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Accessory Publication

Details of the Bayesian Network Model Linking Nutrient Management Actions in the Tully Catchment (North Queensland) with Reef Condition

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This Accessory Publication contains the details of the Tully Bayesian Network (BN) Model.

The Tully BN model consists of three sub-models:

- Sub-model 1 – relates fertiliser (nitrogen) management with nitrate runoff and concentration in the GBR lagoon,
- Sub-model 2 – relates nitrate runoff with GBR lagoon phytoplankton biomass as a proxy for lagoon water quality,
- Sub-model 3 – relating lagoon water quality with ‘reef condition’.

A rigorous evidence-based process was employed in choosing each node in the BN. The evidence and assumptions used in the model building process as well as justification for each of the variables (nodes) in the BN model are summarised below.

Additionally, the following conditional probability tables (CPT) contain estimates derived from the literature. Where exact empirical data was not available extrapolations were used to calculate the maximum, minimum and median values. The low range was then defined as the minimum to median and the high range as the mean to maximum. Where graphical and empirical data were not available, evidence-based estimates were employed, with a focus on trends as opposed to quantitative accuracy.

Further developments of the model would employ detailed quantitative analysis and results from simulation models.

1. Sub-model 1

This model links the cane farm land management activities (*Cropping Technique, Tillage, Fertilizer Management*) with runoff into the Tully River (*Runoff TSS, Runoff P, Runoff Nitrate*), and attempts to gauge the total nutrient and sediment loads transported, and the final nitrate concentration in the GBR lagoon (*Lagoon Nitrate*). The emphasis in this model is on nitrate losses associated with nitrogen fertilizer management practices.

The node states (shown in Figure 2a of the main paper) are fully explained below, and the evidence is summarised in Table 1. The conditional probability tables derived from both the literature and expert opinion are also listed below.

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1.1 Nodes and their states

Cropping technique and tillage - Best practice cane farming techniques in Queensland involves the use of Green Cane Harvesting/Trash Blanketing (GC/TB) and minimum tillage cultivation (Brodie *et al.* 2001a). Additionally, the conversion from a burning to a GC/TB management system is likely to improve the soil organic matter and the nitrogen status of sugarcane soils (Robertson 2003). It is expected that after industry adoption of GC/TB, improved nitrate fertiliser application should be possible in the medium term, although the time scale for reducing nitrogen application will vary from site to site.

Fertilizer (nitrogen) management - The current guideline for fertilizer nitrogen application to cane fields in Queensland is an annual application of 150-200 kg N ha^{-1} of fertilizer N. Moody *et al.* (1996) have shown that for an application rate of 180 kg ha^{-1} y^{-1} of fertilizer N, about 70 kg ha^{-1} y^{-1} is taken up by the cane crop, with the remaining 110 kg ha^{-1} y^{-1} ending up in a number of environmental compartments including the atmosphere (volatilization and denitrification), groundwater, surface runoff and soil storage. The proportion lost to each compartment was found to depend on climate, weather, soil type, cultivation practices, fertilizer application practices and hydrology.

Nitrate trapping – We have assumed that nitrate can be trapped in two ways: (a) by the *Riparian vegetation* or (b) in *Wetlands*. Riparian vegetation is known to efficiently trap nitrate (Osbourne and Kovacic 2007), although the long-term removal of phosphorus is not so efficient, because it either moves through the riparian zone attached to fine sediments or is trapped as particulate phosphorus and then later released as dissolved phosphorus (Whigham *et al.* 1988). Unfortunately, much of the riparian vegetation in the Tully and Murray River catchments has been cleared, with less than 20% of coastal land systems suitable for agricultural production remaining under native vegetation. Wetlands are also known to be efficient in removing nitrate, either as biomass or through denitrification. But, most of the freshwater wetlands on the floodplains south of Cooktown have been destroyed for agricultural and urban use, for example, it is estimated that 40-60% of the wetlands on the Murray-Tully floodplains have been lost.

Runoff-P - Brodie and Mitchell (2005) have shown that phosphorus pollution of northern Australian rivers is dominated by runoff from upstream catchment lands.

Runoff sediment (TSS) - Soil erosion from cane land was recognized as a major source of sediments to river systems when the predominant cultivation technique was burnt cane harvesting (conventional cultivation). Runoff of sediment, nutrients and pesticides has increased over the years, and for most pollutants the load is estimated to be many times the natural amount discharged 150 years ago (Brodie and Mitchell 2005). However, the practice of green cane harvesting and trash blanketing and reduced tillage, has reduced soil erosion rates in sugarcane cultivation to low values, probably in the range 5–15 tonnes ha^{-1} yr^{-1} (Rayment 2003).

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Runoff nitrate - A large fraction of the nitrogen applied to cane fields eventually reaches adjacent streams and rivers, a situation Mitchell *et al.* (2001) have shown for the Tully River. Fertilizer use has been estimated to contribute an average of up to 20,000 tonne yr^{-1} of N to the GBR, or about 25% of the total nitrogen load (Brodie and Mitchell 2005). In areas of intense fertilizer use, such as the wet tropics, the majority of the dissolved inorganic nitrogen (nitrate and ammonia) transported by the rivers comes from fertilizer use (Hunter and Walton 1997, 2008; Mitchell *et al.* 1997).

1.2 Conditional probability tables

Cropping Technique	Prob*	Tillage	Prob**
Cane Burning	25	Conventional Tillage	32
Green Cane Harvesting/Trash Blanketing	75	Minimum Tillage	68

* Surveys show that 75% of growers have adopted green cane trash blanketing, which reduces soil loss from farms to levels equal to or less than soil loss from national parks or native pastures (http://www.reefplan.qld.gov.au/publications/casestudies_sugar.shtm).

** Surveys show that 68% of growers undertake minimum tillage, which improves soil condition, retains organic carbon, reduces the need for fertilisers and increases the water retention capacity of soils (http://www.reefplan.qld.gov.au/publications/casestudies_sugar.shtm).

Riparian Veg Status*	Prob	Wetland Status**	Prob
Modestly Degraded	80	Modestly Degraded	60
Highly Degraded	20	Highly Degraded	40

* The reduction of both riparian vegetation and wetland area in GBR catchments has ultimately altered the composition and nature of river runoff, increasing sediment loads and associated pollutants into the GBR marine park (Brodie *et al.* 2001). These pollutants are estimated to be many times the natural amount discharged 150 years ago (Brodie et al., 2001).

****** In the Tully and Murray River catchments, less than 20% of coastal land systems suitable for agricultural production remain under native vegetation (Tait 1994). "While we have made no attempt to evaluate the ecological status of remaining riparian and wetland areas on the Herbert floodplain in this paper, a recent ecological audit of river catchments in Queensland (Moller, 1996) has shown that the ecological condition of remaining riparian vegetation is "poor" to "very poor" and the condition of freshwater wetlands "moderate" to "poor" (Johnson et al., 1999).

Catchment Denitrification	Prob
Low	80
High	20

Riparian zone denitrification can have an important impact on downstream water quality when significant amounts of nitrate-enriched groundwater are transported at shallow depths through carbon-rich, anoxic riparian soils, at flow rates that allow enough time for the denitrification process to occur (Prange et al., 2005). Denitrification losses of 20% of applied N have been measured on clay soils in sugar- cane areas while leaching losses may occur by movement of solutes down preferential pathways (e.g. soil fauna, root channels and structural weaknesses in the soil profile) (Weier, 1994)

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Runoff/Transport
Season (Southern Hemisphere): **Wet Season: November – April**
Dry Season: May - October

Nitrate Fertilizing (kg/ha)

Fertilizer Mgmt	Tillage	Cropping Tech	Low	Med	High
Current	Conventional	Cane Burning	0	5	95
Current	Conventional	GCTB	0	10	90
Current	Minimum Till	Cane Burning	0	15	85
Current	Minimum Till	GCTB	0	20	80
Six Easy Steps	Conventional	Cane Burning	0	25	75
Six Easy Steps	Conventional	GCTB	10	20	70
Six Easy Steps	Minimum Till	Cane Burning	10	20	70
Six Easy Steps	Minimum Till	GCTB	30	50	20
Nitrogen Replace	Conventional	Cane Burning	25	30	45
Nitrogen Replace	Conventional	GCTB	30	30	40
Nitrogen Replace	Minimum Till	Cane Burning	4	3	3
Nitrogen Replace	Minimum Till	GCTB	50	45	5
N Fixation	Conventional	Cane Burning	90	5	5
N Fixation	Conventional	GCTB	90	5	5
N Fixation	Minimum Till	Cane Burning	90	5	5
N Fixation	Minimum Till	GCTB	95	5	0

The average N-application rate for six farms in the Tully/Murray rivers region was 143 kg N per hectare, with a range of 47 to 290 kg N per hectare (Faithful and Finlayson 2004). In experiments that had been running for 3–6 years (Mackay and Tully), soil organic C and total N were up to 21% greater under trash blanketing than under burning, to 0.10 or 0.25mdepth (most of this effect being in the top 50 mm) (Robertson, 2003).

Calculations of possible long-term effects of converting from a burnt to GCTB production system suggested that, at the sites studied, soil C could increase by 2-18% and soil N could increase by 4-23%, depending on soil and climatic factors, and that it could take 10-35 years for the soils to approach this new equilibrium. Inorganic soil N would be expected to increase under medium-long term GCTB, due to mineralisation of N from trash-derived organic matter, to an amount approaching the annual N return in trash. (Robertson and Thorburn, 2007).

Nitrate Trapping

Wetland	Riparian	Fertilizer Mgmnt	Denitr.	Low	High
Modestly Degraded	Modestly Degraded	Current	Low	25	75
Modestly Degraded	Modestly Degraded	Current	High	30	70
Modestly Degraded	Modestly Degraded	Six Easy Steps	Low	25	75
Modestly Degraded	Modestly Degraded	Six Easy Steps	High	30	70
Modestly Degraded	Modestly Degraded	N Replacement	Low	20	80
Modestly Degraded	Modestly Degraded	N Replacement	High	15	85
Modestly Degraded	Modestly Degraded	N Fixation	Low	5	95

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Modestly Degraded	Modestly Degraded	N Fixation	High	10	90
Modestly Degraded	Highly Degraded	Current	Low	30	70
Modestly Degraded	Highly Degraded	Current	High	35	65
Modestly Degraded	Highly Degraded	Six Easy Steps	Low	30	70
Modestly Degraded	Highly Degraded	Six Easy Steps	High	35	65
Modestly Degraded	Highly Degraded	N Replacement	Low	25	75
Modestly Degraded	Highly Degraded	N Replacement	High	20	80
Modestly Degraded	Highly Degraded	N Fixation	Low	20	80
Modestly Degraded	Highly Degraded	N Fixation	High	15	85
Highly Degraded	Modestly Degraded	Current	Low	80	20
Highly Degraded	Modestly Degraded	Current	High	75	25
Highly Degraded	Modestly Degraded	Six Easy Steps	Low	70	30
Highly Degraded	Modestly Degraded	Six Easy Steps	High	75	25
Highly Degraded	Modestly Degraded	N Replacement	Low	70	30
Highly Degraded	Modestly Degraded	N Replacement	High	60	40
Highly Degraded	Modestly Degraded	N Fixation	Low	65	35
Highly Degraded	Modestly Degraded	N Fixation	High	60	40
Highly Degraded	Highly Degraded	Current	Low	95	5
Highly Degraded	Highly Degraded	Current	High	90	10
Highly Degraded	Highly Degraded	Six Easy Steps	Low	85	15
Highly Degraded	Highly Degraded	Six Easy Steps	High	80	20
Highly Degraded	Highly Degraded	N Replacement	Low	70	30
Highly Degraded	Highly Degraded	N Replacement	High	75	25
Highly Degraded	Highly Degraded	N Fixation	Low	60	40
Highly Degraded	Highly Degraded	N Fixation	High	65	35

Runoff P (µg/L)

Cropping	**Tillage**	**Low**	**High**
Cane Burning	Conventional	10	90
Cane Burning	Minimum	15	85
GCTB	Conventional	75	25
GCTB	Minimum	85	15

Runoff TSS (mg/L)

Tillage	**Cropping Technique**	**Low**	**High**
Conventional Tillage	Cane Burn	5	95
Conventional Tillage	GCTB	20	80
Minimum Tillage	Cane Burn	70	30
Minimum Tillage	GCTB	75	25

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Low TSS concentrations in the cane areas could reflect the increasing use of green harvesting, trash blanketing and minimal tillage that is being adopted by farmers in an attempt to reduce soil erosion (ACTFR, 2007). If zero tillage is adopted as a management practice, soil erosion is reduced and this could be attributed to the undisturbed and compacted nature of the soil surface (Weier, 1994). In contrast, green cane harvesting/trash blanketing (GCTB) using minimum tillage can result in dramatically lower soil erosion rates (average losses of 10 tonnes/ha/year) (www.daff.gov.au).

Runoff Nitrate

Nitrate Fert (kg/ha)	Nitrate Trapping	Low	Med	High
Low	Low	80	10	10
Low	High	90	5	5
Med	Low	10	20	70
Med	High	70	20	10
High	Low	10	10	80
High	High	5	25	70

Soil erosion is a highly variable and often significant source of N loss from cultivated cropping systems ranging from 1 to 100 kg N ha- 1 yr- 1 and seriously affects > 80% of the cropping lands in Queensland (Weier, 1994).

River Flow (ML/day)

The seasonal discharge pattern shows a clear 'wet season' from December to May and the 'dry season' from June to November. The lowest discharge is in October, despite a significant increase in rainfall this month, presumably due to low runoff during this period (ACTFR, 2007).

P Limited Lagoon

Runoff P (ug/L)	River Flow (mg/L)	Runoff TSS	Yes	No
Low	Low	Low	-	-
Low	Low	High	-	-
Low	High	Low	20	80
Low	High	High	15	85
High	Low	Low	-	-
High	Low	High	-	-
High	High	Low	15	85
High	High	High	10	90

Lagoon Nitrate Discharge (µg/L)

River Flow (ML/Day)	Runoff Nitrate (µg/L)	Low	Medium	High
Low	Low	-	-	-
Low	Medium	-	-	-
Low	High	-	-	-
High	Low	75	20	5
High	Medium	25	50	25

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High	High	0	20	80

DIN and more specifically nitrate, in river waters have proven very effective indicators of the degree of catchment development associated with fertiliser use and human population numbers (Caraco and Cole, 1999). Clear relationships have been developed showing linear increases in nitrate concentrations (and loads) with catchment inputs (Brodie and Mitchell, 2005)

2. Sub-model 2 - Lagoon water quality

This sub-model takes the nutrient inputs to the GBR lagoon from the Tully River sub-model and combines these with other relevant parameters (e.g. *Lagoon Water Temperate, Lagoon Light Limited*) to predict phytoplankton biomass (*Lagoon Phytoplankton Biomass*).

The node states (shown in Figure 2b of the main paper) are fully explained below, and the evidence is summarised in Table 2. The conditional probability tables derived from both the literature and expert opinion are also listed below.

2.1 Nodes and their states

Lagoon nitrate - Furnas *et al.* (1995) found that the availability of dissolved inorganic nitrogen usually limits phytoplankton growth in the GBR lagoon. For this reason, when Wooldridge *et al.* (2006) modelled phytoplankton growth in the GBR lagoon, they assumed that dissolve inorganic nitrogen (DIN) was the most influential nutrient in driving chlorophyll-a (Chl-a) concentrations, and that the river-specific load of DIN entrained within runoff plumes would initiate a quantifiable signal in the ‘local’ phytoplankton response.

P-limited lagoon - The growth of phytoplankton (and probably benthic algae) in GBR lagoon waters appears to be generally constrained by nitrogen availability rather than by phosphorus (or silicate) (Furnas and Mitchell 1999; Furnas *et al.* 2005), since algal growth requires 16 times more N than P (Redfield ratio).

Lagoon water temperature and Lagoon light - Coral bleaching occurs when the zooxanthellae are lost and the white calcium carbonate skeleton of the coral becomes visible. Bleaching is a general stress response when corals are exposed to extremes of temperature, UV radiation, salinity and pollutants (Hughes and Connell 1999). Additionally, substantial loss in coral cover, due to anomalously warm water, has occurred throughout the world’s coral reefs during the past three decades (Sheppard *et al*. 2002).

Phytoplankton biomass - Measures of phytoplankton biomass usually provide a better indicator of the nutrient status of reef waters than measured nutrient concentrations, since fast growing phytoplankton populations quickly deplete the concentration of dissolved inorganic nutrients, resulting in localised ‘blooms’ in population densities (Wooldridge *et al.* 2006).

As McCook (2001) pointed out, algae are widely considered to compete with corals for space (or light) and the interactions between the two are frequently interpreted in terms of algal competitive superiority, often due to reduced herbivory or increased nutrient availability. For coral reef macro-algae, attention has focused on two factors: (a) water quality, particularly the nutrients nitrogen and phosphorus, and (b) herbivory (e.g. Littler *et al*. 2005).

2.2 Conditional probability tables

Lagoon Light Limited

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Yes	No
5	95

Lagoon Water Temperature (^{o}C)

Low	Med	High
10	80	10

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Lagoon Phytoplankton Biomass (ug/L)

P Limited Lagoon	Nitrate Discharge (ug/L)	Light Limited	Lagoon Water Temp (^oC)	0-0.5	0.5-0.8	0.8-1.0
Yes	Low	Yes	Low	95	5	5
Yes	Low	Yes	Medium	85	10	5
Yes	Low	Yes	High	85	10	5
Yes	Low	No	Low	75	20	5
Yes	Low	No	Medium	75	20	5
Yes	Low	No	High	75	20	5
Yes	Medium	Yes	Low	85	10	5
Yes	Medium	Yes	Medium	85	10	5
Yes	Medium	Yes	High	85	10	5
Yes	Medium	No	Low	75	20	5
Yes	Medium	No	Medium	70	30	0
Yes	Medium	No	High	65	30	5
Yes	High	Yes	Low	60	30	10
Yes	High	Yes	Medium	10	60	30
Yes	High	Yes	High	20	60	20
Yes	High	No	Low	75	20	5
Yes	High	No	Medium	70	30	0
Yes	High	No	High	60	35	5
No	Low	Yes	Low	40	55	5
No	Low	Yes	Medium	35	50	15
No	Low	Yes	High	30	40	30
No	Low	No	Low	20	60	20
No	Low	No	Medium	10	50	30
No	Low	No	High	5	40	55
No	Medium	Yes	Low	60	20	20
No	Medium	Yes	Medium	60	20	20
No	Medium	Yes	High	60	20	20
No	Medium	No	Low	5	20	75
No	Medium	No	Medium	5	15	80
No	Medium	No	High	5	10	85
No	High	Yes	Low	60	20	20
No	High	Yes	Medium	60	20	20
No	High	Yes	High	60	20	20
No	High	No	Low	5	15	80
No	High	No	Medium	5	10	85

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No	High	No	High	5	5	90

For the lagoonal waters of the GBR, previous studies have shown that that the availability of DIN usually limits phytoplankton biomass (Furnas et al., 2005), and that the dilution of DIN across the runoff:seawater mixing zone follows an essentially conservative mixing process (Devlin and Brodie, 2005).

3. Sub-model 3 - Reef condition

This sub-model assumes that four factors influence the health of coral reefs – *Phytoplankton Biomass, Bleaching Events, Crown of Thorns* and *Reef Herbivory*. The model links the catchment activities (on-farm nitrate fertilizer loads and transport of DIN by the Tully River) to reef condition via the *Phytoplankton Biomass*. This model predicts the probability that the in-shore reefs are either coral dominated (good) or algal dominated (bad).

3.1 Nodes and their states

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Crown of Thorns - It is well known that larval crown of thorns starfish (*A. planci*) eat larger-sized phytoplankton and that young crown of thorns starfish eat encrusting (coralline) algae, which is common among rocks and rubble on the reef (Brodie *et al.* 2005). At about six months of age, they start to eat coral and begin to grow more rapidly, and over the next two years, the starfish can grow from about 1 cm to about 25 cm in diameter. Crown of thorns starfish are the cause of large-scale coral mortality on the reefs of the central GBR (Lizard Island to Mackay). Brodie *et al.* (2005) provided evidence that suggests the frequent crown of thorn starfish outbreaks on the GBR may result from increased nutrient delivery from the land. Nutrient discharges from rivers have increased at least 4-fold in the central GBR over the last century, and concentrations of large phytoplankton (>2 um) in the inshore central GBR shelf in the wet season when *A. planci* larvae develop, is double that in other places and times. Further, the development, growth and survival of *A. planci* increases almost 10-fold with a doubling in the concentrations of these large phytoplankton.

Reef herbivory - Herbivorous fish are known to graze on algae in the GBR, with up to 50% of the algal production removed by grazers (Hatcher and Rimmer 1985; McCook 1999; *Hughes et al.* 2007). Further, at present herbivorous fish are not heavily fished in the GBR, but if their numbers were reduced (e.g. by over-fishing) this could have a major impact on net algal production. There is some possibility that grazing fish are already depleted on inshore GBR reefs due to water quality effects (Fabricius 2005) and this correlation has been noted in other regions (e.g. Mallela *et al.* 2007 in the Caribbean). Thus, management of nutrient runoff from the GBR catchment may be effective in reducing algal abundance on reefs, but only as long as herbivorous fish remain abundant (McCook 1999).

Bleaching events - The factors that most influence coral bleaching are high irradiance, low flow and low water turbidity, especially in combination with high water temperatures (Nakamura and Van Woesik 2001). For the Tully BN, we have assumed that *Bleaching Severity* is influenced by *Lagoon Water Temperature* and *Lagoon Light Level*. At present there is considerable uncertainty regarding these processes, since sea temperature is difficult to quantify (Fitt *et al.* 2001) and bleaching itself is highly subjective and also difficult to quantify (Fabricius 2006). However, as further data and knowledge is obtained it can be incorporated into the model to improve the predictions.

Reef condition - The growth of macro-algae, such as Sargassum, which is often abundant on inner shelf reefs of the GBR (McCook and Price 1997), is known to respond to nutrient enrichment (Schaffelke and Klump 1997). As noted above, degrading reefs often undergo a change of state in which the abundance of corals declines, and the composition of macro-algae changes, with an increase in abundance of larger, fleshy (corticated) macro-algae (Done 1992). Benthic macro-algae play an important role on both healthy and degraded coral reefs, and the abundance and composition of reef macro-algae are critical to the ecological, aesthetic and socio-economic value of coral reefs (McCook 1999).

The two factors that have the greatest potential to cause these phase shifts are: (a) reduction in herbivoury due to over-fishing, and (b) eutrophication or increases in nutrient and/or sediment inputs due to human land-use (McCook 1999). On the GBR, there is particular concern that an abundance of macro-algae on inshore fringing reefs suggest degradation due to increases in terrestrial inputs of sediments and nutrients (McCook and Price 1997).

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With conditions of very high nutrient input and low rates of flushing, the phytoplankton-based food-web appears to replace the benthic algal-based food-web. Ryther (1969) has been calculated that if phytoplankton reach a density of 2 ug L^{-1}, a compensation depth originally at 100 m depth would be moved to 3.5 m depth. In effect, the benthic algal community, and the food-web it supports, would be eliminated below 3.5 m. Phytoplankton could also reduce the amount of nutrients in the water column available to the benthic algae. In the northern Gulf of Thailand, where there are large amounts of river drainage and terrestrial runoff, the coral communities had very little fleshy and filamentous benthic algae below 4 m depth (Kamura and Choonhabandit 1986; Tsuchiya *et al.* 1986). In this system, schooling herbivorous fishes were completely absent, despite the adequacy of the habitat for other fishes.

In summary, there is now a considerable body of empirical data showing that under most circumstances, algal standing crop on coral reefs is maintained at low levels by intense grazing by herbivorous fish, often despite relatively high rates of tissue production (Hatcher 1983). Algal-dominated reefs usually have lower fish stocks (McCook 1999), one of the basis for the Relative Dominance Model (Littler *et al.* 2005).

3.2 Conditional probability tables

Reef Herbivory

Reef Herbivory*	Prob	Crown of Thorns**	Prob
Modestly Depleted	75	Yes	95
Severely Depleted	25	No	5

* The best-protected reefs on the Great Barrier Reef, are the closest to pristine (Pandolfi et al., 2003).

** The crown-of-thorns starfish breed from December to April when water temperature is about 28ºC. In 1999-2000, the highest densities of starfish were recorded in the region between Cairns and Townsville (**http://www.aims.gov.au/monmap/monmap.htm**).

Bleaching Event

Lagoon Light Limited	Lagoon Water Temp	Minor	Moderate	Major
Yes	Low	30	50	25
Yes	Medium	20	50	25
Yes	High	5	55	40
No	Low	35	25	40
No	Medium	30	50	20
No	High	0	10	90

There are numerous combination of temperature and exposure time [light] that lead to mortality (Fitt et al., 2001). In most cases bleaching has been attributed to elevated temperature, but other instances involving high solar irradiance, and sometimes disease, have also been documented (Brown, 1997).

Reef Condition

Crown of	Lagoon Phytoplankton	Reef Herbivory	Bleaching Event	Coral Dominated	Algal Dominated

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Thorns present	Biomass (μg/L)				
Yes	0 to 0.5	Modestly Depleted	Minor	40	60
Yes	0 to 0.5	Modestly Depleted	Moderate	35	65
Yes	0 to 0.5	Modestly Depleted	Major	30	70
Yes	0 to 0.5	Severely Depleted	Minor	40	60
Yes	0 to 0.5	Severely Depleted	Moderate	35	65
Yes	0 to 0.5	Severely Depleted	Major	30	70
Yes	0.5 to 0.8	Modestly Depleted	Minor	20	80
Yes	0.5 to 0.8	Modestly Depleted	Moderate	15	85
Yes	0.5 to 0.8	Modestly Depleted	Major	10	90
Yes	0.5 to 0.8	Severely Depleted	Minor	20	80
Yes	0.5 to 0.8	Severely Depleted	Moderate	15	85
Yes	0.5 to 0.8	Severely Depleted	Major	10	90
Yes	0.8 to 1	Modestly Depleted	Minor	20	80
Yes	0.8 to 1	Modestly Depleted	Moderate	15	85
Yes	0.8 to 1	Modestly Depleted	Major	10	90
Yes	0.8 to 1	Severely Depleted	Minor	20	80
Yes	0.8 to 1	Severely Depleted	Moderate	15	85
Yes	0.8 to 1	Severely Depleted	Major	10	90
No	0 to 0.5	Modestly Depleted	Minor	90	10
No	0 to 0.5	Modestly Depleted	Moderate	80	20
No	0 to 0.5	Modestly Depleted	Major	70	30
No	0 to 0.5	Severely Depleted	Minor	90	10
No	0 to 0.5	Severely Depleted	Moderate	80	20
No	0 to 0.5	Severely Depleted	Major	70	30
No	0.5 to 0.8	Modestly Depleted	Minor	90	10
No	0.5 to 0.8	Modestly Depleted	Moderate	80	20
No	0.5 to 0.8	Modestly Depleted	Major	70	30
No	0.5 to 0.8	Severely Depleted	Minor	50	50
No	0.5 to 0.8	Severely Depleted	Moderate	40	60
No	0.5 to 0.8	Severely Depleted	Major	30	70
No	0.8 to 1	Modestly Depleted	Minor	50	50
No	0.8 to 1	Modestly Depleted	Moderate	40	60
No	0.8 to 1	Modestly Depleted	Major	30	70
No	0.8 to 1	Severely Depleted	Minor	50	50
No	0.8 to 1	Severely Depleted	Moderate	40	60
No	0.8 to 1	Severely Depleted	Major	30	70

Biological communities in the GBR are subject to a range of natural and anthropogenic stressors including cyclones, crown of thorns starfish (COTS), temperature bleaching, fishing, tourism and

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pollutants from adjacent catchments (Brodie, 2003). Larval development, growth and survival increase almost ten-fold with doubled concentrations of large phyto-plankton. This and other lines of evidence suggest that frequent *A. planci* outbreaks on the GBR may indeed be a result of increased nutrient delivery from the land. (Brodie et al., 2006)It is now believed that outbreaks of A. planci are associated with broad scale nutrient enrichment from land runoff and subsequent phytoplankton blooms leading to enhanced survivorship of *A. planci* larvae (Brodie et al..,2004**).** The critical chlorophyll concentration range at which larval survivorship becomes significantly enhanced is 0.5–0.8 ug l^{-1} (Brodie et al., 2004). It is thus possible to use a chlorophyll concentration of 0.5 ug l^{-1} in the larval period of *A. planci* (November to February) as a threshold guideline (Moss et al., 2005).

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Table 1: Nodes and node states for sub-model 1

Node Name	Node Definition	Node States	References
Fertilizer Management	Describes various nitrate fertilizer strategies that can be implemented on cane farms	Current Six Easy Steps Nitrogen Replacement Nitrogen Fixation	Schroeder et al. 2007 Thorburn 2004
Land Use Activity ***- Cropping Technique*** ***- Tillage***	Describes the major land use methods employed on cane farms in the wet tropics area of Queensland	Cane Burning Green Cane Harvesting/Trash Blanketing Conventional Tillage Minimum Tillage	Robertson 2003
Nitrate Fertilizing	Annual amount of nitrate fertilizer applied to cane fields - kg(N) ha^{-1} y^{-1}	Low = 0 - 20 Medium = 80 - 140 High = 150 - 200	Faithful and Finlayson 2005 Mitchell et al. 2007 Rayment 2003
Nitrate Trapping	Describes the amount of nitrate trapped or transformed before entering the river as runoff	Low High	Mitchell et al. 2007
Riparian Vegetation	Describes the condition of the river riparian vegetation	Modestly Degraded Highly Degraded	Johnson et al. 1999 McKergow et al. 2004
Wetland Status	Describes the condition of catchment wetlands	Modestly Degraded Highly Degraded	Kotzli and Grootjans 2001
Catchment Denitrification Efficiency	Denitrification efficiency as the percent of the ammonia that is produced by organic matter remineralization in the sediment which is released to the atmosphere as N_2 gas	Low = 0 – 10% Medium = 10 – 30% High = 30 – 100%	http://www.per.marine.csiro.au Prange 2005
Runoff P	Describes the concentration of phosphorous in the agricultural runoff The focus of the model is on nitrate given the nature of P in the regional waters under consideration in this report	Low = 0-50 High = 50-100	Faithfull and Finlayson 2005 Faithfull et al. 2006 Schoonover et al. 2005
Runoff TSS	Describes concentration of total suspended solids in the agricultural runoff in mg/L	Low = 0-75 High = 75-125	Faithfull and Finlayson 2005 McCulloch et al. 2003 McKergow et al. 2005

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Runoff Nitrate	Describes the concentration of nitrate (DIN) in the agricultural runoff in µg N/L	Low = 0 - 4000 Medium = 4000 - 8000 High = 8000 - 12000	Faithfull et al. 2006, 2007 Faithfull et al. 2006 Mitchell et al. 2007 Davis and Koop 2006
River Flow	Describes the daily volume of water transported (ML/season)	Low High (NB – This study only consider high flow conditions)	Faithfull et al. 2007 Viney et al. 2000
P Limited Lagoon	Indicates whether the lagoon in phosphorus limited.	Yes No	Wooldridge et al. 2006
Lagoon Nitrate	Node describes the concentration of DIN in the river discharged into the Lagoon (µg/L) per season	Low = 0 - 150 Medium = 150 - 250 High = > 250	Wooldridge et al. 2006 Mitchell et al. 2007 Devlin and Brodie 2005

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Table 2: Nodes and node states for sub-model 2

Node Name	Node Definition	Node States	References
Lagoon Water Temperature	Node defines the average temperature of the Lagoon. The scale is chosen with coral bleaching temp as a mutual temperature threshold	Low = 0-19 Degrees Medium = 20-30 Degrees High = >30 Degrees	McClanahan and Maina 2003
Lagoon Light Limitation	Node establishes if the Lagoon is light limited with respect to phytoplankton growth	Yes No	Fabricius 2006
Phytoplankton Biomass	Concentration of Chlorophyll a (µg/L)	0-0.6 µg/L 0.6-0.8 µg/L 0.8-1.0 µg/L These ranges are chosen with respect to conditions that favour the growth of CoT starfish	Wooldrige et al. 2006 Grace et al. 1997 Lapointe et al. 1997

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Table 3: Nodes and node states for sub-model 3 (Reef Condition)

Node Name	Node Definition	Node States	References
Crown of Thorns	The presence of the Crown of Thorn (CoT) Starfish on the reef	**Yes** = CoT detected on reef **No** = CoT not detected on reef	Brodie et al. 2005
Reef Herbivory	Reef herbivory represents all species algal grazers (fish, sea urchins etc) Defines the reduction in Herbivory due to overfishing and/or disease	**Modestly Depleted** = Little or no reduction in natural reef herbivory **Severely Depleted** = Algal grazing species low due to disease and/or overfishing	McCook 1999
Bleaching Event Severity	Defined as the reduction of densities on symbiotic dinoflagellates	**Minor**: reliable reports of low coral bleaching (1–10% of colonies completely white) **Moderate:** reliable reports of moderate coral bleaching (10–50% of colonies completely white) **Major**: reliable reports of severe to extreme bleaching (>50% of colonies completely white)	Fabricius 2006 Fitt et al. 2001 Criteria defined by the Great Barrier Reef Marine Park Authority http://www.gbrmpa.gov.au Brown 1997
Reef Condition	The reef 'ecosystem condition' is defined by the reef coral:macroalgae ratio (see for example Done (1992) "Degrading reefs often undergo a "phase shift" in which the abundance of corals declines, and the composition of macroalgae changes, with an increase in abundance of larger, fleshy (corticated) macroalgae "	**Coral Dominated** **Algal Dominated**	McCook 1999 Littler et al. 2006

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