Interactions between climate change and sugarcane management systems for improving water quality leaving farms in the Mackay Whitsunday region, Australia

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ABSTRACT

Nitrogen (N) lost from cropping is one of the major threats to the health of the Great Barrier Reef (GBR) in northern Australia, and there are government initiatives to change farming practices and reduce N losses from farms. Sugarcane is the dominant crop in most catchments draining into the GBR lagoon, especially those of the Mackay Whitsunday region (8400 km2) where sugarcane represents >95% of cropping in the catchments, and is grown with large applications of N fertiliser. As farmers and farming systems adapt to a future requiring lower environmental impact, the question arises whether climate change may influence the effectiveness of these changes, an issue rarely considered in past water quality studies. To address this question we used the APSIM farming-systems model to investigate the complex interactions between a factorial of five proposed sugarcane management systems, three soil types, three sub-regional climatic locations and four climate change projections (weak, moderate and strong, with historical climate as a ‘control’). These projections, developed from general circulation models and greenhouse gas emission scenarios, estimated that median annual rainfall would be reduced by up to 19%, and maximum and minimum temperatures increased by up to 0.5 °C and 0.6 °C, respectively. Management practices, such as tillage, fallow management and N inputs, were grouped into five systems according to the perceived benefits to water quality. For example, management System A grouped together zero tillage, soybean rotation crops, reduced N inputs and controlled traffic practices. While at the other end of the scale, System E included many severe tillage operations, bare fallows, high N inputs and conventional row spacing; practices that are still in use in some areas. Importantly, this study parameterised controlled traffic systems, which is considered an important component of ‘best’ management in the GBR catchment, but for which water quality benefits have yet to be widely quantified. The study predicted that the improvement in farm management needed to meet water quality improvement goals will not be greatly affected by climate change. However, without any interventions, the frequency of years with very high N losses, and hence extreme ecological risk, was predicted to increase by up to 10–15%. Compared with traditional practices, improved management systems were predicted to reduce N losses by up to 66% during these years. The results support continued adoption of improved management systems to achieve proposed water quality targets in both the current and a range of potential future climates. However, there are important uncertainties about the effects of elevated atmospheric CO2 concentration on plant assimilation rates and the characterisation of extreme climate events that deserve further study.

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1. Introduction

The health of coastal coral reefs is increasingly threatened by exposure to pollutants from agricultural and urbanized catchments (Spalding et al., 2001; Smith et al., 2003). Australia’s Great Barrier Reef (GBR) is an example of a threatened coral reef, its health being affected by a range of pollutants, including nitrogen (N) lost from fertiliser used in agriculture (Bramley and Roth, 2002; Mitchell et al., 2005, 2009). Dissolved inorganic N (DIN) discharging from water courses onto the GBR have increased up to nine times compared to natural N loads in some regions (Kroon et al., in press). Across the whole GBR region, much of this DIN will come from sugarcane (Saccharum spp.) production, as it is both a major crop grown in the GBR and has high N applications rates (Thorburn and
Wilkinson, this issue); N is an essential input to maximising sugarcane productivity (Thorburn et al., 2003). Unfortunately, at farmers’ conventional application rates, N application rates are commonly 100 kg ha$^{-1}$ in excess of N exported in the harvested crop (Thorburn et al., 2003, 2011a). N is highly mobile and can be removed from the soil via water movement (e.g. runoff, deep drainage) and gaseous emissions (e.g. denitrification). In recent years government policies have required regional catchment groups to develop and facilitate adoption of improved management practices, aiming to both reduce N losses to water courses and maintain or boost production of sugarcane crops, to address reef water quality issues. The Mackay Whitsunday region has the largest area (~120,000 ha) and greatest proportion of the catchment (~13%) under sugarcane production within the GBR region. Drewry et al. (2008) have proposed a suite of management systems for sugarcane designed to improve water quality, which include reducing N fertiliser applications, reducing tillage and changing management of fallows prior to planting between sugarcane crops. The adoption of these management systems is being encouraged through government incentives (Thorburn and Wilkinson, this issue). However, there is little information quantifying the effect of these management systems on N lost from sugarcane farms via runoff and deep drainage, especially across different soil types (low vs. highly permeable soils) and climatic conditions.

Together with these uncertain spatial effects (i.e. soils and climate) on N losses and sugarcane yields, there is the even more uncertain impact of climate change. Current predictions for the future Australian climate are increased average temperatures, increased evaporation, more variable rainfall patterns and increases in both temperature and rainfall extremes (CSIRO, 2011). The impacts of these changes on sugarcane yield and loss of N from sugarcane production systems are not clear. Higher temperatures and more variable rainfall may interact, producing either a net positive or negative impact on sugarcane productivity (Park et al., 2010a). On the other hand, increased atmospheric CO$_2$ concentrations may increase the efficiency with which sugarcane uses N, light and water, leading to higher biomass accumulation (i.e. ‘CO$_2$ fertilisation’; De Souza et al., 2008), counteracting negative aspects of other climatic variables. As well, the effect of climate change on loss of N from sugarcane production systems is difficult to estimate in such a complex system. For example, N losses may be reduced through higher crop growth and N uptake, or increased due to more frequent large rainfall events.

There is a need to assess management systems that allow cropping systems to adapt to climate change from both production and minimising environmental perspectives (Ingram et al., 2008; Howden et al., 2007; Keating et al., 2010). There have been a large number of studies of the effect of climate change on crop management and productivity, but most do not consider the environmental implications of these changes. In sugarcane farming systems for example, Knox et al. (2010) predicted that future irrigation needs in Swaziland would increase by 20–22%. But their modelling did not include N cycling, so N losses were not considered. Conversely, there are studies into the effect of climate change on water quality, focussing on hydrological processes at the catchment scale (Bouraoui et al., 2004; Ficklin et al., 2010; Hanratty and Stefan, 1998). But these studies do not explicitly consider changes to either crop productivity or management practices. Studies in other agricultural production systems that do consider the impact of climate change on both productivity and losses of N to the environment generally conclude that there will be management systems that both maintain productivity and reduce environmental impacts under possible future climates. For example, improved N management has been predicted to reduce N leaching or N surplus, and either maintain or improve crop production under both current and future climates in wheat production systems in southern Sweden (Eckerson et al., 2001) and sugarcane in the Australian Wet Tropics (Webster et al., 2009). However, these studies were of limited scope: they did not consider issues such as the uncertainty in possible future climates, changed frequency of extreme events, a wide range of management responses or soil types, or runoff of N from farms.

In this paper, we address the questions of whether climate change will reduce the benefits of management practices being promoted to both minimise N losses via deep drainage and runoff and maintain or improve sugarcane yields in the Mackay Whitsunday region of the GBR. We conclude that most of the promoted management systems will considerably reduce N losses and climate change will not affect the outcome greatly. Also, in some cases climate change may enhance the outcome of the improved management.

2. Methods

2.1. Overview

Cane yields and N losses were simulated with the APSIM (version 7.0) cropping systems model for a factorial combination of soils, meteorological stations, management systems and climate change projections relevant to the Mackay Whitsunday region. Parameters for three soil types were derived from previous experiments in the region and long-term historical climate data obtained for three meteorological stations representative of the range of climates within the region. The management systems represented were those described in the Mackay Whitsunday Water Quality Improvement Plan (WQIP, Drewry et al., 2008). The relevant characteristics of each system were represented in the simulations. The simulated yields and N losses predicted using historical climate data were compared with regional average yield production for the last 10 years and estimates of N losses on similar soils in this region to ensure predictions were consistent with local experience. After this ‘sensibility check’, three potential climate change projections were developed (representing weak, moderate and strong change) and used to assess the impact of climate change on the effectiveness of the various sugarcane management systems. Finally, the regional-scale contribution of N to water courses was estimated for the different climate change projections and planned levels of management adoption and compared to planned future water quality targets. Further details follow.

2.2. Soil parameters and climate data

Information needed to parameterise the APSIM soil modules was obtained from previous studies undertaken in three locations in the Mackay region (Table 1). Although the soils from these locations were selected primarily because of their data quality, they also represented some of the dominant soils typical in the region (i.e. cracking clay, heavy clay loam and a loam).

Daily climate data (maximum and minimum temperature, rainfall, vapour pressure, solar radiation and evaporation) from 1902 to 2007 were obtained from the SILO climate data archive (Jeffrey et al., 2001) maintained by the Queensland Climate Change Centre of Excellence. The data are available from specific meteorological stations. Three stations (Eton, Plane Creek and Proserpine) were chosen to represent the range of climatic conditions in the Mackay Whitsunday region based on a comparison of rainfall distribution for a number of stations with good quality long-term data. The three meteorological stations range in median annual rainfall from 1268 mm at Eton, 1529 mm at Plane Creek and 1724 mm at Proserpine.
Table 1 Details of the three soil types, collected from detailed experimental work in the Mackay Whitsunday sugarcane cropping region and used in APSIM simulations.

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Cracking clay</th>
<th>Heavy clay loam</th>
<th>Loam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment location</td>
<td>Eton (21°14′S, 148°57′E)</td>
<td>Marian (21°12′S, 148°57′E)</td>
<td>Tekowai (21°10′S, 149°07′E)</td>
</tr>
<tr>
<td>Maximum available water (mm) (whole profile)</td>
<td>326</td>
<td>148</td>
<td>122</td>
</tr>
<tr>
<td>Drainable water (mm) (whole profile)</td>
<td>106</td>
<td>174</td>
<td>104</td>
</tr>
<tr>
<td>Lower limit of plant available water (m3/m3 soil) (0–300 mm)</td>
<td>0.21</td>
<td>0.13</td>
<td>0.17</td>
</tr>
<tr>
<td>Total carbon (%) (0–300 mm)</td>
<td>1.7</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>pH range (whole profile)</td>
<td>5.7–6.0</td>
<td>6.0–7.5</td>
<td>5.0–6.0</td>
</tr>
<tr>
<td>C:N (0–300 mm)</td>
<td>12.4</td>
<td>12.6</td>
<td>17.2</td>
</tr>
<tr>
<td>Curve Number (conventional/controlled traffic)</td>
<td>73/62</td>
<td>72/61</td>
<td>65/55</td>
</tr>
</tbody>
</table>

* Maximum volume of water held by the soil between the drained upper limit (or field capacity) and the lower limit (water retained at a pressure of ~1500 kPa).
* Maximum volume of water held by the soil between saturation and the drained upper limit (or field capacity).
* Curve Number was derived independently from the information given in the references.

2.3. Crop management systems

2.3.1. General representation of the sugarcane cropping cycle

For the simulations, a general sugarcane cropping cycle was defined based on common features of production in the Mackay Whitsunday region. Sugarcane is a semi-perennial crop. In the Mackay Whitsunday region it is generally planted in autumn (15 May) and harvested 14 months later. The crop is then allowed to re-grow (ratoon) and harvested approximately 13 months later (harvesting season is June to December). All crops are harvested mechanically. The crop loses vigour after 3–5 harvests. For the sake of simplifying the simulations the crop is destroyed after the fourth harvest, and the field is fallowed for 6 months until the next sugarcane crop is planted. This sequence, planting to planting, is called a cropping cycle, with the crops denoted plant crop, first ratoon crop, etc.

In the simulations, sugarcane was planted at 150 mm soil depth and all crop residues were retained on the surface after harvest. Irrigation was limited to a maximum of 100 mm per year, applied in 50 mm applications with 85% efficiency (i.e. 42.5 mm) to the soil surface. All fertiliser N was applied as urea at a depth of 50 mm.

2.3.2. Management systems

The management of N fertiliser, tillage and fallows (bare or break crop) was grouped together and organised into five management systems broadly following the approach used in developing the Mackay Whitsunday WQIP (Drewry et al., 2008), in which four management “Classes” were defined. Our systems are ranked from System A, assumed (following Drewry et al., 2008) to have the best water quality, through to E with the worst water quality (Table 2). There is reasonable alignment between three of our management systems and the Classes of Drewry et al. (Table 2). However, after local consultation we felt it necessary to divide Drewry et al.’s Class C (based on conventional N fertiliser and traditional tillage management) into two systems having either a bare fallow (our System D) or a break crop (our System C) between sugarcane crop cycles.

Four different fertiliser recommendations were used in the management systems (Table 2) based on a range of N fertiliser management recommendation systems. For management System A, N fertiliser management was based on the “N replacement” strategy (Thorburn et al., 2004, 2011a). The amount of fertiliser N applied with the N replacement strategy (NREP) was 1.0 kg/ha (tonne of cane)−1 removed in the previous harvest. The management of N fertiliser used in System B was based on the current industry nutrient recommendations (known as “Six Easy Steps”; Schroeder et al., 2005, 2006). The “Six Easy Steps” (SES) system uses soil specific nutrient guidelines based on the soil carbon content to determine N application rate. N fertiliser application rates in Systems C and D were the historical industry nutrient recommendations (termed ‘Calcino’, described by Calcino, 1994). The N applied in management System E was based on higher than recommended rates of N application that are known to occur in the region.

The period between crop cycles consisted of either a bare fallow (Systems D and E) or a soybean (Glycine max Leichardt) crop (Systems A, B and C). The purpose of having a soybean crop instead of a bare fallow was to provide the benefits of a ‘break crop’, such as improved soil health and increased yields of subsequent sugarcane crops (Pankhurst et al., 2005). In System A, the soybean grain was harvested at maturity (and residues left on the soil surface) in contrast to Systems B and C where the crop was allowed to ’die’ or was ’killed’ in the model (to represent application of herbicides). Thus, substantially less residue-N was returned to the soil with System A than B or C where crop residues included grain. With System B, the crop residue was left on the soil surface, while in System C this was incorporated via a tillage operation. Since this residue would contain substantial amounts of N, potentially more than the N requirements for a sugarcane plant crop (Park et al., 2010), no fertiliser N was applied to the ‘plant’ crop in Systems A and B. Even though System C also had a fallow soybean crop, plant crop fertiliser N rates in this system were not reduced to account for the N contributed by a soybean crop to reflect standard practice in the region.

The number of tillage operations for the purposes of residue incorporation or weed control declined moving from Systems E to A. This reflected the inclusion of a soybean rotation crop in System A, B and C (that reduced the need to control fallow weeds). In addition, System A further minimised tillage by having zero tillage for all canecrops except for one tillage operation during planting. Tillage increases infiltration of water into soil. This process is represented within APSIM (through reducing Curve Number following tillage), and tillage operations were categorised as having a low, medium or high impact on infiltration (Table 2) representing less (e.g. conventional planter) and more (e.g. ‘centre-busting’) aggressive tillage operations (following Thorburn et al., 2011b).

In the region, management System A also includes controlled traffic management (Drewry et al., 2008) in an effort to reduce soil compaction and improve infiltration. In controlled traffic farming, sugarcane is commonly planted in dual rows (0.8 m apart) into permanent 2 m beds. Controlled traffic was simulated in System A through a reduced Curve Number (Table 1 and described later). There is evidence that controlled traffic management together with a fallow break crop increases crop yields by ~5% in the Mackay Whitsunday region (Garside A, pers. comm.). The mechanisms behind this yield improvement is uncertain, and in the face of
this uncertainty we represented the improved crop growth in controlled traffic management in the simulations through increasing radiation use efficiency by 5% in APSIM-sugarcane.

2.4. Climate change projections

In this study, we were interested in what climate conditions farmers in this region may have to deal with over the forthcoming 20 years (i.e. 2030). Many of the approaches for getting daily climate change projection data are not suited to this relatively short time-frame. Thus, we used an approach that modifies historical daily climate files by the combination of (1) the extrapolation of historical trends in the distribution of climate extremes (i.e. 10th, 50th and 90th percentile daily events) in climate data, with (2) projected changes in mean temperatures and rainfall derived from coupled atmosphere-ocean GCM and greenhouse gas emission scenarios (Crimp et al., 2010).

2.4.1. Historical trends in the distribution of climate extremes

For the historical climate data used in the study, a quantile regression was undertaken (using simple linear regression models) for each month to determine changes in dispersion of daily temperature (i.e. minimum and maximum) and rainfall in that month over the period 1957–2007. Significant (P > 0.95) trends in these temperature and rainfall quantiles were extrapolated forward to 2030 in order to modify the distribution of daily events.

2.4.2. GCM-derived climate change projections

The extrapolated historical climate extremes were combined with changes in mean temperatures and rainfall developed from three climate change projections. The projections were derived from a combination of the selected GCMs and emission scenarios; weaker warming and wetter conditions (weak climate change); moderate warming and drier conditions (moderate climate change) and strong warming and drier conditions (strong climate change). Before these projections were developed, we examined a wide range of potential future climate conditions that may occur in the region based on predictions from a range of GCM’s. We chose eight GCM’s, out of 22 assessed, that have been shown to perform well in Australia (Smith and Chiew, 2009; Crimp et al., 2010). These GCM’s show a range of future climate conditions for the study region, ranging from ‘slightly warmer and wetter’ to ‘significantly warmer and drier’, with five of the eight models producing some form of ‘warmer and drier’ future conditions. In order to represent the range of future climate conditions produced by the eight models we chose GCM’s that represented both the extremes and mid-point of the range of predictions. The three GCM’s chosen were:

- MUIB/KMA ECHO-G – a GCM (Legutke and Voss, 1999); modestly warmer and wetter conditions.
- ECHAM5/MPI-O (Jungclaus et al., 2006); mid-range warmer and drier conditions.
- GFDL-CM2.1 (Delworth, 2006); significantly warmer and drier conditions.

GCMs that produced conditions of significantly warmer and wetter conditions were not examined as part of this analysis as they were ranked in the bottom eight of 22 GCMs originally assessed and hence represent much less likely futures (Smith and Chiew, 2009; Crimp et al., 2010).

The future climate conditions are very strongly related to the extent of future global warming, as well as the pattern of change determined by the GCM examined. Thus, the climate change projections were derived by initialising each GCM with one of three global warming trajectories aligned with ‘low’, ‘medium’ and ‘high’ emission scenarios derived from the Special Report on Emission Scenarios (SRES; IPCC, 2000). The weak climate change projection was derived from a combination of the MUIB/KMA ECHO-G GCM with a low rate of global warming based on the SRES A1B emission scenario. The B1 emissions scenario describes a convergent world with rapid technology development, de-materialisation of the economy, and improving equity. A moderate climate change projection was derived from a combination the ECHAM5/MPI-O GCM with a medium rate of global warming based on the SRES A1B emissions scenario. This describes a future world where globalisation is dominant. Economic growth is rapid and population growth is low with the rapid development and deployment of more efficient technologies. There is a balance between fossil fuel use and other energy sources. The strong climate change projection was developed from a combination of the GFDL-CM2.1 GCM with a high rate of global warming based on the SRES A1FI emissions scenario. This describes a future world where globalisation is dominant. Economic growth is rapid and population growth is low with the rapid development and deployment of more efficient technologies. There is maximum fossil fuel use with coal, oil, and gas dominating the energy supply for the foreseeable future.

The spatial resolution of the climate models was too coarse and needed to be downscaled to the regional level to be useful for this analysis. The results of this downscaling were extracted from the OZCLIM scenario generator developed by CSIRO.
Atmospheric Research and the International Global Change Institute (http://www.csiro.au/ozclim/home.do). In OZCLIM, coarse scale national projections are enhanced to regional scales through a simple linear regression of local seasonal mean temperature (or rainfall) against global average temperature, in order to generate, at each grid point, monthly projections of mean temperature or rainfall. The grid point values can then be mapped to obtain a pattern of response that can be scaled according to an estimate of total global warming (Whetten al., 2001). Monthly OZCLIM projections of mean temperature and rainfall were applied to the modified historical climate data in order to shift the distribution in climate extremes, described previously, in line with the projections from each of the climate models and emission scenarios analysed.

Additional to these three projections, historical climate records were included as a ‘control’ representing the case where no increase level of climate change was applied.

2.4.3. Ancillary climate variables

Climate variables such as, pan evaporation, vapour pressure and solar radiation, did not have sufficient historical data to determine trends or perform extrapolations. So correlations between these ancillary climate variables and maximum temperature and rainfall were determined for each met-station. Using the resulting simple multiple regression relationships and the ‘new’ projected temperature and rainfall, modified evaporation, vapour pressure and solar radiation were generated.

2.4.4. CO₂ fertilisation

The GCM-derived scenarios were based on predicted CO₂ concentrations of 437 ppm in the atmosphere for 2030. We represented the effect of this higher concentration of CO₂ on crop physiology (i.e. CO₂ fertilisation; De Souza et al., 2008) by increasing radiation use efficiency and transpiration efficiency in APSIM-Sugarcane following the method described in Webster et al. (2009).

2.5. APSIM modelling

The APSIM (version 7.0) cropping systems model (Keating et al., 2003; http://www.apsim.info) was used to simulate the impact of different management systems on sugarcane yield and N lost via deep drainage or runoff, under current climates and the different climate change projections. This model was chosen because of its proven capability for modelling N cycling in complex farming systems including sugarcane (Thorburn et al., 2005) within the same or similar regions of Australia as this work refers to. APSIM has the capacity to represent important features of sugarcane production systems and the related environment. These features include; residue decomposition procedures to capture accurately the specific dynamics of green cane trash blanketed systems (Thorburn et al., 2001); improved nitrification and denitrification parameters (Meier et al., 2006; Thorburn et al., 2010); predictions of N in runoff (Thorburn et al., 2011b) and deep drainage (Stewart et al., 2006); and improved simulation of soybean break crops used in rotation with sugarcane (Park et al., 2010b).

2.5.1. Model description

The APSIM model was configured with modules for soil N and C (APSIM-SoilN; Probert et al., 1998), soil water (APSIM-SoilWat; Probert et al., 1998), sugarcane growth (APSIM-Sugarcane; Keating et al., 1999), soybean growth (Roberson et al., 2002) and sugarcane residue (within APSIM-SurfaceOM; Probert et al., 1998).

All modules are one-dimensional, use a daily time-step and are driven by climatic data. The dynamics of water, N, C and roots are simulated in soil layers. The soil water module (SoilWat) is a ‘cascading bucket’ water balance model (Probert et al., 1998), with water (and associated nitrate) moving between layers where gradients exist. In the SoilWat module, runoff is determined based on the Curve Number approach, described in more detail below. The presence of plant residues on the soil surface affects runoff (and hence infiltration) and evaporation. Tillage also affects infiltration and runoff, and can incorporate surface residues into the soil organic matter pools.

The crop module uses intercepted radiation to produce assimilates, which are partitioned into the different plant components. These processes are responsive to radiation and temperature, as well as water and N supply. If water logging occurs, the proportion of the root system exposed to soil water condition at saturation or near saturation (oxdef_photo_rfr) is calculated and used to calculate a water logging stress factor (oxdef_photo). This factor reduces photosynthetic activity via an effect on radiation use efficiency.

To ensure the outcomes of the simulation work was relevant to the region, APSIM-Sugarcane parameters controlling crop lodging and root yield depth (xf) were set so that the predicted long term average sugarcane yield (and hence crop water and N uptake) for System C management was similar to the average regional yield (81 t ha⁻¹) for Mackay Whitsunday. Lodging is common in sugarcane crops and reduces yields through stalk death and constraining photosynthetic activity and the production of assimilates (Singh et al., 2002; Park et al., 2005). These processes are represented in APSIM-Sugar through two factors; deathFr_0_lodge that decreases stalk number after lodging, and lodge_redn_photo that decreases radiation use after lodging. The value of these two factors were set to 0.005 (Singh et al., 2002) and 0.6 (Meier, 2008), respectively. Crops were considered to have lodged when stalk dry weight exceeded 201 ha⁻¹ and daily rainfall was greater than 20 mm (Singh et al., 2002). Maximum sugarcane rooting depth was set to 1 m, as expected when crops do not experience strong water or nutrient stress (Smith et al., 2005).

The soil was divided into seven or eight soil layers to a total depth of 1.5 or 2.0 m. N dynamics, as affected by soil moisture and temperature, are explicitly described in each layer. L lost via deep drainage was the nitrate flux from the lowest soil layer based on water movement and soil N concentration in the deepest soil layer. Movement of nitrate–N via run off was modelled using the APSIM-Erosion module (following Thorburn et al., 2011b). The amount of N removed from the soil was dependent on the soil N concentration and an enrichment factor parameter. The value of this parameter was set based on the experience of Thorburn et al. (2011b). The N in the top soil layer was reduced by the amount of N removed in the runoff event using the ‘Profile reduction’ feature in the EROSION module in APSIM. Denitrification is calculated in each soil layer as a function of NO₃⁻, active C, moisture and temperature using parameters developed by Thorburn et al. (2010).

2.5.2. Parameterisation of runoff

For each of the three soils selected, a Curve Number was assigned for ‘conventional practice’, defined as regularly tilled soil and an industry standard row configuration (single row of sugarcane planted in the centre of 1.5 m wide beds, Table 1). For the cracking clay and loam soils, the Curve Numbers for ‘conventional practice’ were based on soil texture (USDA, 1985). For the heavy clay loam, the Curve Number was determined by simulating measured runoff from that soil under different tillage practices (Masters et al., 2008). In the Mackay region, controlled traffic (part of System A) has been found to reduce runoff by 40% compared with conventional management (Masters et al., 2008). To parameterise this reduced runoff in System A systems, the experiment of Masters et al. (2008) was simulated with APSIM using and the Curve Number parameters calibrated for this management (Fig. 1). The result was that Curve Number was reduced by 15% compared with the ‘conventional practice’ treatment (Table 1). The same proportional reduction in Curve Number was applied to the other soils simulated.

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Many of the tillage operations that are used during sugarcane production not only incorporate surface residues but also increase infiltration by disturbing the soil surface. In APSIM, the effect of tillage operations on infiltration can be represented by changing the Curve Number following tillage, with the extent of the change dependent on the ‘severity’ of the tillage. Three levels of impact of tillage on infiltration were identified, with tillage operations classified as:

- low impact, represented by no change in Curve Number; or,
- medium impact, represented by reducing Curve Number by 15 and gradually restored to the original value after 200 mm of rainfall, or
- high impact; represented by reducing Curve Number by 50 and restored to the original value after 1300 mm of rainfall.

The definition and parameterisation of these impacts was based on previous simulation of runoff in sugarcane production systems (Thorburn et al., 2011b).

In APSIM version 7.0, runoff from irrigation is not explicitly modelled. However, overheard irrigation systems used in the Mackay Whitsunday region generate surface runoff (Masters et al., 2008). To represent this in APSIM, irrigation was applied as ‘extra’ rainfall enabling us to capture interactions between irrigation and other management practices (e.g. tillage, the presence of crop residue, etc.).

2.5.3. Simulation analysis

In the simulations, sugarcane yields were output at harvest, then normalised to a yield over 12 months to account for the differing lengths of the plant and ratoon crops. N losses (through both deep drainage and runoff) were output annually on 15–November, coinciding with the harvest date of the last ratoon.

Events generating high N losses may have substantial ecological impacts, such as causing algal blooms (Devlin and Brodie, 2005), so it is useful to examine the impact of crop management and climate change on the frequency of these events. It is difficult to quantify the magnitude of N losses causing ecological harm, so we have developed a metric to describe the relative frequency of these extreme events. We assume that, under the historical climate, complete adoption of System A management practices would result in the minimum possible N losses from these sugarcane production systems over any given time, and losses exceeding this ‘threshold’ could theoretically be considered avoidable. Thus, we defined a threshold of ‘avoidable’ N losses for each combination of soil and met-station under the historical climate as the maximum annual N loss from System A management. We then determined the number of years that N losses from other management systems (i.e., Systems B–E) and climate change projections exceeded this avoidable threshold.

2.6. Regional scale loads and water quality targets

Regional scale N losses from sugarcane production were estimated for the whole Mackay Whitsunday region under various levels of adoption of the different management systems (Table 3) and compared to the proposed water quality targets. Regional targets for DIN loads discharged from rivers are 2100, 1550 and 1310 t year$^{-1}$ for the years 2007, 2014 and 2050, respectively (Drewry et al., 2008). Estimates of regional scale N losses were derived from field-scale N losses from the simulations aggregated for each of the 29 catchments in the region according to: (1) the area of each management system practiced, (2) the area of each soil type, and (3) the representative meteorological station.

The proportion of catchment area under each management system (Table 3) was assumed the same in all 29 catchments. The area of the three different soils in each catchment was approximated from the similarity between the soils in the catchments (defined by soil survey information: Holz and Shields, 1985; Wills and Baker, 1988) and the parameters of the three soils used in the simulations. Similarly, the met-station used in the simulations most representative of each catchment was determined based on distance from catchment and local expert opinion.

The plausibility of both the distribution of management systems across the region and the N fertiliser rate associated with each system was assessed from regional N fertiliser use statistics. The average regional N fertiliser use (kg ha$^{-1}$ year$^{-1}$ averaged across the region) implied by the analyses was calculated from the total area (ha) estimated to be under each management system (Table 3) and the average use (kg ha$^{-1}$ year$^{-1}$) for that system (Table 2), then compared with fertiliser usage statistics for the same period (made available by the Fertiliser Industry Federation Australia).

Table 3: Percentage adoption of different management systems (A, B, C, D and E defined in Table 2) across the Mackay Whitsunday region for 2000, 2007 and 2014 adoption scenarios developed for the Mackay Whitsunday Water Quality Improvement Plan (Drewry et al., 2008). NB: the adoption of Systems C and D were assumed to be half that for Class C defined by Drewry et al. (2008).

<table>
<thead>
<tr>
<th>Adoption scenarios</th>
<th>A (%)</th>
<th>B (%)</th>
<th>C (%)</th>
<th>D (%)</th>
<th>E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>0</td>
<td>5</td>
<td>17.5</td>
<td>17.5</td>
<td>60</td>
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<tr>
<td>2007</td>
<td>5</td>
<td>10</td>
<td>22.5</td>
<td>22.5</td>
<td>40</td>
</tr>
<tr>
<td>2014</td>
<td>50</td>
<td>30</td>
<td>7.5</td>
<td>7.5</td>
<td>5</td>
</tr>
</tbody>
</table>

3. Results

3.1. Projected changes in temperature, radiation and rainfall

Median annual rainfall was predicted to decrease compared with historical climate in all three climate change scenarios for all met-stations (e.g. Plane Ck met-station, Fig. 2a). Temperature (Fig. 2b), both maximum and minimum, and daily solar radiation (Fig. 2c) were predicted to increase in all three climate change scenarios for all met-stations. Strong climate change was predicted to increase median values for maximum and minimum temperature by 0.50 °C and 0.57 °C, respectively, averaged across all three met-stations (data not shown). Consequently, median daily radiation was predicted to increase by ~2% based on the correlations with maximum temperature and rainfall.
3.2. Regional variability due to soil type and met-station

The predicted historic average sugarcane yield across all soils and met-stations was 86 t ha$^{-1}$, which compared well with the long-term (1996–2007) regional average yield (81 t ha$^{-1}$), thus ensuring that simulated plant N and water uptake was realistic and not adversely affecting the N and water balance results. Sugarcane yields were influenced by rainfall and soil type (mainly expressed through different water holding capacity) in the simulations (e.g. Fig. 3). Largest yields were simulated with the cracking clay, which had the highest water holding capacity (Table 1), in combination with the Proserpine met-station climate data (highest average rainfall). Conversely, the loam and Eton met-station had the lowest yields. The simulated relationship between N loss and soil type/met-station was more complex. N losses varied consistently across met-stations (Eton highest and Proserpine lowest, Fig. 3), although the differences most pronounced with the loam soil and least with the clay (Fig. 3). Broadly, the soil type and met-station combinations that resulted in the highest yield had the lowest N losses (Fig. 3) as is expected when assuming identical N application rates. The effect of climate change and management on yield and N losses was consistent across all combinations of soil and met-stations (data not shown). So for the remainder of the paper only examples or averages of soils and met-station are given.

3.3. Yield affected more by climate change than management system

The differences in simulated cane yields between management systems were small (<2 t ha$^{-1}$ year$^{-1}$, Fig. 4a), suggesting that there were no difference in N or water limitations (stresses to which cane yield responds in APSIM) imposed by any of the management systems simulated. Relative to the historical climate, simulated median yields increased by 8% and 4% with weak climate change and moderate climate change, respectively (Fig. 4a), but were reduced by 10% with strong climate change. This pattern was consistent for all combinations of management systems (Fig. 4a). The temporal variability in yields was affected by climate change, with the greatest variability occurring with strong climate change and least for the historical climate or weak climate change (Fig. 5).

Simulated yields were substantially influenced by 'CO$_2$ fertilisation', with yields 10–14% larger than an identical scenario without 'CO$_2$ fertilisation' (Fig. 5). Given that N losses and yields are approximately inversely related in the simulations (Fig. 3), the yield increases due to CO$_2$ fertilisation led to reduced N losses (data not shown). Thus, the results of this study, especially for weak and moderate climate change are dependent on the CO$_2$ fertilisation effect being represented accurately in this study.
3.4. Median N losses affected by management more than climate change

The choice of management system had a substantial impact on simulated N losses. For historical climate, median N losses decreased from 31 kg N ha\(^{-1}\) year\(^{-1}\) for System E to 3 kg N ha\(^{-1}\) year\(^{-1}\) for System A, i.e. a 90% decrease (Fig. 4b). Interestingly, management System C had higher N losses than System D, with the main difference in management between these systems being the inclusion of a soybean crop in System C (Table 2). The higher N losses reflect the N input from the soybeans (Park et al., 2010b). In comparison to the impact of management systems, the effect of climate change on median annual N losses in the simulations was small and decreased with improved management (e.g. System A c.f. E, Fig. 4b).

3.5. Frequency of ‘avoidable’ N losses

For all climate change projections and all management systems from B to E, there was an increase in the frequency of (theoretically) avoidable N losses, i.e. the frequency of years where annual N losses exceed the maximum annual N losses for management System A with historical climate (Fig. 6). The patterns in frequency of avoidable N losses (means across soil types and met-stations) across management systems was similar to that for the median N losses (Fig. 4), i.e. highest frequencies in Systems C and D, and lowest in A (Fig. 6). However, there were no consistent trends across management systems. For example, the frequency of avoidable N loss was lower in System E than C, even though N fertiliser applications and the number of tillage operations were higher in System E. Likewise, System D had a lower mean frequency than B except with strong climate change. For management Systems C–E, increasingly severe climate change projections increased the mean and maximum frequency of avoidable annual N losses.

3.6. Estimated effect on regional-scale water quality

For the levels of adoption of the different management systems across the Mackay Whitsunday region in the year 2000 (Table 3), the regional-scale fertiliser usage was calculated to be 170 kg N ha\(^{-1}\). This agrees well with the 172 kg N ha\(^{-1}\) actually used in the region over the 2000–2003 (Fertiliser Industry Federation Australia, personal communication), and supports the assumptions made about the N fertiliser applications and the area of each management system in the region.

This rate of N fertiliser application to sugarcane in the Mackay Whitsunday region is equivalent to 28,742 t N year\(^{-1}\), with mean predicted N lost via runoff from the whole region being 1,227 t N year\(^{-1}\) (or 4.3% of this applied N) for the 2000 level of management system adoption (Fig. 7a). This prediction compares well with the monitoring-based estimate of regional DIN load of 1746 t year\(^{-1}\) (Kroon et al., in press), which is accompanied by considerable uncertainty. There is substantial temporal variability in predicted N losses, with median N in runoff (204 t year\(^{-1}\)) being much lower than the means given above. N lost through deep drainage (median of 3049 t year\(^{-1}\) or 10.6% of applied N, Fig. 7b) was much higher than runoff.

Climate change projections affected the N losses in the region inconsistently. For example, for the levels of management system...
adoption for 2000 there was a decrease in regional N lost through both deep drainage and runoff with weak climate change (Fig. 7). Conversely, with strong climate change there is an overall increase in N losses of 25% mainly due to increases in N lost via deep drainage. However, simulated N losses were affected to a much greater extent by changes in management adoption levels: e.g. N losses were predicted to reduce by 66% with the greater area of System A and B management in the 2014 management system adoption scenario compared with 2000. Greater adoption of System A and B management is also predicted to reduce the range of annual N losses (Fig. 7).

The 2050 water quality targets for DIN loads in the Mackay Whitsunday Water Quality Improvement Plan (Drewry et al., 2008) are higher than the predicted mean and median N in runoff for all combinations of climate change and management system adoption scenarios (Fig. 7a). For the 2014 adoption scenario, median (although not mean) N lost via deep drainage is predicted to be similar to 2050 target value. However, the predictions are highly skewed with 25% of years for this level of management adoption producing over 6454 t year$^{-1}$, almost 5 times higher than the 2050 target value (Fig. 7b).

### 4. Discussion

This simulation analysis has shown that, in the Mackay Whitsunday region, crop management practices will have a greater effect on median N losses from sugarcane cropping than the degree of climate change likely by the year 2030 (Fig. 4). Weak and moderate climate change scenarios were predicted to reduce median annual N losses, an outcome that should assist with improving water quality in the region. Previous studies (Hanratty and Stefan, 1998; Webster et al., 2009) also concluded that the impact of substantial management practice change is likely to have a greater impact than climate change on water quality in cropped lands. This study extends the results of these previous studies by including a more complete representation of management practices, crop productivity and environmental impacts than previous studies.

Although the predicted impact of climate change on median N losses is small, the temporal variability in N losses was highly skewed (Fig. 7), with a small number of years with relatively high N losses. Moreover, the more severe the climate change projection, the more frequently theoretically ‘avoidable’ annual N loss events occurred compared with historical climate records (Fig. 6). Transport of pollutants, such as N, during extreme events have a substantial impact on the ‘health’ of GBR ecosystems (Devlin and Brodie, 2005; De’ath and Fabricius, 2010). Hence, an increase in these episodic, extreme events may have more important effects than is indicated by changes in mean or median N losses. Climate change projections indicate that the frequency and severity of events such as cyclones and flooding, which may increase runoff and deep drainage, are likely to increase (CSIRO, 2011). Our analysis suggests that in the face of more frequent extreme events, greater adoption of improved management practices could help to manage these effects (Fig. 6). However, even under current best management practice (i.e. System A), the frequency of ‘avoidable’ annual N losses increased compared to historical climate. This result needs to be considered in light of the limitations of the methodology used here. The approach used to represent increased variability in climate extremes, based on historical climate records less than 100 years long and the method of downscaling GCMs, will not capture well the effect of such extreme events (Fig. 4; Allan and Soden, 2008; Min et al., 2010). Consequently, our predictions may underestimate the impact of the projected extremes in rainfall on reef water quality. Conversely, the frequency of very dry periods is also predicted to increase raising the possibility that median N losses may not alter substantially even though annual variability may increase (Lough, 2007).

Although the full extent of the annual variability in N losses is uncertain, this study suggests that extensive adoption of Systems A and B management practices would be required to achieve the water quality targets set for the Mackay Whitsunday region (Fig. 7). Extensive adoption of improved management practices will be even more important if the targets represent a maximum acceptable (as opposed to average) annual N load, and/or N lost via deep drainage is a significant source of N found in the region’s water courses. In fact, deep drainage was predicted to be the dominant N loss pathway compared to runoff (Fig. 7), similar to conclusions of experimental studies in other sugarcane producing regions in Australia (Thorburn et al., 2011b; Webster et al., submitted for publication). At face value, the difference between the predicted long-term average N in runoff (1227 t year$^{-1}$) and the regional DIN load (1746 t year$^{-1}$, Kroon et al., in press) implies another, and substantial (30%), source of DIN in the regions rivers. Groundwater has been shown to contribute significantly to river and creek N in other catchments in the GBR (Rasiah et al., 2005, 2010). The role of groundwater in contributing N to creeks and rivers in the region is worthy of further investigation to test the efficacy of some of the proposed management practices. If N in groundwater is significantly contributing to the water quality issue, then consideration needs to be given to the choice of management practices (such as...
reducing N applications, or promoting more vigorous crop growth) that not only aim to reduce N lost by runoff but also reduce N lost via deep drainage. Reducing N losses by all pathways (run off, deep drainage and gaseous losses such as denitrification) will ultimately give the assumed water quality benefits, as well as more general profitability and sustainability benefits sought from sugarcane production in the region.

There have been assumptions made during this study that will make contributions to uncertainties in the predictions and represent knowledge-gaps worthy of future research. Firstly, the simulated increases in yield caused by CO₂ fertilisation (Fig. 5) were a result of changes in the model to radiation use and transpiration efficiencies. Although there is evidence that yield increases due to CO₂ fertilisation in sugarcane are possible (De Souza et al., 2008), there are limited studies outside of laboratories. Secondly, the yield benefits associated with management System A, such as controlled traffic and break crops, have not been proven across a range of soils and climates. So the associated yield increases programmed into simulations in this study may not be widely applicable. Thirdly, the predicted N lost via runoff was based on parameters developed on experimental work (Thorburn et al., 2011b) conducted outside of the Mackay region. Further local research on the impact of current and proposed management practices on N lost via runoff, and other N loss pathways, would help quantify this for the Mackay region and beyond.

5. Conclusions

From this study, we conclude that the targeted levels of management practice improvement needed to meet water quality targets for N in the Mackay Whitsunday region will not be greatly affected by the degree of climate change that is projected to occur in the near term (2030). However, the frequency of years with very high N losses is predicted to increase under projected climate change, and improved farming practices may more effectively limit N losses in these years than traditional practices. Management practices may require even further improvements if N lost via deep drainage has an important influence on N in water ways in the region, an outcome implied by the results of this study.

References


