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# The expected impact of climate change on nitrogen losses from wet tropical sugarcane production in the Great Barrier Reef region

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**Abstract.** The Great Barrier Reef is under threat from diffuse agricultural pollutants and potential climate change. Nitrogen loads are examined using the nitrogen surplus of simulated sugarcane production systems in the Tully–Murray catchment, comparing current management practice regimes with best management practice regimes under present day and future climate scenarios – nominally 2030 and 2070. These future scenarios are represented by increased carbon dioxide, increased temperature and increased rainfall variability. Simulation results suggest that the impact of potential climate change on diffuse agricultural nitrogen loads from sugarcane production in the Tully–Murray catchment to the Great Barrier Reef is likely to be small and negligible in comparison to the impacts of management practice change. Partial gross margin analysis suggests climate change will not noticeably alter the profitability of sugarcane production and, hence, is unlikely to be a driver of change for this land use in the Tully–Murray catchment. Improvements in water quality from sugarcane production are more likely to come from identification and adoption of best management practices.

**Additional keywords:** agriculture, APSIM, crop model, dissolved inorganic nitrogen, modelling, nitrogen surplus, wet tropics.

## Introduction

The World Heritage-listed Great Barrier Reef, stretching along the north-eastern Australian coast, has outstanding environmental (Lucas *et al*. 1997) and economic (Access Economics 2005) values. To help protect these environmental values, and hence its potential to provide economic benefits, the Queensland and Australian Governments developed the Reef Water Quality Protection Plan (Anonymous 2003). This plan has the explicit goal 'to halt and reverse the decline in water quality entering the Reef within 10 years', specifically targeting anthropogenic sources of sediments, nutrients and pesticides in waters entering the Great Barrier Reef lagoon.

Nitrogen (as nitrate) has been identified as a priority terrestrially sourced pollutant for Great Barrier Reef receiving waters (Brodie and Mitchell 2005), with elevated concentrations having the potential to degrade reef ecosystems (Brodie *et al*. 2005). Nitrates originating from agricultural fertiliser use have been detected in waters draining into the Great Barrier Reef lagoon (Bramley and Roth 2002), with current nitrate losses to the Great Barrier Reef estimated to be three to five times higher than what occurred before European settlement (Brodie *et al*. 2003).

The Tully–Murray catchment, in the wet tropics bioregion of northern Queensland, drains into the Great Barrier Reef lagoon. The floodplain of the Tully–Murray catchment is characterised by high, summer-dominant rainfall (average 4082 mm, Bureau of Meteorology 2008), and is used extensively for agriculture, with sugarcane – the major cropping system – occupying ~30 000 ha. Measured nitrate levels in the Tully River have been increasing over the same time period in which the agricultural area (including sugarcane) has been increasing in the catchment (Mitchell *et al*. 2001).

Sugarcane is fertilised annually with nitrogenous fertilisers in the order of 150+ kg nitrogen per hectare (Calcino *et al*. 2000). Not all applied nitrogen is utilised by the sugarcane crop (Thorburn *et al*. 2003*b*), and losses of nitrogen from sugarcane production systems have been detected in surface water (Reghenzani *et al*. 1996; Bengtson *et al*. 1998; Ng Kee Kwong *et al*. 2002) and groundwater (Rasiah *et al*. 2003*a*, 2003*b*; Thorburn *et al*. 2003*a*; Stewart *et al*. 2006).

A tool for reducing the impact of agricultural production systems on downstream water quality is the identification and implementation of best management practices (Anderson and Flaig 1995). Adoption of agricultural best management practices for improved water quality, specifically targeting a reduction in nitrogen losses from sugarcane production, is an integral part of the Tully–Murray Water Quality Improvement Plan (Kroon 2009).

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**Table 1. Projected seasonal climate extremes (#1 and #3) and average (#2) for rainfall (R1 to R3) and temperature (T1 to T3) for 2030 and 2070 in the Tully–Murray catchment (Cai *et al.* 2005)**

| Months | 2030 | | | | | | 2070 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rainfall (% change) | | | Temperature (°C change) | | | Rainfall (% change) | | | Temperature (°C change) | | |
| | R1 | R2 | R3 | T1 | T2 | T3 | R1 | R2 | R3 | T1 | T2 | T3 |
| Dec, Jan, Feb | −7 | +3 | +13 | +0.2 | +0.90 | +1.6 | −20 | +10 | +40 | +0.7 | +2.75 | +4.8 |
| Mar, Apr, May | −13 | −3 | +7 | +0.2 | +0.75 | +1.3 | −40 | −10 | +20 | +0.7 | +2.75 | +4.8 |
| Jun, Jul, Aug | −20 | −10 | 0 | +0.2 | +0.75 | +1.3 | −60 | −30 | 0 | +0.7 | +2.35 | +4.0 |
| Sep, Oct, Nov | −20 | −10 | 0 | +0.2 | +0.90 | +1.6 | −60 | −30 | 0 | +0.7 | +2.75 | +4.8 |

Recent studies have demonstrated that elevated dissolved inorganic nitrogen loads in the Great Barrier Reef lagoon may increase the propensity of reef thermal bleaching impacts (Wooldridge 2009). Thus, the effects of terrestrial run-off on the Great Barrier Reef are likely to interact with those of climate change. Moreover, climate change may also impact agricultural production (e.g. Ingram *et al*. 2008), and the impact of agriculture on water quality (Bouraoui *et al*. 2004; Wilby *et al*. 2006). The predictions for the future Australian climate include increased levels of atmospheric carbon dioxide ($CO_2$), more variable annual rainfall, increased average temperatures, sea level rises, increased evaporation, enhanced drying associated with El Niño events, and increased cyclone intensity and frequency (CSIRO 2001). However, the relationship between climate change, agricultural production and the mitigation of water pollutant delivery remains largely untested. The present paper investigates the impact of potential climate change scenarios (elevated $CO_2$, increased temperature and increased variability of rainfall) on sugarcane productivity, partial gross margin and potential nitrogen losses for current and best management practice regimes.

## Methods

To assess the impact of climate change scenarios on current and best management practice regimes in sugarcane production, Intergovernmental Panel on Climate Change (IPCC)-based climate change scenarios are defined (Cai *et al*. 2005) for use in the Agricultural Production System Simulator (APSIM) cropping system simulation model (Keating *et al*. 2003). Subsequently, yield, gross margin and nitrogen loss indicators are determined and analysed.

### Climate change scenarios

Projections for atmospheric variation in $CO_2$ suggest concentrations will rise from present-day levels of ~375 ppm to the range of 425–449 ppm in 2030 and 518–702 ppm in 2070 (McCarthy *et al*. 2001). Potential changes in seasonal (Dec–Feb; Mar–May; Jun–Aug; Sep–Nov) rainfall and temperature for the years 2030 and 2070, in comparison with averages over the 1961 to 1990 period, have been estimated for all areas of Queensland by Cai *et al*. (2005) including the Tully–Murray region, which is also the study area of the present study (Table 1).

Climate change for two future scenarios (nominally 2030 and 2070) was modelled, with each future scenario represented by an elevated atmospheric $CO_2$ concentration, three rainfall scenarios and three temperature scenarios. Modelled atmospheric $CO_2$ levels were determined by taking the average of the range of $CO_2$ projected for 2030 (437 ppm) and 2070 (610 ppm) by McCarthy *et al*. (2001). Rainfall and temperature scenarios for 2030 and 2070 were determined by multiplying baseline climate data for Tully (17.94°S, 145.93°E) by the extremes presented by Cai *et al*. (2005) (Table 1) as well as by the average of these extremes. Climate scenarios are defined for low (#1), average (#2) and high (#3) projections for rainfall (R#) and temperature (T#), giving nine (a matrix of three rainfall by three temperature) climate scenarios for each of 2030 and 2070.

### Cropping system simulation

The APSIM (v5.1) cropping systems model (Keating *et al*. 2003) was used to simulate whole-crop water and nitrogen balances. The model configuration consisted of modules for soil nitrogen and carbon (APSIM-SoilN; Probert *et al*. 1998), soil water (APSIM-SoilWat; Probert *et al*. 1998), sugarcane growth (APSIM-Sugarcane; Keating *et al*. 1999) and sugarcane residue dynamics (APSIM-SurfaceOM; Thorburn *et al*. 2001).

The sugarcane module uses intercepted radiation to produce assimilates, which are partitioned into the plant components and sugar. These processes are responsive to radiation and temperature, as well as water and nitrogen supply. Elevated concentrations of atmospheric $CO_2$ were modelled by multiplying the default transpiration efficiency and radiation use efficiency coefficients by the $CO_2$ factors produced using Eqns 1 and 2 (Park *et al*. 2007) where *CO2* is the predicted atmospheric $CO_2$ for each year.

$$Transpiration\_Efficiency = 0.0008 \times CO2 + (1 - 0.0008 \times 350) \quad (1)$$

$$Radiation\_Use\_Efficiency = 0.000143 \times CO2 + 0.94995 \quad (2)$$

Farming operations were specified through the APSIM-Manager and Operation modules. Climate data for the crop model was obtained from the Queensland Department of Natural Resources Enhanced Meteorological Dataset (Jeffrey *et al*. 2001).

All simulations used a common soil parameter file based on a well drained medium to heavy clay soil of alluvial origin, which is a common type of soil in the Tully–Murray catchment (Murtha 1994).

All simulations of the sugarcane crop cycle started with a plant crop planted in the second week of June, which was harvested in the middle of September the following year. The crop

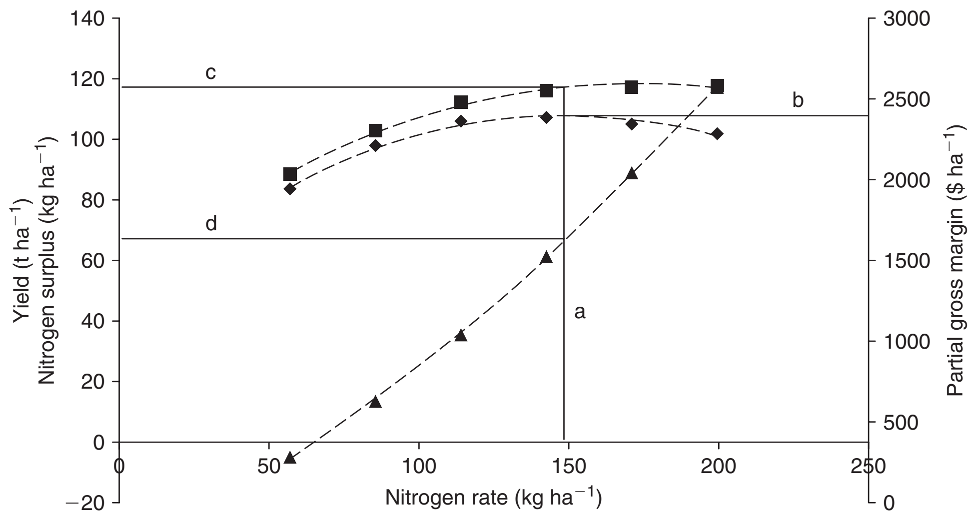


**Fig. 1.** Simulated yield (■), partial gross margin (♦) and nitrogen surplus (▲) for current management practices at the baseline climate. Dashed lines represent quadratic curves of best fit (yield = $-0.0023\chi^2 + 0.7713\chi + 52.582$, partial gross margin = $-0.053\chi^2 + 15.727\chi + 1235.7$, nitrogen surplus = $0.0016\chi^2 + 0.4601\chi - 36.808$). The optimised partial gross margin is obtained at the optimal nitrogen application rate of 148 kg N $ha^{-1}$ (line a) and corresponds to a partial gross margin of \$2402 $ha^{-1}$ (line b), a yield of 116 t $ha^{-1}$ (line c) and a nitrogen surplus of 67 kg N $ha^{-1}$ (line d).

was ratooned and harvested another year later in the middle of September. A total of four ratoons were simulated in each crop cycle with harvest in the middle of September for all except the final harvest, which occurred in the first week of November. After harvest, all crop residue was returned to the soil surface. Where a legume fallow was simulated, the planting date was the middle of December following the fourth ratoon harvest and was terminated in the second week of the following May. Legume residue was left on the soil surface before another crop cycle commencing in the second week of June. Bare fallow simulations followed the same time sequence without a legume crop planted. To reach a point of equilibrium in soil carbon and nitrogen, the first two crop cycles were excluded from the dataset. In total, 16 crop cycles were included in the dataset, simulating sugarcane cropping over 95 years using base climate for the period 1910 to 2005.

APSIM was used to simulate two management practice regimes, representing: (a) the commonly practiced current management system for sugarcane production in the Tully–Murray catchment; and (b) the best management system that industry stakeholders perceive would deliver economic and environmental sustainability to the Tully–Murray catchment sugarcane industry (Roebeling and Webster 2007). The two management systems were differentiated by tillage level, fallow management and nitrogen application rate. The current management system simulation was characterised by tillage before planting, a bare fallow management between crop cycles and nitrogen management that applies 75% of the nitrogen application rate to the plant crop. The best practice management system was characterised by zero tillage, a legume fallow between crop cycles and zero nitrogen application to plant crops. Both management systems included six nitrogen application rates in 30 kg $ha^{-1}$ increments between 60 and 210 kg N $ha^{-1}$, with the optimal nitrogen application rate determined for each scenario by optimisation as described below.

### *Analysis*

Yields of all simulated years for a specific management combination and nitrogen application rate were averaged. Yield response to nitrogen application rate was plotted and a curve of best fit applied using a quadratic equation (Fig. 1).

Partial gross margin was determined for all averaged yields of a management system and nitrogen application rate combination based on Eqn 3, where *Yield* is the averaged yield for all years (t $ha^{-1}$) and *NRate* is the nitrogen application rate (kg $ha^{-1}$) to achieve that yield. Based on Roebeling *et al.* (2007), we assume growers receive \$30 for a tonne of cane, nitrogen costs \$2.4 per kilogram and harvesting costs to be \$6.5 per tonne of cane.

$$Partial\_Gross\_Margin\ (\$\,ha^{-1}) = (Yield \times 30) - (NRate \times 2.4) - (Yield \times 6.5) \quad (3)$$

Partial gross margins were plotted against nitrogen application rate and a curve of best fit applied using a quadratic equation (Fig. 1).

The method for estimating potential nitrogen losses from sugarcane production systems is the nitrogen surplus – the difference between applied nitrogen and the nitrogen exported in produce (van Eerdt and Fong 1998). Nitrogen surpluses were determined for each nitrogen application rate by management system combination using Eqn 4 where *NRate* is the nitrogen application rate (kg $ha^{-1}$) and *Yield* is the averaged yield for all years (t $ha^{-1}$). It is assumed that 0.7 kg of nitrogen is exported from the block in every tonne of harvested cane, based on nitrogen concentrations in harvested cane measured by Thorburn *et al.* (2009).

$$Nitrogen\_Surplus\ (kg\,ha^{-1}) = NRate - (Yield \times 0.7) \quad (4)$$

Nitrogen surplus was plotted against nitrogen application rate and a curve of best fit applied using a quadratic equation (Fig. 1).

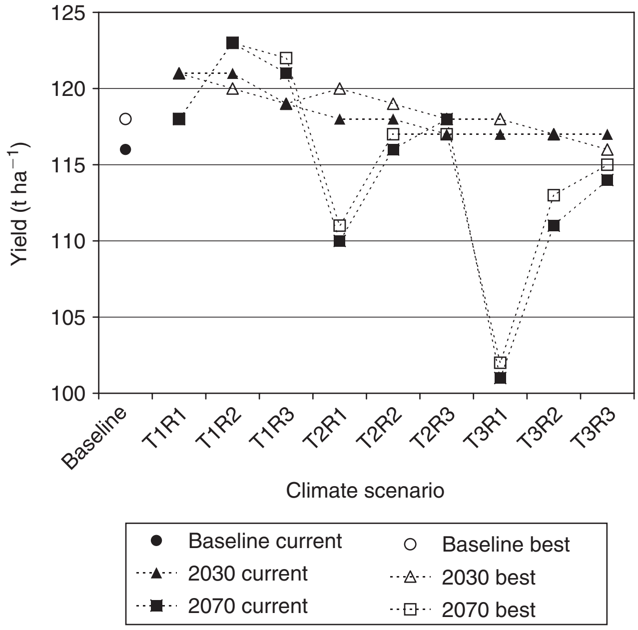


**Fig. 2.** Sugarcane yield (t ha$^{-1}$) predictions for current and best management practices under current (baseline) and projected 2030 and 2070 climates scenarios. T1, T2 and T3 represent the low, average and high temperature projections for 2030 and 2070, respectively, and R1, R2 and R3 represent the low, average and high rainfall projections for 2030 and 2070, respectively (see Table 1).

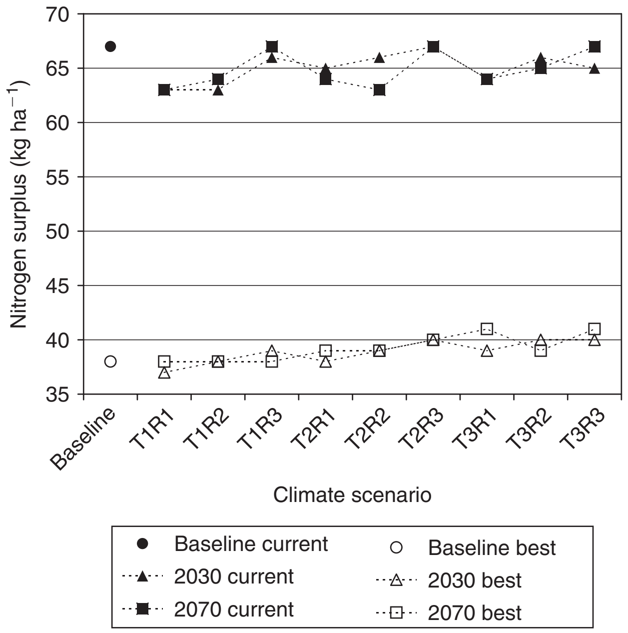


**Fig. 3.** Nitrogen surplus (kg N ha$^{-1}$) predictions for current and best management practices under current (baseline) and projected 2030 and 2070 climates scenarios. T1, T2 and T3 represent the low, average and high temperature projections for 2030 and 2070, respectively, and R1, R2 and R3 represent the low, average and high rainfall projections for 2030 and 2070, respectively (see Table 1).

The optimal nitrogen application rate was defined for each scenario as the rate at which the highest partial gross margin was achieved (determined by solving the maximum point on the partial gross margin quadratic curve of best fit). The nitrogen surplus and yield at this nitrogen application rate was then calculated from the respective quadratic curves of best fit for each scenario (Fig. 1).

## Results

In all climate scenarios, the optimal nitrogen application rate is appreciably less for best management practices than in the current management practices. The 2030 climate scenarios made very little difference to optimal nitrogen application rates, ranging between 147 and 150 kg N ha$^{-1}$ for current management practices and 121 and 122 kg N ha$^{-1}$ for best management practices. The majority of the 2070 climate scenarios produced very little change in optimal nitrogen application rates, except for the low rainfall (R1) scenarios in combination with average or high temperature predictions (T2 and T3), which predicted lower (up to 13 kg N ha$^{-1}$) optimal nitrogen application rates as compared with the current climate scenario.

Yield at the optimal nitrogen application rate is very similar between current and best management practices (Fig. 2). There is a slight yield improvement in the 2030 climate scenarios in comparison to the current climate scenario (up to 5 t ha$^{-1}$ improvement). The 2070 climate scenarios predict yield improvements of up to 7 t ha$^{-1}$ in the low temperature scenarios (T1) in combination with average and high rainfall scenarios (R2 and R3). Both current and best management practices are predicted to have larger yield reductions (up to 15 t ha$^{-1}$) in 2070 in the low rainfall scenarios (R1) when temperature is predicted to increase according to the average or high scenarios (T2 and T3).

The simulated nitrogen surplus is markedly less for best management practices as compared with current management practices for both current and all projected climate scenarios (Fig. 3). Under both management practice regimes, there is very little change in nitrogen surplus from current to 2030 and 2070 climate scenarios. Under current management practices, there tends to be a slight (~5%) decrease in nitrogen surplus in the low (R1) and average (R2) rainfall scenarios, a trend not apparent in best management practices. For best management practices, nitrogen surpluses tend to respond more to temperature, being highest in the extreme temperature scenario (T3).

The trends in optimised partial gross margin values between current and best management practices are predicted to be the same for all climate scenarios (Fig. 4), with best management practices producing slightly better partial gross margins than current management practices (\$2473 ha$^{-1}$ and \$2402 ha$^{-1}$ respectively, under base climate conditions). Both current and best management practices regimes are impacted much more by the 2070 climate projections than by the 2030 projections in the simulations, with the low rainfall scenarios (R1) producing much lower partial gross margins under both average and high temperature predictions (T2 and T3). In 2030 and 2070 at the low temperature projections (T1), both average and high rainfall scenarios (R2 and R3) are predicted to increase partial gross margin in the order of \$100 ha$^{-1}$ over current partial gross margins.

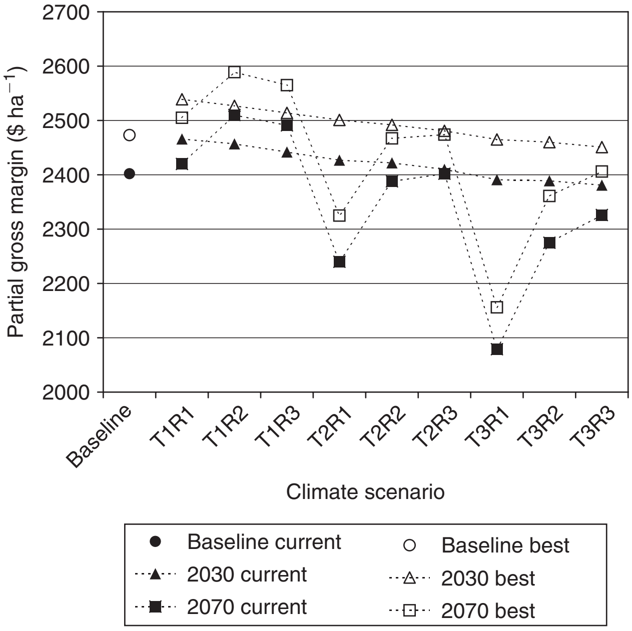


**Fig. 4.** Optimised partial gross margin ($ ha$^{-1}$) predictions for current and best management practices under current (baseline) and projected 2030 and 2070 climate scenarios. T1, T2 and T3 represent the low, average and high temperature projections for 2030 and 2070, respectively, and R1, R2 and R3 represent the low, average and high rainfall projections for 2030 and 2070, respectively (see Table 1).

## Discussion

This analysis shows that climate change (out to the extreme scenarios projected for the year 2070) will have only a minor impact on altering nitrogen contributions (when estimated using the nitrogen surplus) from sugarcane production to the Great Barrier Reef in the Tully–Murray catchment. The reduction in nitrogen surplus resulting from using best management practices instead of current management practices is much greater than the small changes in nitrogen surplus resulting from predicted climate change. This finding supports the arguments made by Hanratty and Stefan (1998) who found that land management practices were likely to have a greater impact on water quality than climate change, and called for improvements to modelling frameworks to investigate this claim further.

The impact of predicted climate change on financial viability of sugarcane farming in the Tully–Murray catchment, when measured through partial gross margin, is expected to be minor in most climate scenarios. The partial gross margin of sugarcane production is negatively impacted by reduced rainfall (R1) under the higher temperature climate scenarios (T2 and T3). This impact is primarily due to a reduced yield under these climate scenarios. These results suggest that climate change will neither be an important driver determining the productivity or profitability of sugarcane production, nor its impact on water quality, in the Tully–Murray catchment under the assumptions made in this study.

The promotion of best management practice adoption by sugarcane farmers should continue to be prioritised without concern for climate change severely impacting nitrogen contributions to the Great Barrier Reef. Reducing nitrogen export to the Great Barrier Reef is more critical under increased temperature scenarios because higher nitrogen loads in combination with higher temperatures could be exacerbating coral bleaching (Schlöder and D'Croz 2004). The results in the present study provide a compelling case for policies to support the widespread implementation of the identified best management practices in sugarcane production in the Tully–Murray catchment.

The nitrogen surplus is a qualitative indicator of potential nitrogen losses to water, representing the amount of nitrogen *available* to be lost, and thus, a lower surplus is likely to indicate lower actual losses (Meisinger and Randall 1991). Not the entire nitrogen surplus ends up in water, as losses also occur to the atmosphere through denitrification and volatilisation. One assumption made in the present paper is that all management practices under all climate scenarios result in the same proportion of the nitrogen surplus being contributed to water. Testing the validity of this assumption would help clarify the argument that the suite of management practices presented in this paper will contribute to the goal of the Water Quality Improvement Plan 'to halt and reduce the decline in water quality entering the Reef within 10 years' (Anonymous 2003) and that climate change scenarios will not affect their ability to positively contribute.

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