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Research article

Estimating economic and environmental trade-offs of managing nitrogen in Australian sugarcane systems taking agronomic risk into account

John Kandulu[a,*], Peter Thorburn[b], Jody Biggs[b], Kirsten Verburg[c]

[a] CSIRO Land and Water, Waite Campus, Adelaide, Australia
[b] CSIRO Agriculture and Food, Brisbane, Australia
[c] CSIRO Agriculture and Food, Canberra, Australia

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ABSTRACT

Use of chemical agricultural inputs such as nitrogen fertilisers (N) in agricultural production can cause diffuse source pollution thereby degrading the health of coastal and marine ecosystems in coastal river catchments. Previous reviewed economic assessments of N management in agricultural production seldom consider broader environmental impacts and uncertain climatic and economic conditions. This paper presents an economic risk framework for assessing economic and environmental trade-offs of N management strategies taking into account variable climatic and economic conditions. The framework is underpinned by a modelling platform that integrates Agricultural Production System sIMulation modelling (APSIM), probability theory, Monte Carlo simulation, and financial risk analysis techniques. We applied the framework to a case study in Tully, a coastal catchment in north-eastern Australia with a well-documented N pollution problem. Our results show that switching from managing N to maximise private net returns to maximising social net returns could reduce expected private net returns by \$99 ha^{-1}, but yield additional environmental benefits equal to \$191 ha^{-1}. Further, switching from managing N to maximise private returns in years with the highest profit potential (hereafter, *good years*) to maximising mean social net returns could reduce expected private profits in good years by \$277 ha^{-1}, but yield additional environmental benefits equal to \$287 ha^{-1}. We contend that it is essential to incorporate farmer risk behaviour and environmental impacts in analyses that inform policies aimed at enhancing adoption of management activities for mitigating deterioration of the health of coastal and marine ecosystems due to diffuse source pollution from agricultural production.

1. Introduction

Agricultural production in coastal river catchments has been identified as an important contributor to diffuse source pollution degrading the health of coastal and marine ecosystems (Howarth, 2008; Rabalais et al., 2009). Increasing nitrogen fertiliser application rates (hereafter, *N rates*) is often associated with higher yields and profits; however, high N rates can result in losses of N to the environment through runoff, deep drainage, volatilisation and denitrification (Canfield et al., 2010; Harmel et al., 2008; Schlesinger, 2009; Thorburn and Wilkinson, 2013). N losses, in particular in the form of dissolved inorganic nitrogen (DIN), can cause problems such as eutrophication, habitat degradation and loss of biodiversity in affected coastal marine ecosystems (Howarth, 2008; Rabalais et al., 2009). In addition, N loss from soils in the form of nitrous oxide (N_2O), a potent greenhouse gas, contributes to global warming (Thorburn et al., 2010). Management of N in agricultural production is necessary to mitigate environmental impacts from loss of N however, consideration of effects of N management on profitability of agricultural enterprises ensures adequate adoption of N management activities (Roebeling et al., 2009).

Assessments of alternative N management activities need to take into account trade-offs between competing environmental and economic objectives (van Grieken et al., 2013a). However, economic assessments of N management in agricultural systems, typically assess the impact of applying various N rates on profitability of agricultural enterprises without taking environmental impacts into account (Brennan et al., 2007; Rajsic and Weersink, 2008). Ignoring environmental costs can lead to the application of a higher private economically optimum N rate than the socially optimum N rate that takes environmental costs into account (termed, *externalities*).

Few studies have incorporated environmental costs in assessments of N management activities using measures of central tendency including long-term mean and median cost and benefit values to identify and compare long-term average private and social optimum N rates

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[*] Corresponding author.
E-mail address: john.kandulu@csiro.au (J. Kandulu).

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(Brentrup et al., 2004; Tegtmeier and Duffy, 2004; Van Grinsven et al., 2013; Von Blottnitz et al., 2006). The reviewed studies did not quantify the combined risk from variable climatic and economic factors. However, N application decisions and environmental N losses, are largely influenced by variable climatic and economic conditions (Gandorfer et al., 2011; Monjardino et al., 2013; Rajsic and Weersink, 2008; Sadras, 2002; Sheriff, 2005; Yu et al., 2008). Most agriculturists engaged in production of high-value crops typically apply a higher rate of N than the long-term average economic optimum rate to realise high profits under favourable climatic and economic conditions and to minimise economic losses in years with the lowest profit potential (henceforth, *bad years*) (Gandorfer et al., 2011; Shillito et al., 2009). Economic assessments that seek to identify long-term average N rates for maximising average private and social returns under expected conditions have limited use and application in contexts where agriculturalists' objectives are to maximise on large profits in years with the highest profit potential, good years, and to minimize the risk of big losses in bad years.

This paper presents a framework for assessing the economic and environmental impacts of N management strategies taking into account uncertainty in both climatic and economic conditions. The assessment framework is underpinned by a modelling approach that integrates agricultural production system simulation and financial risk assessment measures of Conditional Value at Risk (CVaR) for the expected return of the lowest and highest possible outcomes with a cumulative probability of five percent (termed, $CVaR_{0.05}$ and $CVaR_{0.95}$). CVaR has been applied to assess the risk-mitigating benefit from diversification agricultural enterprises (Kandulu et al., 2012) and the risk mitigating benefit from increasing N rates above the regional optimum (Monjardino et al., 2013). Here we apply the framework to assess economic and environmental impacts of N management in sugarcane production in a sugarcane growing region (Tully) on the Wet Tropical coast of Australia, adjacent to the Barrier Reef World Heritage Area. We use our results to quantify the benefit of adequately incorporating environmental costs and agriculturalists' risk-mitigating behaviour in N management policy decisions for mitigating deterioration of the health of coastal and marine ecosystems due to diffuse source pollution from agricultural production.

2. Case study context

The Tully sugarcane growing region is among the major sugarcane growing regions in Australia's Wet Tropics. Stretching along Australia's north-eastern coastline in Queensland, the Wet Tropics sugar growing region is parallel to the Great Barrier Reef, a World Heritage Site and Australia's most visited tourist attraction containing extensive areas of coral reef, seagrass meadows and fisheries resources (Kroon et al., 2016) (Fig. 1). The broader Wet Tropics region covers an ecologically diverse World Heritage listed area covering 2.2 million hectares and encompassing vast wet tropical rainforests (Kroon et al., 2016).

Sugarcane is cultivated as a monoculture in the broader Wet Tropics region with yields varying from year to year between 52 and 125 tonnes ha^{-1} in response to variable climate with annual rainfalls ranging from 2200 to over 6000 mm. Historical N rates applied by sugarcane growers in the Wet Tropics region range between 140 and 200 kg ha^{-1} (Thorburn and Wilkinson, 2013). Market prices for sugar and N fertiliser and other farm inputs also vary considerably.

Discharges of dissolved inorganic N (DIN) and other pollutants from coastal catchments into the GBR ecosystem is causing a decline in the coral cover and seagrass meadows of the Great Barrier Reef ecosystem (Kroon et al., 2016). N fertiliser applications to sugarcane crops is a major source of DIN exports, and DIN discharges from catchments in the Wet Tropics pose the greatest risk to the health of the GBR (Waterhouse et al., 2012). Annual rates of N applied to sugarcane in the Wet Tropics are estimated at 100 kg ha^{-1} greater than the amount of N removed from farms in the form of harvested sugarcane (Thorburn and Wilkinson, 2013). In addition, N applied to sugarcane is linked with substantive emissions of nitrous oxide (N_2O) from soils (Thorburn et al., 2010).

The Australian and Queensland governments have, since 2003, implemented policies and targets to reduce exports of pollutants, including N, to the Great Barrier Reef (Kroon et al., 2016; RWQPP, 2009). The sugarcane industry in Queensland has committed to reducing N loss through the adoption of better soil management, use of climate forecasts, legume fallow crops, and N replacement fertiliser management (Schroeder et al., 2010; Thorburn et al., 2011b). The Tully region case study assessment addresses a growing interest by policymakers and agriculturalists to better understand the economic benefits and costs of alternative N management activities.

3. Methods and data

Our methodology involved six distinct steps: 1) developing a conceptual model for calculating net returns and environmental impacts under the three N application strategies, 2) modelling sugarcane yield responses to N application, 3) quantifying uncertainty in parameter values, 4) calculating net returns to sugarcane farmers with and without including environmental costs at six N rates, 5) Comparing the effect on net returns of changing N management strategies under three alternative N management objectives, and 6) systematic uncertainty analysis.

3.1. Developing a conceptual model for calculating net returns

Net returns, *NR*, were calculated using partial budget analysis as the difference between farm revenues and the sum of fertilizer costs and harvesting costs (Fig. 2). To understand the incremental cost vs benefits variable costs of implementing the option, we carried out a gross margin analysis of alternative N management strategies taking into account costs that vary with varying N rate omitting fixed and overhead costs. For example, the fixed component of harvesting costs would not be expected to change with changes in N rates because the call-out fee for harvesters under current contractual arrangements is the same. Thus in a partial or marginal budget analysis, only the difference in the variable component of harvesting costs under different N rates, as influenced by differences in yields under the two N rates, are considered.

Farm revenues were calculated as the product of yield and the market price of sugar taking into account: 1) cane payment formula (CPF) – a formula used by Queensland sugar industry to allocate net income from sugar sales between farmers and millers; and 2) cane sugar content (CCS) – calculated as the ratio of the weight of extractable sugar to the weight of one sugarcane at harvest (Di Bella et al., 2014). The costs included were: 1) the cost of N fertiliser based on N rate and unit cost of N fertilisers (assuming the cost of applying fertiliser was constant across all N rates); and 2) the cost of harvesting operations calculated as the product of the unit harvesting cost ($/tonne) charged by contractors to harvest sugarcane and yield per hectare. In addition, environmental costs were quantified and subtracted from farm revenues to calculate social net return based on 1) DIN loss calculations and the unit abatement cost for DIN discharged to coastal ecosystems; and 2) N_2O emission calculations, converted to CO_2 equivalent (CO_2e), and the unit abatement costs for greenhouse gas N_2O emitted from soils.

3.2. Modelling crop yields

The Agricultural Production sIMulator (APSIM) was used to simulate annual sugarcane yields under six N rates between 30 kg N ha^{-1} and 180 kg N ha^{-1} in increments of 30 kg N ha^{-1} over a period of 108 years between 1902 and 2010 (Thorburn et al., 2011a). The sugarcane growth simulation model operates on a daily time step and simulates yields driven by variability in climate, N inputs, soil-water balances and nitrogen balances across the 108 simulated years based on historical