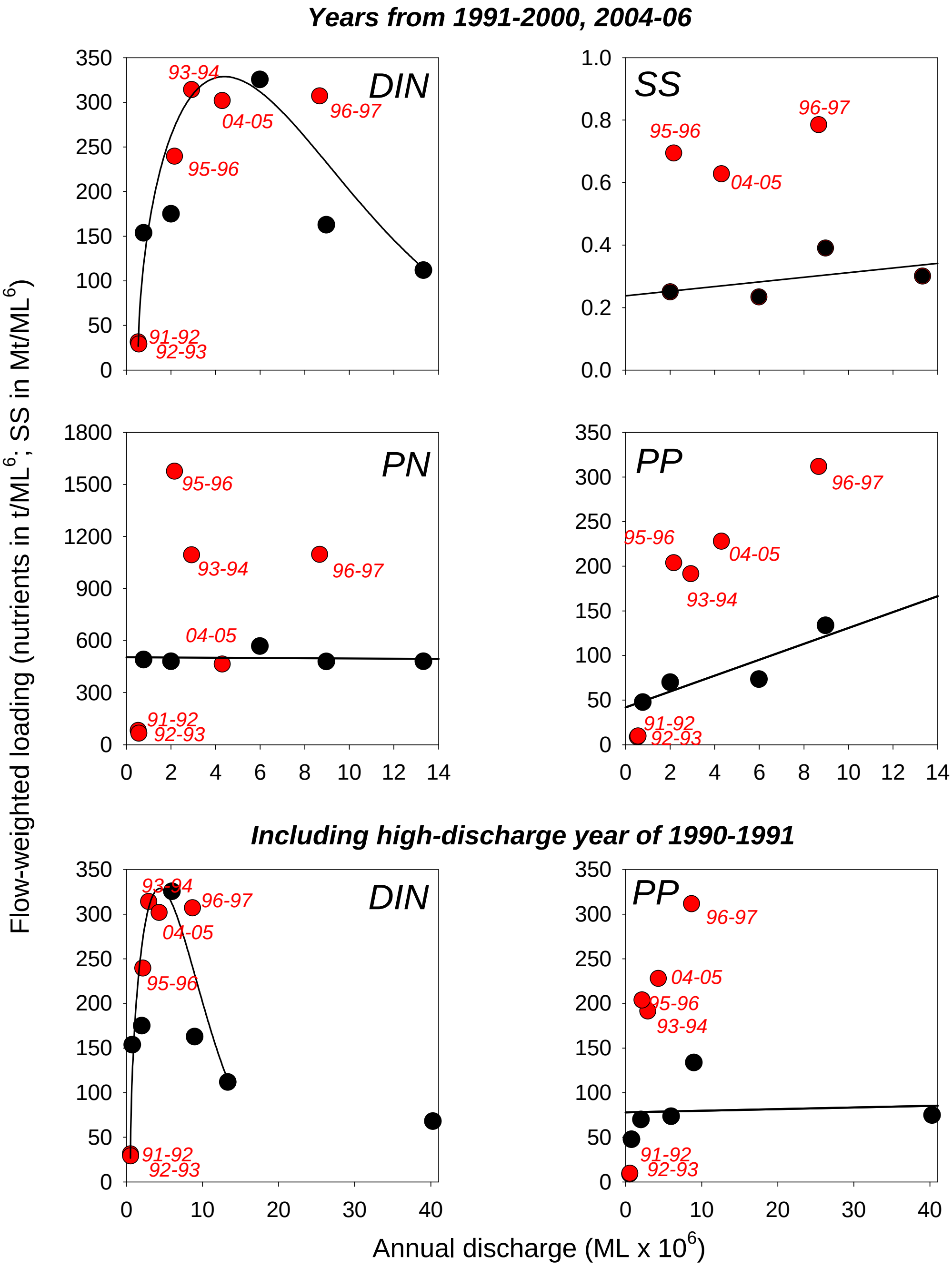

Figure 2. Flow-weighted nutrient (DIN, PN and PP) and suspended sediment loadings plotted against yearly discharge for the two periods 1991-2000 and 2004-2006 (top 4 graphs). DIN and PP flow-weighted loadings are also plotted (bottom 2 graphs) to include the adiditonal high-discharge 1990/91 wet season. Symbols shown in red indicate years of extreme drought (1991/92 and 1992/93 or years following drought-like wet seasons (1993/94, 1995/96 and 1996/97). The regression curves are only drawn through normal years (symbols in black), aside from DIN for which all data points have been used (sourced from Mitchell et al., 2006).

The point source contribution of suspended sediment and particulate nutrients is negligible in the Burdekin River catchment (Mitchell et al., 2007). The vast majority of sediments and particulate nutrients are derived from the grazing land use (diffuse sources). While the mining industry is a possible point source contribution, this industry only comprises a very small area of the Burdekin catchment and would only contribute a minor proportion of the sediment load.

While sediment and particulate nutrients are largely derived from diffuse sources, the Burdekin Dry Tropics NRM community water quality monitoring project has identified specific ‘hot spot’ areas (see Figure 3) within the Burdekin catchment (Bainbridge et al., 2007). These areas include the north-western upper Burdekin catchment (includes Camel Creek, Dry River, Clarke River, Gray Creek), the Bowen River catchment, the ‘east Burdekin’ catchment above the Burdekin Falls Dam (Elphinstone Creek area) and the upper Belyando/ Mistake Creek catchment (Figure 3). While the identified sediment erosion ‘hotspots’ are likely to be naturally more prone due to geomorphological features such as soil type and slope, the relative sediment contribution is probably exacerbated by the cattle grazing industry. These hotspots have also been identified by recent SedNet modelling (see Figure 4; Kinsey-Henderson et al., 2007). Estimated TSS loads for major Burdekin sub-catchments were higher in the monitored data compared with the modelled outputs, with the exception of the Cape River, where modelled TSS loads were greater by ~60%. The SedNet model may be overestimating sediment loads for the Cape sub-catchment, with consistently low wet season sediment loads being monitored compared to the other major sub-catchments (Bainbridge et al., 2007). A reasonable agreement was found between modelled and monitored TSS loads for the upper Burdekin (within ~30%) and Belyando (~10%) sub-catchments, while comparisons for the Suttor (~80%) and Bowen (~65%) sub-catchments were considerably different.

Modelling scenarios have been developed to examine the reduction in end of catchment sediment loads for the Burdekin River with changes in ground cover, gully density and riparian condition (Kinsey-Henderson et al., 2007). While the models have many deficiencies, they provide the only tool available to assess relative changes in sediment loads. Currently the SedNet model appears to overestimate the proportion of hillslope erosion in the Burdekin sub-catchments where field observations suggest that gully erosion makes up an important contribution (Bartley et al., 2007; Kinsey-Henderson et al., 2007). Therefore, the scenarios designed to reduce hillslope erosion (i.e. increase in ground cover) were seen to result in the highest reduction of sediment loads at the end of Burdekin River (Kinsey-Henderson et al., 2007). End of catchment sediment loads were reduced by between 3 and 8% when ground cover was improved in eight Burdekin sub-catchments identified by the SedNet model as high contributors of hillslope erosion (Kinsey-Henderson et al., 2007). A reduction in gully erosion in four priority catchments reduced end of catchment sediment loads by 2%, while an improvement in riparian zone condition at 4 sub-catchments reduced the end of catchment load by 4%. The model findings suggest that catchment-wide improvements in groundcover, gully density and riparian condition in the Burdekin River catchment would reduce end of catchment sediment loads by 60% (Kinsey-Henderson et al., 2007).

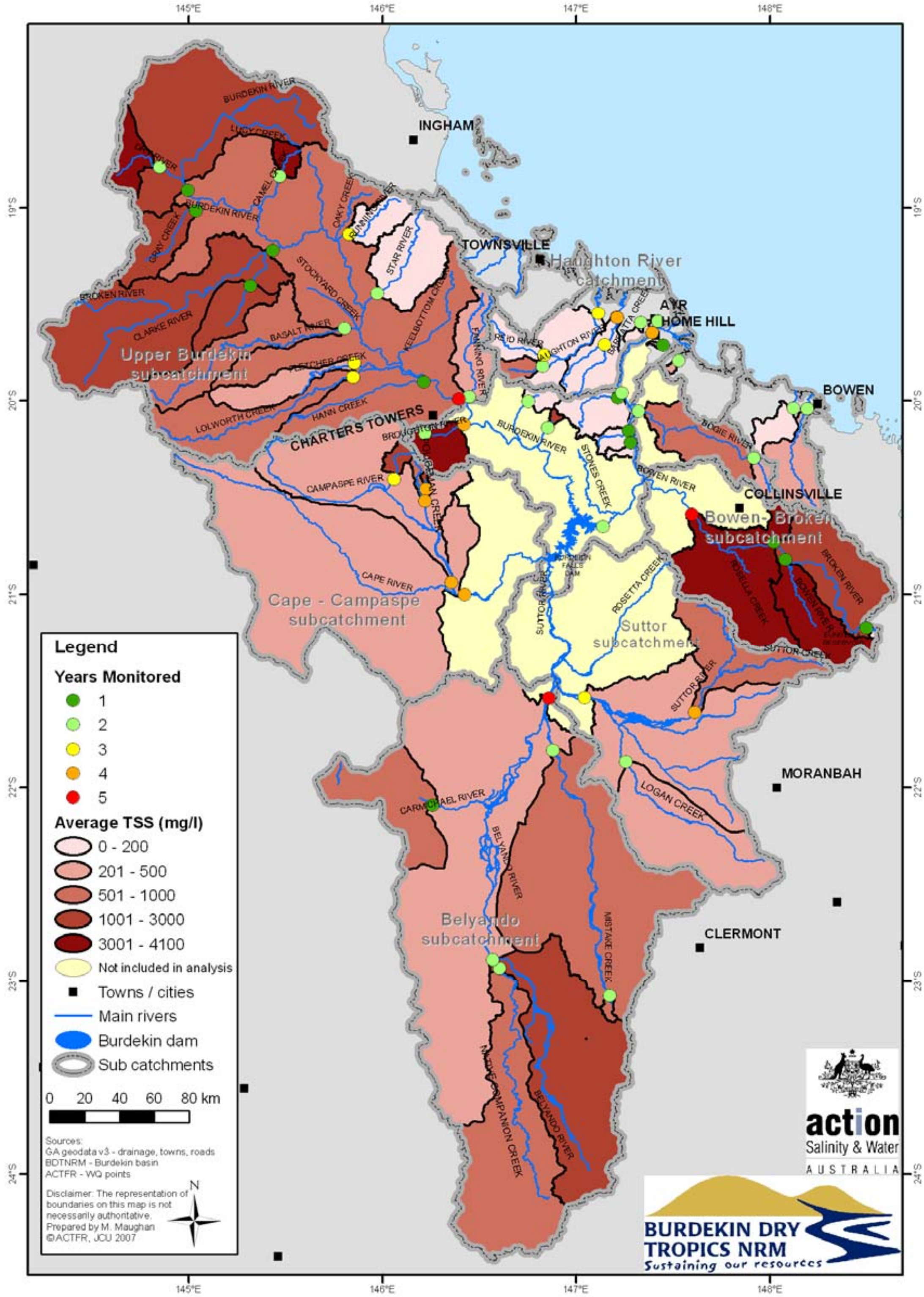

Figure 3. Average TSS concentrations in the Burdekin River catchment from five years of sub-catchment monitoring data reveal 'hot spot' areas of soil erosion (sourced from Bainbridge et al., 2007).

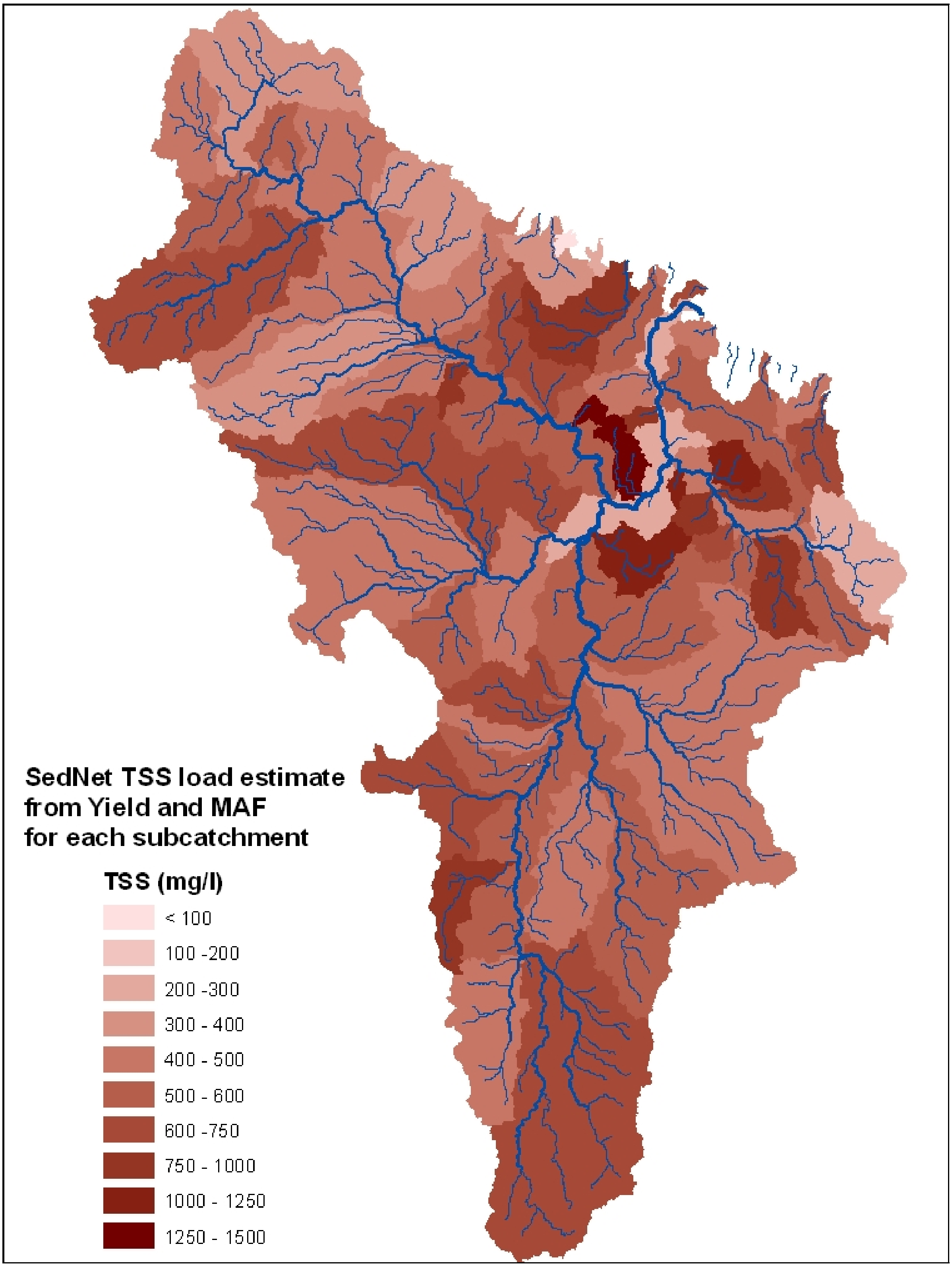

Figure 4. Average TSS concentrations in the Burdekin River catchment from SedNet modelling (sourced from Kinsey-Henderson et al., 2007).

Trigger values in the marine environment

The increased SS loads are believed to cause increased turbidity in marine waters with adverse effects on coral reefs through loss of light and sedimentation (Fabricius, 2005; Philipp and Fabricius, 2003). The potential area of influence of increased suspended sediment loads from the Burdekin River extends widely over the GBR lagoon with transport of material as far north as Cairns (Devlin and Brodie, 2005). The relationship between suspended sediment loads from rivers discharging to the GBR, such as the Burdekin, and long-term regional turbidity is not fully understood, much less quantified. It is clear that turbidity in the inshore and coastal waters of the GBR is primarily driven by resuspension (Larcombe et al., 1995) in depths of 10m or less associated with the south-easterly wind regime. However some authors hold that sediment supply to cause turbidity is not limited by sediment supply from the rivers, and hence increased sediment supply will not cause increased sediment accumulation or turbidity (Larcombe and Woolfe, 1999). Alternatively other authors hold that each river sediment discharge event leads to the formation of a ‘more resuspendable’ benthic sediment layer and hence to a period of higher turbidity until the layer is dispersed or compacted. Evidence for this second scenario is currently limited but the topic is the subject of current research (Wolanski and Spagnol, 2000; Wolanski et al., 2005, 2008). An acceptable standard for turbidity for coral reefs is highly controversial as the depth of water, physical factors such as clouds and tides (Anthony et al., 2004), the autotrophic/heterotrophic balance of the coral feeding (Anthony and Fabricius, 2000), the nature of the particulate material (Weber et al., 2006; Fabricius et al., 2003) and other factors all interact to cause adverse effects (Yentsch et al., 2002; Cooper et al., 2007).

For the purposes of target setting in the Burdekin context we make the assumption that coastal turbidity is directly proportional to river suspended sediment loads i.e. if load has doubled the turbidity in coastal waters will double. This assumption is obviously of extreme uncertainty to the extent it may be completely incorrect!

Based on studies correlating reef condition with sediment conditions, the current best estimate trigger value for turbidity is a minimum mean annual Secchi depth of 10 m for both coastal and inshore zones (De’ath and Fabricius, 2007). This relates to a trigger value for total suspended sediments of 2 mg/L in these coastal and inshore waters (De’ath and Fabricius, 2007; GBRMPA, 2008). Current suspended sediment concentrations for the marine waters of the Burdekin region are shown in Table 1 (De’ath and Fabricius, 2007). At the moment the current concentrations for coastal waters (5.47 mg/L) exceed the trigger value (2 mg/L) by 3.5 mg/L, a factor of 2.7 times. For inshore waters the current concentrations (2.48 mg/L) exceeds the trigger value (2 mg/L) by 0.5 mg/L, a factor of 1.24 times. Similar data is shown for particulate nitrogen and phosphorus (Table 1).

Table 1. Current TSS concentrations (mg/L) in Burdekin region marine waters (from Table 2; De'ath and Fabricius, 2007).

Zone	TSS concentration (mg/L)		Particulate Nitrogen (µg N/L)		Particulate Phosphorus (µg P/L)	
	Mean	SE	Mean	SE	Mean	SE
Coastal	5.47	0.41	37	2.1	5.5	0.3
Inshore	2.48	0.21	26	1.4	3.2	0.2
Offshore	0.92	0.14	19	1.8	2.1	0.2
All Zones	1.85	0.19	23	1.7	2.8	0.2

Current estimates of average annual suspended sediment loads from the Burdekin River range between 3.6 million tonnes from modelling studies using SedNet (Kinsey-Henderson et al., 2007) to 3.7 million tonnes estimated from monitoring studies (Mitchell et al., 2006). Thus overall our best estimate of current suspended sediment load is assumed to be 3.7 million tonnes with a moderate level of uncertainty (Sherman et al., 2007). To reach the TSS trigger value of 2 mg/L in Burdekin coastal waters where current TSS concentrations are 5.47 mg/L, the Burdekin River suspended sediment load needs to be reduced by 2.7 times. Thus the suggested total maximum pollutant load (TMPL) target becomes 1.35 million tonnes, a reduction of 63% (see Table 2). Similarly, to reach the TSS trigger value of 2 mg/L in Burdekin inshore waters where current TSS concentrations are 2.48 mg/L the load needs to be reduced by 1.24 times. Thus the suggested TMPL target becomes 3 million tonnes, a reduction of 20% (Table 2). Similar calculations were used for particulate nitrogen and phosphorus using the trigger values of 20 µg N/L (PN) and 2.8 µg P/L (PP) (De'ath and Fabricius, 2007).

Modelling of various land use scenarios on the Burdekin catchment involving improvements in pasture cover, reductions in gully erosion and reductions in streambank erosion then allows estimates to made of the approach to the TMPL target (Kinsey-Henderson et al., 2007). In Table 3 the effects of a number of combined scenarios are displayed together with the estimated associated river load. The scenarios are built around three forms of erosion management – hillslope erosion which can be managed through increasing pasture cover, gully erosion for which management responses are currently highly uncertain and streambank erosion for which the management remedy is improved riparian vegetation. Management can be targeted at 'priority' sub-catchments where SedNet modelling shows the particular form of erosion is most significant (Kinsey-Henderson et al., 2007). While the approach to the TMPL target is set at a 50 year time frame, intermediate targets can be planned over shorter time frames e.g. 5 and 12 years in the examples in Table 3. The quantitative basis of the scenarios is generally uncertain as quantitative information on the effectiveness of current grazing land management practices e.g. the Grazing Lands Management (GLM) package (Chilcott et al., 2003) to prevent hillslope erosion is at best moderately certain (O'Reagain et al., 2005), mechanisms to control gully erosion highly uncertain and riparian vegetation restoration as a means of reducing streambank erosion moderately uncertain.

Table 2: Current and target suspended sediment, particulate nitrogen and particulate phosphorus loads for the Burdekin River (Inkerman).

Target Loads	Sediment		Particulate Nitrogen		Particulate Phosphorus	
	Reduction (%)	**Load (million tonnes/year)**	**Reduction (%)**	**Load (tonnes)**	**Reduction (%)**	**Load (tonnes)**
Current load	-	3.7	-	6400	-	1400
Load to meet trigger value in coastal waters	63%	1.35	46%	3500	49%	710
Load to meet trigger value in inshore waters	20%	3.0	23%	4900	12%	1200

Table 3. Scenario reductions in suspended sediment, particulate nitrogen and particulate phosphorus from the Burdekin Rangelands area.

Erosion target with possible timeline	Erosion type	Scenarios (from Kinsey-Henderson et al., 2007)	Sediment		Particulate Nitrogen		Particulate Phosphorus	
			Reduction (%)	Load (million tonnes/year)	Reduction (%)	Load (tonnes)	Reduction (%)	Load (tonnes)
Current	-	Current	-	3.7	-	6400	-	1400
50 year – 60% reduction	Hillslope Gully Riparian	70% cover everywhere Decrease by 50% everywhere Riparian vegetation restored to 95% everywhere	60%	1.5	60%	2600	60%	560
12 year – 14% reduction	Hillslope Gully Riparian	70% cover on priority subcatchments (8 listed) 50% cover on priority subcatchments (4 listed) Restoration to 95% on priority subcatchments (4 listed)	14%	3.2	14%	5400	14%	1200
5 year	Hillslope, gully and riparian	70% cover on all priority subcatchments	8%	3.4	8%	5900	8%	1300
5 year	Rangelands	50% cover everywhere	13%	3.2	13%	5600	13%	1200
	Rangelands	60% cover everywhere	19%	3.0	19%	5200	19%	1100
	Rangelands	70% cover everywhere	27%	2.7	27%	4700	27%	1000
	Riparian	Riparian vegetation restored on 95% everywhere	23%	2.8	23%	2000	23%	400
	Gully	Decrease by 50% everywhere	8%	3.4	8%	2400	8%	500
The assumption made for PN and PP is that we are using the nitrogen and phosphorus content of TSS at Home Hill as a surrogate of all eroding soil in the catchment								

5. TARGET SETTING FOR THE LOWER BURDEKIN SUGAR LANDS (COMPONENT B)

5.1 NITROGEN LOSS TARGETS

The reduced coral biodiversity evident in the area of the GBR off the region between the Burdekin to Port Douglas (Figure 1; between 15-20° latitude) is ascribed to the effects of poor water quality in this region compared to analogous reefal areas further north (adjacent to Cape York), where water quality is better (Fabricius et al., 2005; DeVantier et al., 2006). The poorer state of the water quality in the affected area is quantified through a water quality index which includes measures of nutrient and suspended sediment concentrations (Fabricius and De'ath, 2004; Fabricius et al., 2005). As an indicator of water quality reflecting nutrient status chlorophyll *a* has been used widely internationally and in the GBR (Brodie et al., 2007). Chlorophyll *a* concentrations in the less impacted waters of Cape York average 0.2 µg/L, while in the area of coral reef biodiversity loss (Wet Tropics coast) concentrations average 0.7 µg/L (Brodie et al., 2007). The difference is ascribed to the increased nutrient discharge from rivers such as the Tully and Burdekin caused by increased erosion and fertiliser loss (Brodie et al., 2007; Furnas, 2003; McKergow et al., 2005a; Mitchell et al., 2001). The increased nutrient loads from rivers are also the cause of the increased outbreaks of the crown of thorns starfish which have devastated reefs in the central GBR (Brodie et al., 2005). As a result of these considerations a target of 0.5 µg/L has been set for reef health in this area based on the concentrations below which crown of thorns starfish populations do not outbreak and no adverse effects on coral reefs are evident (Moss et al., 2005). The level of uncertainly on our attribution of nutrient excess causing coral biodiversity loss is medium, while the level for our confidence in the value of 0.5 µg/L as a guideline value is also medium.

In the lower Burdekin sugarcane cultivation is the predominant agricultural activity. Priority water quality contaminants sourced from sugarcane cultivation are dissolved inorganic nutrients (typically nitrate and phosphate), herbicide residues (principally diuron and atrazine) and a range of dissolved oxygen reducing substances (Mitchell et al., 2007). The first stage of target setting will concentrate on what is seen as the priority pollutant – dissolved inorganic nitrogen (mainly nitrate).

To connect a chlorophyll *a* target to river discharge targets the ChloroSim model is used, by which chlorophyll *a* concentrations are correlated with river dissolved inorganic nitrogen (DIN) loads (Wooldridge et al., 2006). To achieve a chlorophyll *a* target of 0.5 µg/L in waters off the Burdekin the model requires a reduction in DIN loading in all the adjacent rivers (including Tully, Herbert and Burdekin) of 80% of current loading. Our confidence level in this model step is also medium as the model relationship is confined to one form of nutrient correlation and ignores many of the other factors which probably add to the causation of phytoplankton growth including other forms of nitrogen and phosphorus compounds and light (Devlin and Brodie, 2005).

The next step in the target setting process is to run fertiliser management scenarios through the catchment model to determine what level of management is needed (a target), to achieve the required load at the end of the system. Potential management scenarios include adoption of "Six easy steps" (6ES; Schroeder et al., 2006) which uses soil tests to work out optimal fertiliser rates, and nitrogen replacement method (NR; Thorburn et al., 2005) which only replaces the fertiliser used by the crop or lost from the system in the previous crop year.

A combination of modelling using the APSIM-Sugarcane cropping system model (Thorburn et al., 2005), validated on data collected from four farm blocks in the Burdekin (Stewart et al., 2006; Attard et al., 2008) results has been used to estimate loss of nitrate from a range of farming systems on different lower Burdekin soil types and hydrology (Thorburn et al., 2008). The farming systems are a combination of fallow, tillage and nitrogen fertiliser management practices. The farming systems have been simplified to five possible levels, developed from among the practices actually being recommended or used, or in early development in the lower Burdekin though discussions involving a working group representing CSIRO, BSES, DPI&F, ACTFR and local growers. The five farming systems are detailed in Table 4.

Table 4. Fertiliser and tillage management within management classes.

Management class	**Tillage system**[1]	**N fertiliser management system**[2]
E	Bare fallow, then higher tillage	330 kg/ha on Plant cane/ 400 kg/ha on Ratoon cane
D	Bare fallow, conventional tillage practice	190-210 kg/ha on Plant cane/ 270 kg/ha on Ratoon cane
C	Bare fallow, then DDOP	Calcino recommendations
B	Bare fallow, then DDOP	‘SIX EASY STEPS’ or ‘N replacement’
A	Low N legume cover crop, then DDOP	‘SIX EASY STEPS’ or ‘N Replacement’ adjusted for legume

[1]Tillage system

Bare fallow: A fallow kept free of weeds.

Higher tillage:

- Fallow – 8 tillage operations (disc & rip). These tillage operations are used to destroy old stool and control weeds.
- Pre-planting – 5 tillage operations (grub, rip, rotary, markout, planting). These tillage operations are used to prepare soil tilth for planting conventionally.
- Establishment – 6 tillage operations (cutaway, semi-hillup, hillup)
- Post-harvest – 2 tillage operations (centrebust, trash incorporation)

Conventional tillage:

- Fallow – 4 tillage operations (disc & rip). These tillage operations are used to destroy old stool and control weeds.
- Pre-planting – 5 tillage operations (grub, disc, rotary, markout, planting). These tillage operations are used to prepare soil tilth for planting conventionally.
- Establishment – 2 tillage operations (semi-hillup, hillup)
- Post-harvest – 1 tillage operation (trash incorporation)

DDOP:

- Fallow – 5 tillage operations (disc, rip, bedform). These tillage operations destroy old stool and recreate new beds. Herbicide is then used to control weeds over the fallow period.
- Establishment - DDOP

[2]N fertiliser management systems

Calcino recommendations: Based on Calcino (1994). Rates are the same across soils and crop yields: 135-150 kg/ha on Plant cane/210-250 kg/ha on Ratoon cane

'SIX EASY STEPS': Based on Schroeder et al. (2005). Rates vary according to soil type (i.e. soil organic matter), target yield, fallow management, etc. Organic matter amounts were taken from measurements of the different soils and a target yield of 150 t/ha was used, as has been applied in trials in the region (Dowie, 2008).

'N Replacement' adjusted for legume: Based on Thorburn et al. (2007) and Park et al. (2008) for burnt crops in the Burdekin. N applied depends on trash management (burning or not), the amount of cane harvested from the block in the previous fertiliser crop, fallow management, etc.

The estimated loss of nitrate to surface runoff or deep drainage loss calculated from the APSIM modelling are shown in Figure 5 (Thorburn et al., 2008).

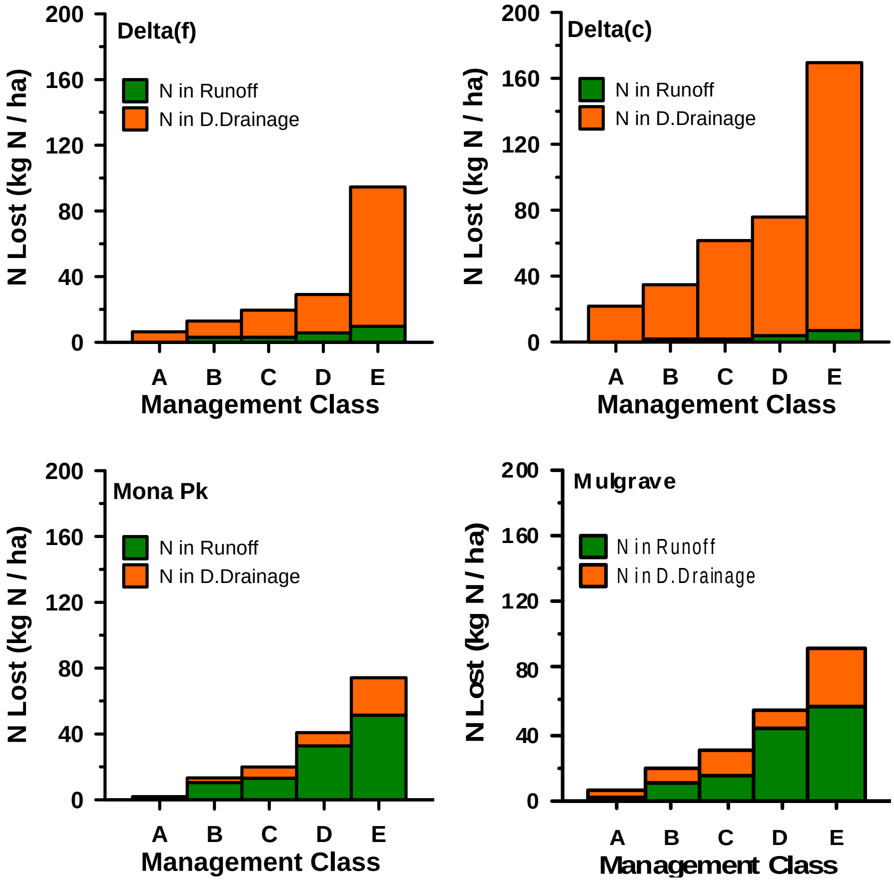

Figure 5. Nitrogen losses in runoff and drainage under different fertiliser regimes (sourced from Thorburn et al. 2008).

The areas of each broad soil type were estimated from expert knowledge of the area by Evan Shannon (BSES Limited) and Rob Milla (QDPI&F). The mapping is shown in Figure 6.

The area of cane within each division was estimated from QLUMP 2004 land use data and is shown in Figure 7 (yellow colour) and listed in Table 5.

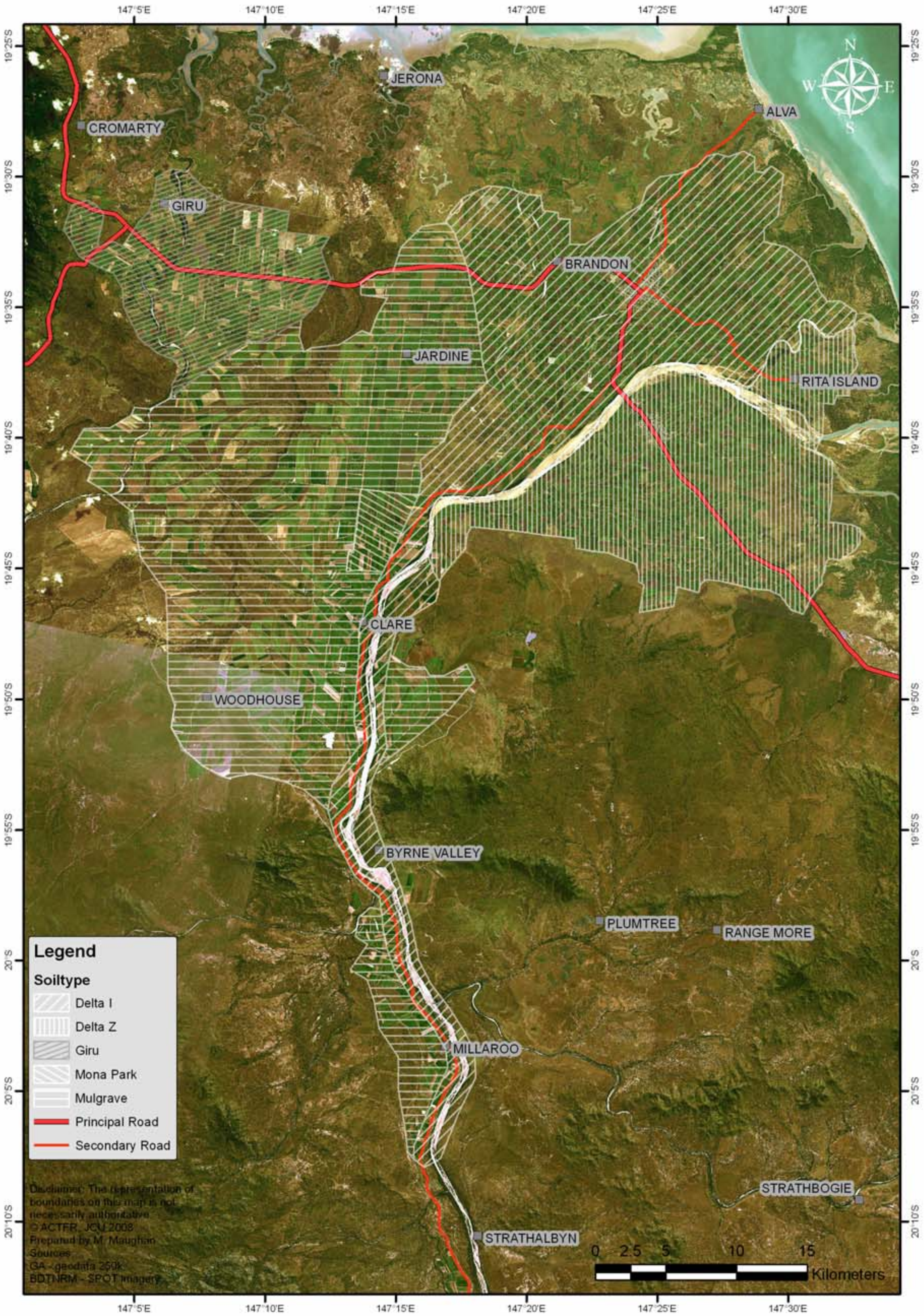

Figure 6. Defined areas of each soil type within the lower Burdekin, as estimated by Evan Shannon (BSES Limited) and Rob Milla (QDPI&F).

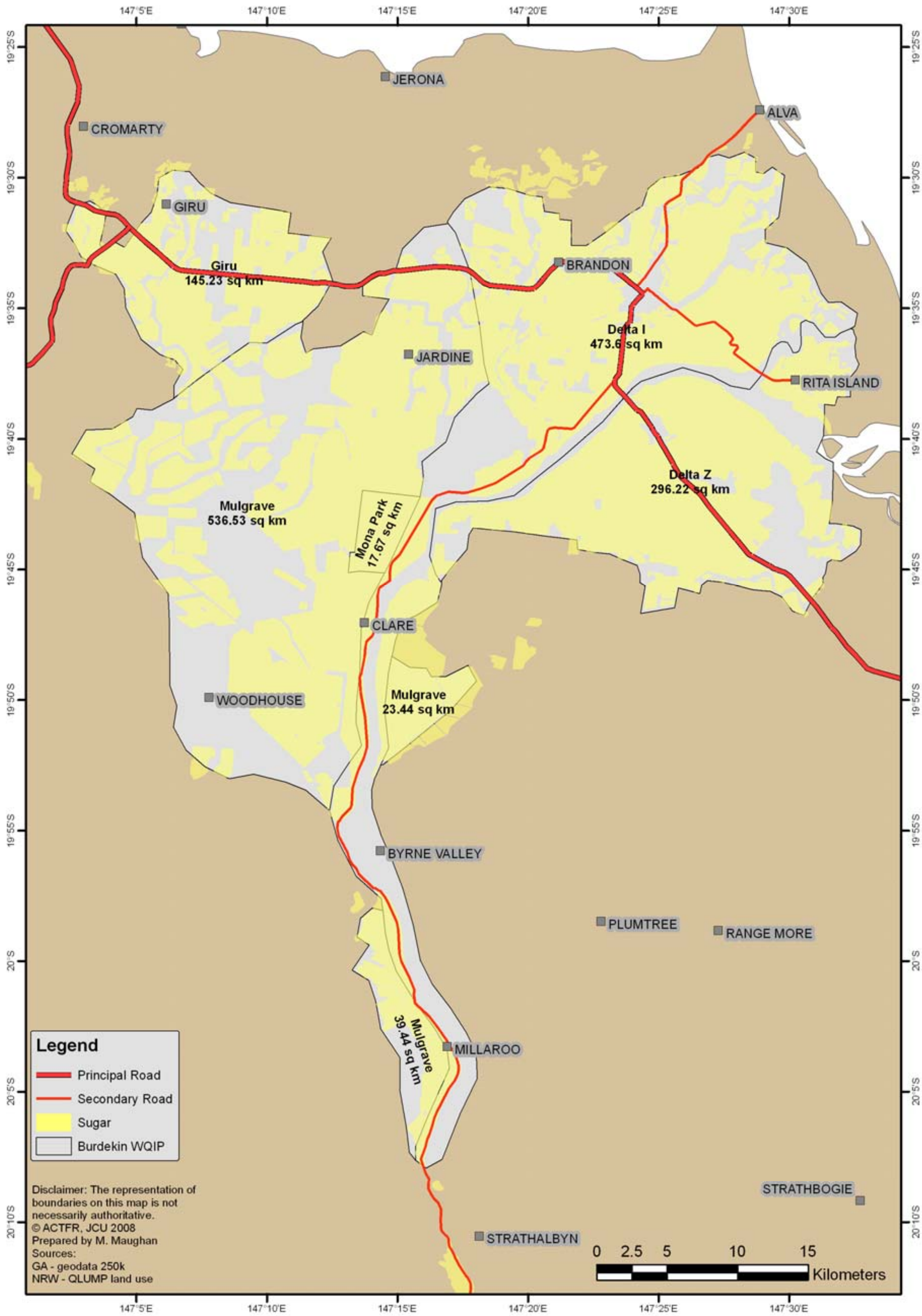

Figure 7. Sugar area within the defined soil types. Areas shown are total area. QLUMP sugarcane area from NRW.

Table 5. Area of sugar and total area within each soil type.

Soil type	ID	Sugar (km^2)	Total (km^2)
Mona Park	5	17.64	17.68
Mulgrave	3	22.93	23.44
	4	25.54	39.44
	6	333.45	536.56
Delta 1	2	293.55	473.61
Delta 2	1	216.13	296.21
Giru	0	103.47	145.22

The percentage of farmers using the different fertiliser rate regimes in each area in the 2007 season was estimated from farmer surveys and local knowledge and is listed in Table 6.

Table 6. Percentage of farmers in each fertiliser management category by area.

Management class	Delta 1 (%)	Delta 2 (%)	Giru (%)	Mona Park (%)	Mulgrave (%)
E	10	10	10	10	10
D	60	70	55	50	50
C	20	15	25	30	30
B	10	5	10	10	10
A	0	0	0	0	0

From the data in Tables 4, 5, and 6 it is possible to calculate total loss of nitrate per year at different scales and the total loss from the lower Burdekin and validate this result against monitored loss. Our current best estimate of mean annual nitrate load in the Burdekin River (Inkerman) is 1430 tonnes (Bainbridge et al., 2007) but this loading is derived primarily from the grazing lands of the Burdekin catchment and does not include the majority of drainage from the lower Burdekin sugarcane area. Estimating the total mean annual nitrate load for the lower Burdekin sugarlands is very difficult as drainage does not occur through one single discharge point and groundwater discharge is also assumed. An estimate of mean annual nitrate load can be made by a number of crude methods. Currently 15,000 tonnes of nitrogen (fertiliser) is applied annually in the lower Burdekin sugarlands (*pers comm.*, E.Shannon). A reasonable estimate of losses to water (including both surface and sub-surface drainage) of nitrogen fertiliser is 10% (Rayment, 2003) reaching the end of the system. Applying this to the lower Burdekin sugarlands gives an estimate of 1800 tonnes for mean annual loss to the end of the system. A second estimate can be calculated using a hydrological model (Charlesworth and Bristow, 2004), which predicts an annual leaching (sub-surface) load of 1300-4000 (mean of 2600) tonnes across the Delta region. An estimate of surface losses can be calculated from the limited monitoring data (three wet seasons; Bainbridge et al., 2006a; 2006b; 2007) available for the Barratta Creek (mean of 80 tonnes/yr) and Haughton River (mean of 90 tonnes/yr). If we assume these loads are half the total sugarlands runoff (i.e. missing the Delta area and the right bank particularly), a very crude estimate of total annual surface loss might be 400 tonnes. Thus our combined estimate by this method of surface and sub-surface annual losses is 3000 tonnes.

It is then possible to change the rate of fertiliser use in certain areas and among selected farmer groups (basically setting up a new fertiliser use scenario) as a future action and estimate the change in total loss of nitrate compared to current practice. A table model has been developed by Peter Thorburn and colleagues to allow these scenarios to be run easily so various options can be explored. The model was used in the stakeholder target setting workshops. Note that loss of DIN (nitrate) is assumed to occur via both deep drainage and surface runoff but both routes are assumed to have highly efficient delivery to the GBR. This is likely to be an incorrect assumption as drainage DIN is likely to not be transported to the GBR as well as DIN from surface runoff, however given our lack of knowledge of the size of this effect we take the precautionary approach and assume efficient transport. Some denitrification of nitrate is likely in the ground water pathway (Thayalakumaran et al., 2004) but the extent of this is not yet accurately known.

The calculation of the load targets to meet various targets at set periods in the future was done as follows. Estimated amounts are based on expert opinion, mill data, monitoring data, modelling data and groundwater dynamics understanding.

Calculation of current loss (annual basis)

Current N fertiliser application = 15,000 tonnes
N removal in crop = 7,000 tonnes
N retained in system = 8,000 tonnes
N loss by surface water runoff = 2,000 tonnes
N loss to GBR waters by surface water pathway = 2,000 tonnes
N loss to groundwater = 3,500 tonnes
N to soil storage = 1,500 tonnes
Uncertainty estimate of N storage = 1,000 tonnes
N loss to GBR waters by groundwater pathway = 1,000 tonnes
N stored in groundwater or denitrified in Groundwater = 2,500 tonnes
Total N exported to GBR waters via surface water and groundwater discharge = 3,000 t

Calculation of aspirational nitrate target

Aspirational GBR lagoon chlorophyll water quality target = 0.5 ug/L
Aspirational nitrate reduction target to meet chlorophyll target = 20% of current nitrate loads to GBR
Estimated current nitrate loss to GBR from lower Burdekin sugar lands = 3,000 tonnes
Aspiration target for nitrate loss from lower Burdekin sugar lands = 600 tonnes (50 year target)

Figure 8 shows the path through time to the aspirational target and the estimated load reductions needed at various interim target periods.

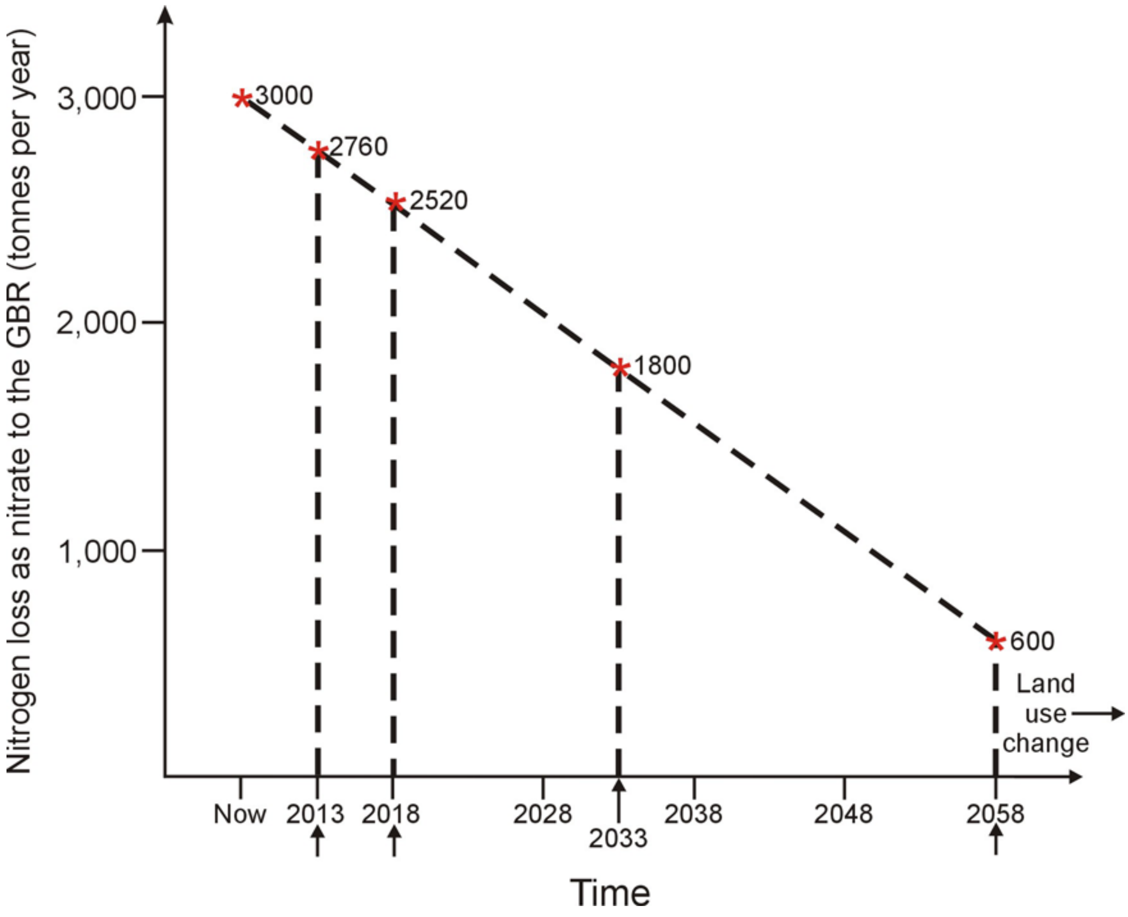

Figure 8. Targets for nitrate loss at various periods in the future moving towards the 50 aspirational target.

Calculation of targets against the A, B, C, D, E farm practices criteria

Table 7 shows our estimates of current and Reef Rescue interim 2013 targets for nitrate loss, with both a ‘stretch’ value and a ‘minimal’ value, at the paddock scale against current farm practices and future farm management scenarios where farmers move from one practice class up to higher practice classes.

N losses deep drainage and runoff			% Farms in A practice class	B	C	D	E
Current	5,500 t		0	0	31	53	16
2013	4,400 t	- 20%	0	10	34	53	3
2013 stretch	4,100 t	- 25%	1	15	42	40	2
2013 minimum	5,000 t	- 10%	0	3	36	50	11

Analysis of the figures in Table 7 shows a scenario for 2013 of :

1. 13% of farmers currently in E class to move to D class
2. 13% of farmers currently in D class to move to C class
3. 10% of farmers currently in C class to move to B class

will achieve a reduction in nitrate loss of the paddock scale of 1,100 tonnes (5,500 to 4,400) by 2013 and a reduction in nitrate loss to the GBR of 240 tonnes (Figure 7 – 3,000 to 2,760). This represents our interim target position.

5.2 PESTICIDE LOSS TARGETS

Considerable evidence now exists showing loss of pesticide residues from sugarcane cultivation in the lower Burdekin (Lewis et al., 2007; Davies et al., in press; Ham, 2006, 2007), and in fact all sugar cane lands in the GBR catchment area (e.g. Rohde et al., 2006, 2008; Faithfull et al., 2007, 2008). The pesticides of concern in the lower Burdekin situation are the herbicides diuron, atrazine, ametryn, hexazinone and 2,4 –D. These pesticides have been detected (not all in every case) in farm scale runoff, in drains, in streams (e.g. Baratta Creek) in high flow conditions and in low flow conditions, in groundwater, in marine flood plume waters and in marine waters in non-flood times. The concentrations detected exceed ANZECC guidelines in some instances.

A possible target situation is obviously to get pesticide residue concentrations below ANZECC guidelines and to do this a crude estimate suggests that if losses were halved of atrazine and diuron specifically this could be achieved. To do this will require 80% of farmers to be in Class B and that this might be possible by 2018 (10 year target). Thus our interim target for 2018 becomes 80% of farmers in Class B while the Reef rescue 2013 interim target would be by interpolation 40% of farmers in Class B. Unfortunately we do not have current data on % pesticide management classes. Further refinement of these targets should be a foundation activity in Reef Rescue.

6. CONCLUSIONS

We are thus faced with a linked set of models from the ecosystem end point target to the management action target, each link of which is moderately uncertain and the whole chain of quantitative causation highly uncertain. However this is still preferable to the previous processes to set targets for nitrogen from GBR rivers (Brodie et al., 2001b) which was much more ‘ad hoc’ with no attempt to connect a marine ecosystem end-point to the river load.

We have found that the severe lack of quantitative knowledge between river pollutants loads and Reef ecological effects makes target setting a highly uncertain process in this environment. However it still appears that using a set of quantitative models provides more transparency than the ‘ad hoc’ target setting process of the past. The process also allows management scenarios to be run using the models and a comparison of the results to fixed end point targets to be made. The major challenge is to improve modelling such that we can have a greater degree of confidence that the level of management is adequate to provide the ecosystem protection level we require. Another approach being trialled is the use of Bayesian Belief Networks as a model integration tool (Thomas et al., 2005; Shenton et al., 2007). The Bayesian model allows us to have one model linking paddock to reef. The individual models mentioned in this target setting process can be used as components to populate the BBN.

7. REFERENCES

Anon. 2003. Reef Water Quality Protection Plan for catchments adjacent to the Great Barrier Reef World Heritage Area. Queensland Department of Premier and Cabinet, Brisbane.

Anthony, K.R.N. and Fabricius, K.E. 2000. Shifting roles of heterotrophy and autotrophy in coral energetics under varying turbidity. *Journal of Experimental Marine Biology and Ecology*, **252**: 221-253.

Anthony, K.R.N., Ridd, P.V., Orpin, A.R., Larcombe, P., Lough, J. 2004. Temporal variation of light availability in coastal benthic habitats: Effects of clouds, turbidity and tides. *Limnology and Oceanography*, **49**: 2201-2211.

Attard, S.J., Thorburn, P.J., Biggs, J., Kemei, J., and Anderson, T. 2008. Farming Practices to meet the water quality challenge in the Burdekin region. (N symposium) *Proceedings Australian Society Sugar Cane Technologists*, **30**: 353-354.

Bainbridge, Z., Brodie, J., Lewis, S., Faithful, J., Duncan, I., Furnas, M. & Post, D., 2006a. *Event based Water Quality Monitoring in the Burdekin Dry Tropics Region: 2004/2005 Wet Season.* ACTFR Report No. 06/01 for BDTNRM. ACTFR, JCU, Townsville. 83pp.

Bainbridge, Z., Lewis, S., Brodie, J., Faithful, J., Maughan, M., Post, D., O'Reagain, P., Bartley, R., Ross, S., Schaffelke, B., McShane, T. and Baynes, L. 2006b. *Monitoring of sediments and nutrients in the Burdekin Dry Tropics region: 2005/2006 wet season.* ACTFR Report No. 06/13 for BDTNRM. ACTFR, JCU, Townsville. 97pp.

Bainbridge Z., Lewis S., and Brodie J. 2007. Event-based community water quality monitoring in the Burdekin Dry Tropics Region: 2002-2007. Volume 2: Integrated Wet Season (2002-2007) Report. ACTFR Report 07/22 Vol. 2. for the Burdekin Dry Tropics NRM. ACTFR, James Cook University, Townsville.

Bartley, R., Hawdon, A., Post, D.A. and Roth, C.H. 2007a. A sediment budget for a grazed semi-arid catchment in the Burdekin Basin, Australia. *Geomorphology*, **87** (4): 302-321.

Brodie, J., Christie, C., Devlin, M., Haynes, D., Morris, S., Ramsay, M., Waterhouse, J. and Yorkston, H. 2001a. Catchment management and the Great Barrier Reef. *Water Science and Technology*, **43**(9): 203-211.

Brodie, J., Furnas, M., Ghonim, S., Haynes, D., Mitchell, A., Morris, S., Waterhouse, J., Yorkston, H., Audas, D., Lowe, D., and Ryan, M. 2001b. Great Barrier Reef Catchment Water Quality Action Plan. Great Barrier Reef Marine Park Authority, Townsville, 116p.

Brodie, J., Fabricius, K., De'ath, G. and Okaji, K. 2005. Are increased nutrient inputs responsible for more outbreaks of crown-of-thorns starfish? An appraisal of the evidence. *Marine Pollution Bulletin*, **51**: 266-278.

Brodie, J. De'ath, G. Devlin, M. Furnas, M. and Wright, M. 2007. Spatial and temporal pattern of near-surface chlorophyll *a* in the Great Barrier Reef lagoon. *Marine and Freshwater Research*, **58**: 342-353.

Bruno, J.F. and Selig, E.R. 2007. Regional decline of coral cover in the Indo-Pacific: Timing, extent and subregional comparisons. *PLoS ONE* **2**(8): e711.

Calcino, D.V. 1994. Australian Sugarcane Nutritional Manual. Bureau of Sugar Experiment Stations. Indooroopilly, Australia.

Charlesworth, P. B., and Bristow, KL. 2004. Sustainable Management of the Burdekin Groundwater System, *Final report to the National Program for Sustainable Irrigation*. (CLW 32), CSIRO, Townsville.

Chilcott, C.R., McCallum, B.S., Quirk, M.F. and Paton, C.J. 2003. *Grazing Land Management Education Package Workshop Notes* – Burdekin. Meat and Livestock Australia Limited, Sydney.

Cooper, T.F., Uthicke, S., Humphrey, C. and Fabricius, K.E. 2007. Gradients in water column nutrients, sediment parameters, irradiance and coral reef development in the Whitsunday Region, central Great Barrier Reef. *Estuarine, Coastal and Shelf Science*, **74**.

De'ath, G. and Fabricius, K. 2007. Water quality of the Great Barrier Reef: Distributions, effects on reef biota and trigger values for conservation of ecosystem health. Final report to the Great Barrier Reef Marine Park Authority. Australian Institute of Marine Science, Townsville. 100pp.

DeVantier, L., De'ath, G., Turak, E., Done, T. Fabricius, K. 2006. Species richness and community structure of reef-building corals on the nearshore Great Barrier Reef. *Coral Reefs*, **25**: 329-340.

Devlin, M.J. and Brodie, J. 2005. Terrestrial discharge into the Great Barrier Reef Lagoon: nutrient behaviour in coastal waters. *Marine Pollution Bulletin*, **51**: 9-22.

Dowie, J. 2008. Reducing nitrogen application in the Burdekin to increase profitability and sustainability whilst reducing environmental impacts. Nitrogen management options. GREAT 2008: 15. BSES Limited Technical Publication TE08008.

Fabricius, K.E. 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: Review and synthesis. *Marine Pollution Bulletin*, **50**: 125-146.

Fabricius, K. and De'ath, G. 2004. Identifying ecological change and its causes: a case study on coral reefs. *Ecological Applications*, **14**: 1448-1465.

Fabricius, K.E., Wild, C., Wolanski, E. and Abele, D. 2003. Effects of transparent exopolymer particles and muddy terrigenous sediments on the survival of hard coral recruits. *Estuarine, Coastal and Shelf Science*, **57**: 613-621.

Fabricius, K.E., De'ath, G., McCook, L.J., Turak, E. and Williams, D. 2005. Coral, algae and fish communities on inshore reefs of the Great Barrier Reef: Ecological gradients along water quality gradients. *Marine Pollution Bulletin*, **51**: 384-398.

Furnas, M.J. 2003. Catchments and Corals: Terrestrial Runoff to the Great Barrier Reef. Australian Institute of Marine Science and Reef CRC, Townsville.

GBRMPA. 2008. Water quality guideline for the Great Barrier Reef Marine Park (draft). Great Barrier Reef Marine Park Authority, Townsville.

Kinsey-Henderson, A., Sherman, B. and Bartley, R. 2007. Improved SedNet modelling of grazing lands in the Burdekin catchment. CSIRO Land and Water Science Report 63/07 for Burdekin Dry Tropics NRM, CSIRO, Townsville.

Larcombe, P. and Woolfe, K. 1999. Increased sediment supply to the Great Barrier Reef will not increase sediment accumulation at most coral reefs. *Coral Reefs*, **18**: 163-169.

Larcombe, P., Ridd, P.V., Prytz, A. and Wilson, B. 1995. Factors controlling suspended sediment on inner-shelf coral reefs, Townsville, Australia. *Coral Reefs*, **14**: 163-171.

Lewis S.E., Brodie J., Ledee E. and Alewijnse M., 2006. The Spatial Extent of Delivery of Terrestrial Materials from the Burdekin Region of the Great Barrier Reef Lagoon. ACTFR Report No. 06/02, Australian Centre for Tropical Freshwater Research, James Cook University, Townsville.

Lewis, S., Shields, G., Kamber, B. and Lough, J. 2007. A multi-trace element coral record of land-use changes in the Burdekin River catchment, NE Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **246**: 471-487.

Lough, J. M. 2008. A changing climate for coral reefs. *Journal of Environmental Monitoring,***10**: 21-29.

McCulloch, M.T., Fallon, S., Wyndham, T., Hendy, E., Lough, J. and Barnes, D. 2003. Coral record of increased sediment flux to the inner Great Barrier Reef since European settlement. *Nature*, **421**: 727-730.

McKergow, L.A., Prosser, I.P., Hughes, A.O. and Brodie, J. 2005a. Sources of sediment to the Great Barrier Reef World Heritage Area. *Marine Pollution Bulletin*, **51**: 200-211.

McKergow, L.A., Prosser, I.P., Hughes, A.O. and Brodie, J. 2005b. Regional scale nutrient modelling: exports to the Great Barrier Reef World Heritage Area. *Marine Pollution Bulletin,* **51**: 186-199.

Mitchell, A.W. and Furnas, M.J. 2001. River loggers- a new tool to monitor riverine suspended particle fluxes. *Water Science and Technology,* **43**: 115-120.

Mitchell, A., Furnas, M., De'ath, G., Brodie, J. and Lewis, S. 2006. A report into the water quality condition of the Burdekin River and surrounds based on the AIMS end-of-catchment sampling program. ACTFR Report 06/06, James Cook University, Townsville.

Mitchell, A., Lewis, S., Brodie, J., Bainbridge, Z. and Maughan, M. 2007. Water quality issues in the Burdekin Region. ACTFR Report 07/03 for the Burdekin WQIP. Australian Centre for Tropical Freshwater Research, JCU, Townsville.

Mitchell C., Brodie J. and White I., 2005. Sediments, nutrients and pesticide residues in event flow conditions in streams of the Mackay Whitsunday Region, Australia. *Marine Pollution Bulletin*, **51**: 23-36.

Moss A., Brodie J. and Furnas M., 2005. Water Quality Guidelines for the Great Barrier Reef World Heritage Area: A basis for development and preliminary values. *Marine Pollution Bulletin*, **51**: 76-88.

O'Reagain, P.J., Brodie, J., Fraser, G., Bushell, J.J., Holloway, C.H., Faithful, J.W., and Haynes, D. 2005. Nutrient loss and water quality under extensive grazing in the upper Burdekin river catchment, North Queensland. *Marine Pollution Bulletin*, **51**: 37-50.

Pandolfi, J.M., Bradbury, R.H., Sala, E., Hughes, T.P., Bjorndal, K.A., Cooke, R.G., McArdle, D., McClenachan, L., Newman, M.J.H., Paredes, G., Warner, R.R., and Jackson, J.B.C. 2003. Global Trajectories of the Long-Term Decline of Coral Reef Ecosystems. *Science*, **301**: 955-958

Park, S., Horan, H., Webster, T., Biggs, I., Biggs, J. and Thorburn, P. 2008. Adapting sugarcane nitrogen management practices to take account of legume fallows (N symposium) *Proceedings Australian Society Sugar Cane Technologists*, **30**: 365-366.

Philipp, E. and Fabricius, K. 2003. Photophysiological stress in scleractinian corals in response to short-term sedimentation. *Journal of Experimental Marine Biology and Ecology*, **287**: 57-78.

Rayment, G.E. 2003. Water quality in sugar catchments in Queensland. *Water Science and Technology*, **48** (7): 35-47.

Schroeder, B.L., Wood, A.W., Moody, P.W., Bell, M.J. and Garside, A.L. 2005. Nitrogen fertiliser guidelines in perspective. *Proc. Aust. Sugar Can Technol.*, **27**: 2005: 291-304.

Schroeder, B.L., Wood, A.W., Moody, P.W., Panitz, J.H., Agnew, J.R., Sluggett, R.J. and Salter, B. 2006. Delivering nutrient management guidelines to growers in the central region of the Australian sugar industry. *Proceedings Australian Sugar Cane Technologists*, **28**: 2006.

Shenton, W., Hart, B.T. and Brodie J., 2007. Development of a Bayesian Network Model for Linking Management Actions, Nutrient Targets and Ecosystem Condition in the Tully Catchment, North Queensland. LWA/MDBC Project UMO43.

Sherman, B., Brodie, J., Cogle, L. and Carroll, C. 2007. The appropriate use of catchment models for water quality target setting and land use management. In: *IAHS Symposium on Water Quality and Sediment Behaviour of the Future: Predictions for the 21st Century*, 2007.

Stewart, L.K., Charlesworth, P.B., Bristow, K.L. and Thorburn, P.J., 2006. Estimating deep drainage and nitrate leaching from the root zone under sugarcane using APSIM-SWIM. *Agricultural Water Management*, **81**: 315–334.

Thayalakumaran, T., Charlesworth, P.B., Bristow, K.L., van-Bemmelen, R.J. and Jaffrés, J. 2004. Nitrate and ferrous iron concentrations in the lower Burdekin aquifers: assessing denitrification potential. SuperSoil 2004: 3rd Australian New Zealand Soils Conference, 5 – 9 December 2004, University of Sydney, Australia.

Thomas, C., Hart, B., Nicholson, A., Grace, M., Brodie, J. and Pollino, C. 2005. Development of criteria for simplifying ecological risk models. In*:* A. Zerger and R. M. Argernt (eds.). *MODSIM 2005 International Congress on Modelling and Simulation.* Modelling and Simulation Society of Australia and New Zealand, 2005: 772-778.

Thorburn, P.J., Meier, E.A. and Probert, M.E. 2005. Modelling nitrogen dynamics in sugarcane systems: Recent advances and applications. *Field Crops Research*, **92**: 337-352.

Thorburn, P.J., Webster, A.J., Biggs, I.M., Biggs, J.S., Park, S.E. and Spillman, M.F. 2007. Innovative management of nitrogen fertiliser for a sustainable sugar industry. *Proceedings Australian Society Sugar Cane Technologist*, **29**: 85-96.

Thorburn, P.J., Attard, S.J., Biggs, J.S. and Kemei, J. 2008. Farming practices to improve water quality in the Burdekin region. Submitted to 14*th* *Australian Agronomy Conference*, Adelaide, Sept 2008.

Weber, M., Lott, C. and Fabricius, K.E. 2006. Sedimentation stress in a scleractinian coral exposed to terrestrial and marine sediments with contrasting physical, organic and geochemical properties. *Journal of Experimental Marine Biology and Ecology*, **336**: 18-32.

Wolanski, E. and Spagnol, S. 2000. Pollution by mud of Great Barrier Reef coastal waters. *Journal of Coastal Research*, **16**: 1151-1156.

Wolanski, E., Fabricius, K., Spagnol, S. and Brinkman, R. 2005. Fine sediment budget on an inner-shelf coral-fringed island, Great Barrier Reef of Australia. *Estuarine, Coastal and Shelf Science*, **65**: 153-158.

Wolanski, E., Fabricius, K.E., Cooper, T.F., and Humphrey, C., 2008. Wet season fine sediment dynamics on the inner shelf of the Great Barrier Reef. *Estuarine, Coastal and Shelf Science*, **77**: 755-762.

Wooldridge, S., Brodie, J. and Furnas, M. 2006. Exposure of inner-shelf reefs to nutrient enriched runoff entering the Great Barrier Reef Lagoon: Post-European changes and the design of water quality targets. *Marine Pollution Bulletin*, **52**: 1467-1479.

Yentsch, C.S., Yentsch, C.M., Cullen, J.T., Lapointe, B., Phinney, D.A. and Yentsch, S.W. 2002. Sunlight and water transparency: cornerstones in coral research. *Journal of Experimental Marine Biology and Ecology*, **268**: 171-183.