CSIRO SUSTAINABLE ECOSYSTEMS

Environmental-economic analysis for exploration of efficient land use and land management arrangements, water quality improvement targets and incentives for best management practice adoption in the Tully-Murray catchment

A report to FNQ-NRM Ltd, prepared by:

P.C. Roebeling[1]
M.E. van Grieken[1]
A.J. Webster[2]

[1] CSIRO Sustainable Ecosystems, Davies Laboratory, Private Mail Bag, PO Aitkenvale, QLD 4814
[2] CSIRO Sustainable Ecosystems, Tropical Forest Research Centre, PO Box 780, Atherton, QLD 4883

CSIRO

July 2007

Executive Summary

This report has been prepared for the Cardwell Shire Floodplain Program, coordinated by the Far North Queensland Natural Resource Management board (FNQ-NRM Ltd) under Task 2.8, 2.12 and 3.5 of the Water Quality Improvement Plan (WQIP) for the Tully-Murray catchment. This study explores efficient water quality improvement targets, associated industry land management arrangements and incentives for industry adoption of best management practices for water quality improvement by the sugarcane, horticulture, grazing and forestry industries in the Tully-Murray catchment.[i] More specifically, the objectives of this study are to:

- Explore industry land management arrangements that most cost-effectively achieve specified fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) water quality targets.
- Explore efficient FSS and DIN water quality improvement targets in a linked terrestrial and marine ecosystem.
- Assess the effectiveness of price policy instruments in promoting industry adoption of best management practices achieving FSS and DIN water quality improvement.

We therefore apply and link the EESIP model (based on Roebeling et al., 2006) and the CROWPA model (based on Roebeling, 2006). The Environmental Economic Spatial Investment Prioritization (EESIP) model integrates a land use and value chain model (see Smith et al., 2005) with the water quality model SedNet/ANNEX (see Bartley et al., 2004). It is not only used to explore cost-efficient industry specific land management arrangements for water quality improvement and to assess the effectiveness of price policy instruments in promoting industry best management practice adoption, but also to determine terrestrial (agricultural) benefit functions for use in the Catchment to Reef Optimal Water Pollution Abatement (CROWPA) model. The CROWPA model relates economic benefits from terrestrial agricultural activities and associated water pollution to changes in marine based economic values in order to explore efficient water quality improvement targets (see Roebeling, 2006). Current industry best management practices included in this environmental-economic analysis are taken from the financial-economic analysis identified in Task 3.3 b,c,d (Roebeling et al., 2007). For sugarcane production they include tillage management, fallow management, nitrogen application rate and nitrogen application method. For horticulture (banana) production they include interrow management and fertilizer application rate. For grazing, stocking rate and nitrogen application rate are included as best management practices, whereas for forestry interrow management is considered.

Based on the current industry best management practices and actual land use pattern in the Tully-Murray catchment, this study shows that total FSS and DIN delivery from the Tully-Murray catchment can be reduced by about 10% and 15%, respectively, through the adoption of current win-win best management practices[ii] in sugarcane production (reduced tillage, zero tillage, economic optimum rates of fertilizer application, nitrogen replacement and split nitrogen application). In case there are beneficial spillovers from reduced water pollution that amount to, say, 200$/t FSS and 40,000$/t DIN, this study shows that maximum welfare gains can be obtained by reducing total FSS and DIN delivery from the Tully-Murray catchment by another 20% and 30%, respectively, through a reduction in the industry production area in combination with the adoption of lose-win best management practices[iii] in sugarcane production (further decrease in nitrogen application), horticulture production (further reduced fertilizer application rates) and grazing production (further decrease in stocking rate and nitrogen application rates). In addition, it is shown that FSS delivery is most cost-effectively reduced on paddocks that are located on the steepest slopes, on the least productive soil types and furthest away from Tully, while DIN delivery is most cost-effectively reduced on paddocks that are located on the least productive soil types and furthest away from Tully.

[i] The terms water quality, water pollution and water quality improvement refer to water pollutant delivery to the coast.
[ii] Win-win management practices provide a benefit to the industry as well as to the wider community.
[iii] Lose-win management practices incur a cost to the industry though provide a benefit to the wider community.

Incentives for industry adoption of best management practices for water quality improvement can be provided through various price policy instruments. Water pollutant delivery taxes as well as water pollutant delivery abatement subsidies provide cost-efficient incentives for water quality improvement, though associated costs need to be carried by the involved industries or the government, respectively. In contrast, water pollutant supply taxes as well as a N-fertilizer tax provide non-cost-efficient incentives for water quality improvement because best management practices are adopted throughout the catchment independent of their actual effectiveness in reducing water pollution (i.e. water pollutant delivery to the coast). Although emission based taxes and subsidies are cost-efficient, it is generally hard and costly to measure actual diffuse source emissions (i.e. water pollutant deliveries) and, consequently, it may be more practical to base taxes and subsidies on (non-cost-efficient) diffuse source emission proxies (water pollutant supplies), inputs (N-fertilizers) or management practices (Perman et al., 1999).

A number of caveats to this study need to be mentioned. First, it must be emphasized that industry water pollution abatement costs are based on current best management practices as well as the current land use pattern in the Tully-Murray catchment and, consequently, do not include future best management practices and inter-industry land use change. It can be expected that industry water pollution abatement costs are lower if future best management practices would be taken into account and, similarly, that aggregate water pollution abatement costs are lower if land use change would be taken into account. Second, less reliable welfare maximizing rates of water quality improvement have been identified for the horticulture and forestry industries, as associated water pollution abatement costs are most likely overestimated given that they are based on: i) a limited number of best management practices, and ii) a target-oriented production systems simulation model. Third, we have not been able to identify the welfare maximizing rate of water pollution control for the Tully-Murray catchment, as there are no reliable estimates on the downstream costs from water pollution. Consequently, we evaluated the sensitivity of the model with respect to the downstream costs from water pollution while assuming a fixed cost per unit of water pollution. Finally, the welfare maximizing rates of water quality improvement presented in this study are most likely underestimated as re-suspension of water pollutants and uncertainty in marine benefits from Great Barrier Reef (GBR) conservation have not been taken into account. Consequently and self-evidently, presented results provide an indication of the gross direction and magnitude of change – not an exact recipe for change.

Acknowledgements

This study was commissioned by and funded through the Far North Queensland Natural Resource Management board (FNQ-NRM Ltd), which is currently co-ordinating the development of a Water Quality Improvement Plan (WQIP) for the Tully-Murray catchment. We thank all industry representatives and experts from CSIRO, ACTFR, NRW, DPI&F, CaneGrowers, GrowCom and ITC for their valuable contribution to the underlying information used in this report. Also, we would like to thank the Cardwell Shire Floodplain Program (CSFP) and the Production Action Team (PAT) for their continuous support and feedback.

Table of contents

1. Introduction

The development of a water quality improvement plan for the Tully-Murray catchment, which is co-ordinated by the Far North Queensland Natural Resource Management board (FNQ-NRM Ltd), requires the integration of results from Tasks outlined in the Water Quality Improvement Plan (WQIP) for the Tully-Murray catchment. The objective of this project is to assess and identify landscape management (i.e. the way in which land is used and managed) and arrangement (i.e. the spatial distribution of land use and management) options and pathways for water quality improvement in the Tully-Murray catchment. To this end, the following Tasks described in the WQIP for the Tully-Murray catchment will be developed simultaneously:

- Task 2.8 — Identify the specific locations where investment in improved riparian, wetland and instream conditions may deliver cost-effective reductions in pollutants.
- Task 2.12 — Estimate WQIP targets for suspended sediments, nitrogen, phosphorus and pesticides to the receiving water body, to be applied during the period of this WQIP for the purpose of achieving the water quality objectives and total maximum load objectives.
- Task 2.15 — Describe how the impacts of future growth and climate change will be accounted for in proposed management measures and control actions, and attainment and maintenance of the total maximum pollutant load for key pollutants to the receiving water body.
- Tasks 3.3a,b,c,d — Review of strengths and weaknesses of best-management-practices in Wet Tropics catchments, in particular as related to water quality improvement.
- Task 3.5 — Evaluate incentives for uptake and long-term implementation of BMPs.

This report addresses Task 2.8, 2.12 and 3.5, thereby focussing on land management change (rather than land use change) for water quality improvement by the sugarcane, horticulture, grazing and forestry industries in the Tully-Murray catchment. In particular, we will: i) explore industry land management arrangements that most cost-effectively achieve specified water quality targets, ii) explore efficient water quality improvement targets, and iii) assess incentives for industry adoption of best management practices achieving water quality improvement.[1] To explore industry specific land management arrangements that most cost-effectively achieve specified fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) water quality targets, we use the Environmental Economic Spatial Investment Prioritization (EESIP) model which is a spatial environmental-economic approach that integrates a land use and value chain model with a hydrological model (see Roebeling et al., 2006). To explore efficient FSS and DIN water quality improvement targets, we use the Catchment to Reef Optimal Water Pollution Abatement (CROWPA) model which is a deterministic optimal control approach that relates economic benefits from terrestrial agricultural activities and associated water pollution to changes in marine based economic values (see Roebeling, 2006). Finally, we again use the EESIP model to assess the effectiveness of price policy instruments in promoting industry adoption of best management practices for FSS and DIN water quality improvement.

The structure of the report is as follows. Chapter 2 describes the methodology applied in this study, which applies and links a spatial environmental-economic modelling approach and a deterministic optimal control approach to explore efficient water quality improvement targets and associated industry land management arrangements as well as incentives for industry best management practice adoption. In Chapter 3 results are presented and analysed, thereby focusing on FSS and DIN water pollution in the sugarcane, horticulture, grazing and forestry industries in the Tully-Murray catchment. Finally, Chapter 4 provides key results, concluding remarks and observations.

[1] Throughout the document the terms water quality, water pollution and water quality improvement refer to the delivery of water pollutants to the coast.

2. Approach to environmental-economic analysis

Water quality targets can be met and set in a number of ways. In this report we use the Environmental Economic Spatial Investment Prioritization (EESIP) model (based on Roebeling et al., 2006) to explore industry land management arrangements that most cost-effectively achieve specified water quality targets (see Section 2.1), the Catchment to Reef Optimal Water Pollution Abatement (CROWPA) model (based on Roebeling, 2006) to explore optimal (i.e. efficient) rates of water quality improvement in a linked terrestrial and marine ecosystem (see Section 2.2) and, in turn, the EESIP model to assess the effectiveness of price incentives in promoting industry adoption of best management practices for water quality improvement (see Section 2.1). Note that the notation used in Section 2.1 and Section 2.2 is not interchangeable.

2.1 Spatial environmental-economic land use model

There are numerous spatially explicit explorative approaches in agricultural and environmental economics that relate land use location to economic opportunities and environmental consequences (Nelson, 2002; Khanna et al., 2003; Rounsevell et al., 2003; Hajkowicz et al., 2005; Jansen et al., 2005). These studies are, however, either relatively weak from an economic point of view (plot level economic indicators aggregated to the regional level) or relatively weak from an environmental point of view (plot level environmental indicators aggregated to the regional level). In contrast, we use the Environmental Economic Spatial Investment Prioritization (EESIP) model (based on Smith et al., 2005; Roebeling et al., 2006), which is a spatial environmental-economic approach that integrates a land use and value chain model with a hydrological model to: i) explore land use and land management arrangements that most cost-effectively achieve specified fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) water quality targets, and ii) assess the effectiveness of price policy instruments in promoting industry adoption of best management practices for FSS and DIN water quality improvement.

The developed approach recognizes that: i) bio-physical characteristics of the land vary widely according to location and, in turn, determine agricultural production potentials, ii) climatic and geomorphologic conditions differ according to location and, in combination with land use and management practice, determine diffuse source water pollutant delivery to the coast, and iii) farmers make use of existing (non-straight line) infrastructure to transport their produce to the processing plant or market. Moreover, differences in fixed and variable costs and potential benefits from alternative agri-industrial processing options are considered.

Land use and land management are allocated at the regional scale on the basis of which land use and management practice on a particular land unit contributes most to regional agricultural income, where regional agricultural income is estimated as (per hectare) production value (based on final products) less corresponding fixed and variable production, transport and processing costs. The mathematical model, which is solved using GAMS 2.50 (Brooke et al., 1998), is structured as follows.

The total agricultural area a in the region is divided into uniform blocks of land $L_{i,j,k}$, where each block of land is: i) geographically referenced by a site specific identification tag (i), ii) used to grow a specific crop (j), and iii) using a particular management practice (k). Each land use site $L_{i,j,k}$ is characterized by a specific distance to the processing plant or market by road $d_{i,}^{road}$ or rail $d_{i,}^{rail}$ (in km), specific soil characteristics and yields $y_{i,j,k}$ (in t/ha), and specific production costs $q_{i,j,k}$ (in \$/ha) (based on Roebeling et al., 2007). The region maximizes regional agricultural income π, so that

$$\begin{aligned}\underset{L_{i,j,k}}{Max}\,\pi = &\sum_{i,j,k}\left(p_j h_j y_{i,j,k} L_{i,j,k} - q_{i,j,k} L_{i,j,k}\right)\\ &-\left[\sum_{i,j,k}\left(v^{road} d_i^{road} y_{i,j,k} L_{i,j,k}\right)\right]_{j=1..n} - \left[\sum_{i,j,k}\left(v^{rail} d_i^{rail} y_{i,j,k} L_{i,j,k}\right)\right]_{j=n+1..N}\\ &-\sum_{i,j,k}\left(v^{proc} y_{i,j,k} L_{i,j,k}\right) - f^{rail} - f^{proc}\end{aligned} \tag{1}$$

where p_j is the price of final product j (market price in \$/t), h_j is the fraction of final product per unit of crop, v^{road} and v^{rail} are the variable transport costs by road and rail (in \$/t/km), and where f^{rail} and f^{proc} are total fixed costs associated to rail and processing infrastructure (in \$). Note that for each product j the mode of transport is pre-defined to be either road (j = 1..n) or rail (j = n+1..N). The objective function is maximized subject to an *ID* block size and regional area constraint, which are respectively given by

$$\sum_{j,k} L_{i,j,k} \le a_i \tag{2}$$

$$\sum_{i,k} L_{i,j,k} \le a_j \tag{3}$$

with a_i the maximum block size over all crops and a_j the maximum crop area over all blocks (in ha).[2]

Fine suspended sediment (FSS) delivery D_i^{FSS} (in t) and dissolved inorganic nitrogen (DIN) delivery D_i^{DIN} (in t) to the river mouth that originate from land uses and management practices at location i, are estimated using SedNet/ANNEX (see Prosser et al., 2001; Bartley et al., 2004) in combination with estimates for plot level FSS supply c^{FSS} and DIN supply c^{DIN} for land uses j and management practices k (see Roebeling et al., 2007), such that

$$D_i^{FSS} = \sum_{j,k} \chi_i^{FSS} c_{i,j,k}^{FSS} L_{i,j,k} \tag{4}$$

$$D_i^{DIN} = \sum_{j,k} \chi_i^{DIN} c_{i,j,k}^{DIN} L_{i,j,k} \tag{5}$$

where χ_i^{FSS} and χ_i^{DIN}, respectively, the fraction of FSS and DIN supply from location i ending up at the river mouth. Total water pollutant deliveries to the coast from all land uses in the catchment are given by the sum of water pollutant deliveries for all locations i in that catchment.

To explore land use and land management arrangements that most cost-effectively achieve specified fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) water quality targets, these total water pollutant deliveries are constrained by specified water quality targets t, so that

$$\sum_i D_i^{FSS} \le t^{FSS} \tag{6}$$

$$\sum_i D_i^{DIN} \le t^{DIN} \tag{7}$$

with t^{FSS} and t^{DIN} the FSS and DIN water quality targets, respectively.

[2] The maximum crop area a_j corresponds to the total industry area in the region, i.e.: $a_j \le \sum_{ID} a_{ID}$.

To assess the effectiveness of price policy instruments in promoting industry adoption of best management practices to achieve FSS and DIN water quality improvement, either parameter values are changed (e.g. in the case of input price tax) or additional lines are added to the objective function (e.g. in the case of water pollutant tax or water pollutant abatement subsidy) to reflect the changes brought about by the price policy instrument. Price instruments assessed in this study include a water pollutant delivery tax, a water pollutant supply tax, a water pollutant delivery abatement subsidy and a nitrogen (N) fertilizer tax. To this end we add the following lines to the objective function (regional agricultural income π – see Eqn 1) for the first three instruments

- water pollutant delivery tax - FSS: $-p^{FSS}\sum_{i,j,k}\left(\chi_i^{FSS}c_{i,j,k}^{FSS}L_{i,j,k}\right)$

  - DIN: $-p^{DIN}\sum_{i,j,k}\left(\chi_i^{DIN}c_{i,j,k}^{DIN}L_{i,j,k}\right)$
- water pollutant supply tax - FSS: $-p^{FSS}\sum_{i,j,k}\left(c_{i,j,k}^{FSS}L_{i,j,k}\right)$

  - DIN: $-p^{DIN}\sum_{i,j,k}\left(c_{i,j,k}^{DIN}L_{i,j,k}\right)$
- water pollutant delivery abatement subsidy - FSS: $+s^{FSS}\left(\left[D^{FSS}\right]_{Baseline}-\sum_{i,j,k}\left(\chi_i^{FSS}c_{i,j,k}^{FSS}L_{i,j,k}\right)\right)$

  - DIN: $+s^{DIN}\left(\left[D^{DIN}\right]_{Baseline}-\sum_{i,j,k}\left(\chi_i^{DIN}c_{i,j,k}^{DIN}L_{i,j,k}\right)\right)$

where p^{FSS} and p^{DIN} the water pollutant tax (in \$/t), where s^{FSS} and s^{DIN} the water pollutant abatement subsidy (in \$/t), and where $[D^{FSS}]_{Baseline}$ and $[D^{DIN}]_{Baseline}$ the baseline water pollutant deliveries (in t) for FSS and DIN, respectively.

The N-fertilizer tax is simply reflected by adjusting the specific production costs $q_{i,j,k}$ (see Eqn 1) in accordance with the fertilizer tax.

2.2 Environmental-economic optimal control model

There are a number of studies throughout the world that relate economic benefits from terrestrial water pollution to (indicators of) reef health and subsequent changes in marine based economic values (Hodgson and Dixon, 1988; Ruitenbeek et al., 1999; Ruitenbeek and Cartier, 1999; Gustavson and Huber, 2000; Cesar et al., 2002; Wielgus et al., 2002; Roebeling, 2006). We use the Catchment to Reef Optimal Water Pollution Abatement (CROWPA) model (adapted from Roebeling, 2006), which is a deterministic optimal control approach used to explore optimal rates of fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) water quality improvement in a linked terrestrial and marine ecosystem.

Let $B_{ter}(R_t)$ denote total terrestrial benefits from agriculture in a Great Barrier Reef (GBR) catchment that are a function of the rate of (agricultural) water pollution R_t (control variable), and let $B_{mar}(P_t)$ denote total marine benefits from economic use and non-use values of the GBR catchment lagoon that are a function of the level of (GBR catchment lagoon) water pollution P_t (stock variable). The annual flow of net benefits $\pi(P_t,R_t)$ is given by the sum of terrestrial and marine benefits, and is given by

$$\begin{aligned}\pi(P_t,R_t) &= B_{ter}(R_t) + B_{mar}(P_t)\\ &= \left(\alpha_1+\alpha_2 R_t-\alpha_3 R_t^2\right)+\left(\beta_1^{use}+\beta_1^{non-use}\right)-\left(\beta_2^{use}+\beta_2^{non-use}\right)P_t\end{aligned} \tag{8}$$

where α_1 is the value of agricultural production without water pollution, α_2 and α_3 are the terrestrial benefit coefficients (note there are decreasing marginal benefits from the rate of water pollution), and where β_1 reflects the economic value of the GBR catchment lagoon in the absence of water pollution

($\beta_1 > 0$) and β_2 reflects the water pollution cost coefficient ($\beta_2 > 0$) corresponding to local use (β^{use}) and global non-use ($\beta^{non\text{-}use}$) values of the GBR catchment lagoon. The optimal control welfare (W) maximizing problem now becomes

$$\underset{R_t}{Max}\, W = \int_0^\infty [\pi(P_t, R_t)] e^{-rt} dt \qquad (9)$$

subject to

$$\dot{P}_t = b + R_t - aP_t \qquad (10)$$

and

$$P_0 > 0 \text{ and } R_0 > 0$$

$$P_t \geq 0 \text{ and } R_t \geq 0$$

where r is the time discount rate, $\dot{P}_t$ is the equation of motion for P_t, and where a dot over a variable denotes the derivative of that variable with respect to time t. The equation of motion $\dot{P}_t$ for the level of water pollution P_t is determined by the annual level of exogenous water pollution originating from World Heritage and non-agricultural areas (b), the rate of water pollution associated to agricultural production (R_t) and the fraction of total water pollution permanently lost from the system through deposition, transport, uptake and other biophysical processes (aP_t).

Based on Roebeling (2006), it can now be shown that the optimal rate of (agricultural) water pollution R^* and the optimal level of water pollution P^* in the steady state are, respectively, given by

$$R^* = \frac{\alpha_2(r+a) - (\beta_2^{use} + \beta_2^{non-use})}{2\alpha_3(r+a)} \qquad (11)$$

$$P^* = \frac{b + R^*}{a} \qquad (12)$$

It can be observed that the rate of water pollution R^* is decreasing in α_3 and β_2, and increasing in α_2, r and a (see Eqn 11), while the level of water pollution P^* is decreasing in a, and increasing in b and R^* (see Eqn 12).

This model can now be used to determine the optimal rate of water pollution R^* for each industry and each water pollutant separately, because: i) we take marine benefits $B_{mar}(P_t)$ to be linearly decreasing in the level of water pollution P_t (see Eqn 8) which implies that the cost per unit of water pollution is constant (β_2) and thus independent of water pollution from other industries, and ii) there is no significant correlation between the assessed water pollutants FSS and DIN (Roebeling et al., 2007).

3. Results of the environmental-economic analysis

In this chapter we apply the EESIP and CROWPA models (described in Chapter 2) to a case study in the Tully-Murray catchment, to explore industry land management arrangements that most cost-effectively achieve specified fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) water quality targets (see Section 3.1), to explore efficient water quality improvement targets for FSS and DIN water pollution in a linked terrestrial and marine ecosystem (see Section 3.2), and to assess the effectiveness of price policy instruments in promoting industry adoption of best management practices to achieve FSS and DIN water quality improvement (see Section 3.3). Note that as there is no hydrological model available that accurately describes the relationship between plot level persistent herbicide concentrations and persistent herbicide delivery (see Roebeling et al., 2007), we focus on FSS and DIN water pollution in the sugarcane, horticulture, grazing and forestry industries.

3.1 Efficient industry land management arrangements

The EESIP model presented in Section 2.1 is used to explore industry land management arrangements that most cost-effectively achieve specified water quality targets. To this end we constrain fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) water pollutant delivery in the sugarcane, horticulture, grazing and forestry industries (using Eqns 6 and 7) in a stepwise fashion, thereby relaxing the fixed land management constraint per industry assumed in the base scenario (i.e. reflecting current industry management practices in the Tully-Murray catchment) while not allowing for land use change between industries (i.e. reflecting current land use in the Tully-Murray catchment). These results are, in turn, used in Section 3.2, to determine terrestrial (agricultural) benefit functions for each industry and for each water pollutant.

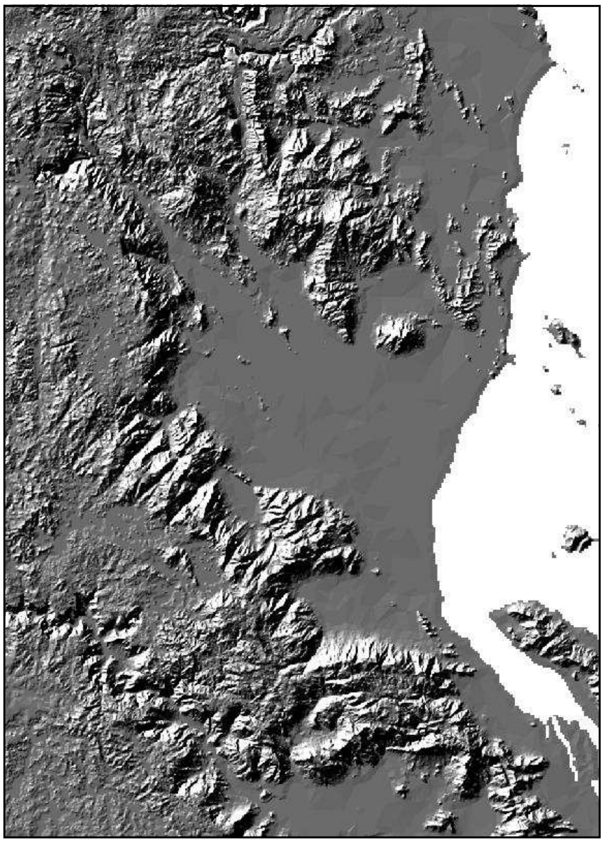
The model is parameterized and calibrated using constant 2005 input prices and average 2003 to 2005 output prices as well as detailed input-output figures for production systems and management practices in sugarcane, horticulture, grazing and forestry production (Roebeling et al., 2007), in combination with digital elevation (QLUMP, 2004), soil class (based on Murtha and Smith, 1994; see Roebeling et al., 2007),[3] and rail and road distance (see Roebeling et al., 2006) information (Figure 1). Regarding the input-output figures for production systems and management practices, it should be noted that 576 sugarcane, 54 horticulture, 660 grazing and 6 forestry management practice combinations are included in the analysis (from Roebeling et al., 2007).

The following sections provide an overview of the baseline, the fine suspended sediment reduction and the dissolved inorganic nitrogen reduction scenarios, respectively.

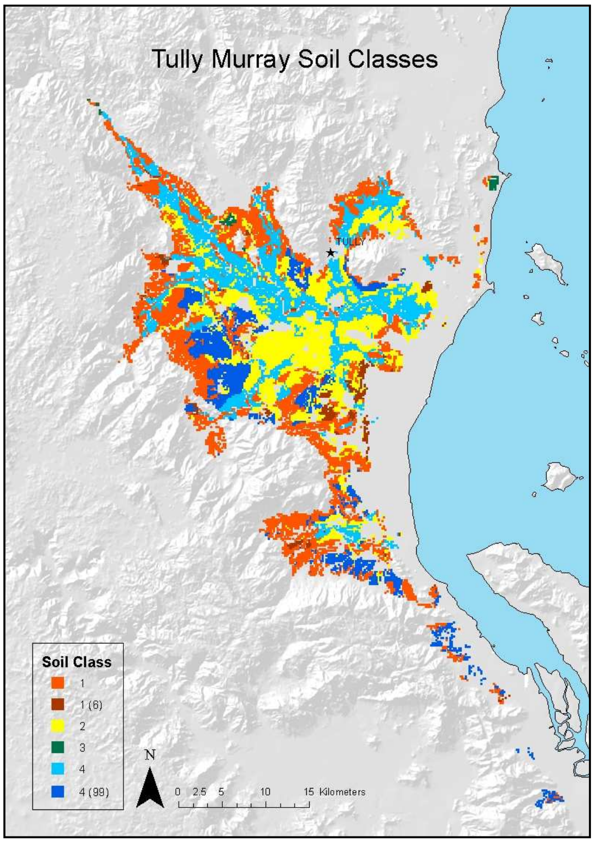
[3] The area distribution amongst the four soil classes S1 to S4 is 27,377 ha of soil class S1, 18,880 ha of soil class S2, 321 ha of soil class S3 and 26,782 ha of soil class S4.

Figure 1 Contour (a), soil class (b), rail distance (c) and road distance (d) maps for the Tully-Murray catchment

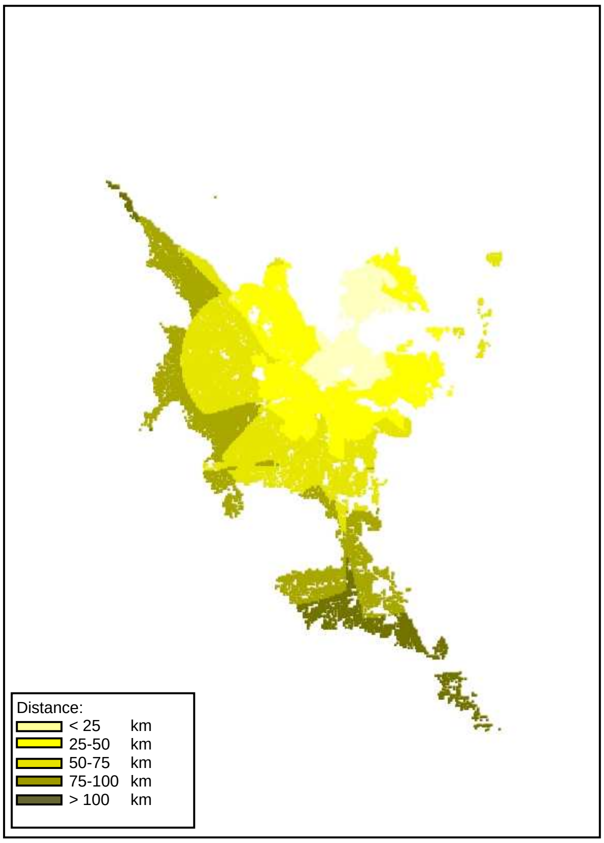
(a)



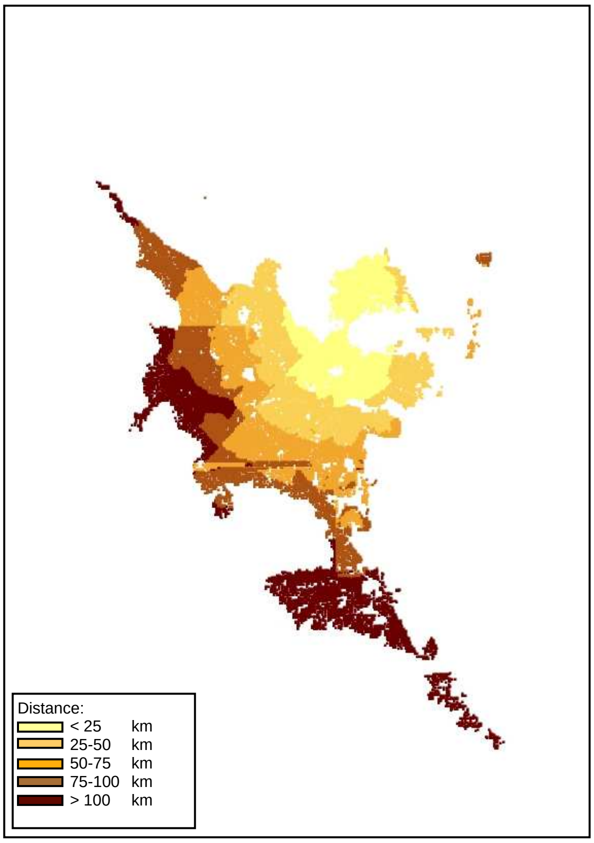
(b)



(c)



(d)

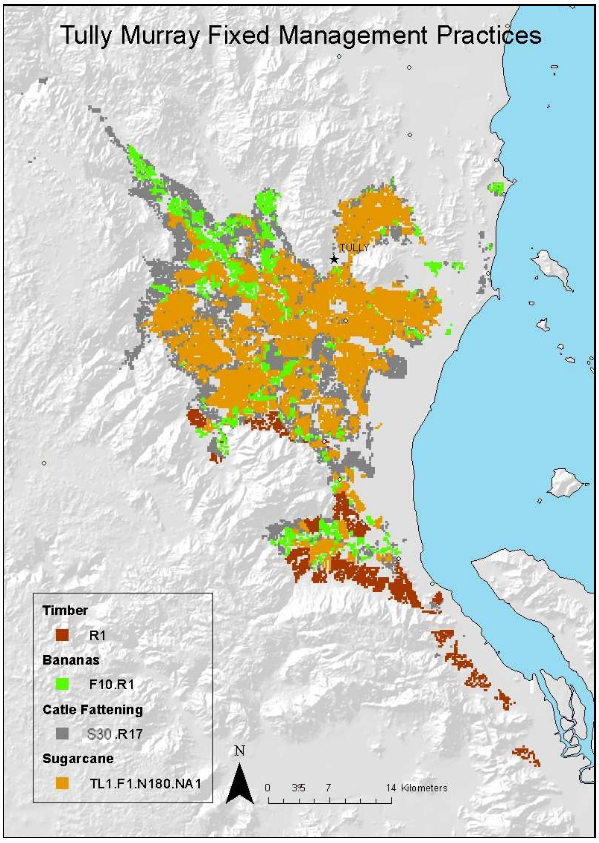


3.1.1 Baseline scenario

Baseline model results per industry and associated land management arrangements in the Tully-Murray catchment are shown in Table 1 and Figure 2, respectively. Total agricultural land use in the Tully-Murray catchment equals just over 72,000 ha, with sugarcane and grazing the dominant land uses covering, respectively, about 50% and 30% of the total agricultural land use area. Horticulture and forestry only account for 12% and 8% of the agricultural land use area, respectively.

From an economic perspective, however, sugarcane and horticulture are the most important industries in the Tully-Murray catchment. The sugarcane and horticulture industry account for, respectively, about 50% and 40% of the regional agricultural income, while the grazing and forestry industry account for, respectively, 7% and 3% of the agricultural income in the Tully-Murray catchment. Regional agricultural income in the Tully-Murray catchment equals about 125 million $ per year.

Figure 2 Baseline land management arrangements in the Tully-Murray catchment



Notes: Timber:		R1 = bare interrow; R2 = grassed interrow.
Bananas:		F02 = 20% of fertilizer requirements; …; F10 = 100% of fertilizer requirements. R1 = bare interrow; R2 = grassed interrow.
Cattle fattening:		S20 = 0% nitrogen fertilizer requirements; …; S30 = 0% nitrogen fertilizer requirements. R11 = 0.5 animal units per hectare; …; R25 = 4.0 animal units per hectare.
Sugarcane:		TL1 = actual tillage; TL2 = minimum tillage; TL3 = zero tillage. F1 = bare fallow; F2 = legume fallow. N060 = 60 kg N/ha; …; N210 = 210 kg N/ha; N888 = nitrogen replacement. NA1 = single nitrogen application; NA2 = split nitrogen application.

Rates of fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) water pollution from sugarcane, horticulture, grazing and forestry production are, roughly, proportional to the relative land use distribution for each of the industries in the Tully-Murray catchment. Total FSS delivery equals

about 55 kt/yr, while noting that sugarcane, horticulture and forestry production contribute about 10% to 15% more to FSS delivery as compared to their relative land share. Similarly, total DIN delivery equals almost 650 t/yr, while noting that sugarcane and horticulture production contribute up to 20% more to DIN delivery as compared to their relative land share.

3.1.2 Fine suspended sediment delivery scenarios

Reduced FSS delivery scenario results per industry and associated land management arrangements in the Tully-Murray catchment are shown in Table 1 and Figure 3, respectively. From Table 1 it can be observed that FSS water pollution control becomes increasingly expensive at larger rates of FSS water pollution abatement, while there are large differences between industries.

Table 1 Model results per industry in the Tully-Murray catchment for the baseline and a 20%, 40% and 60% reduction in fine suspended sediment (FSS) delivery

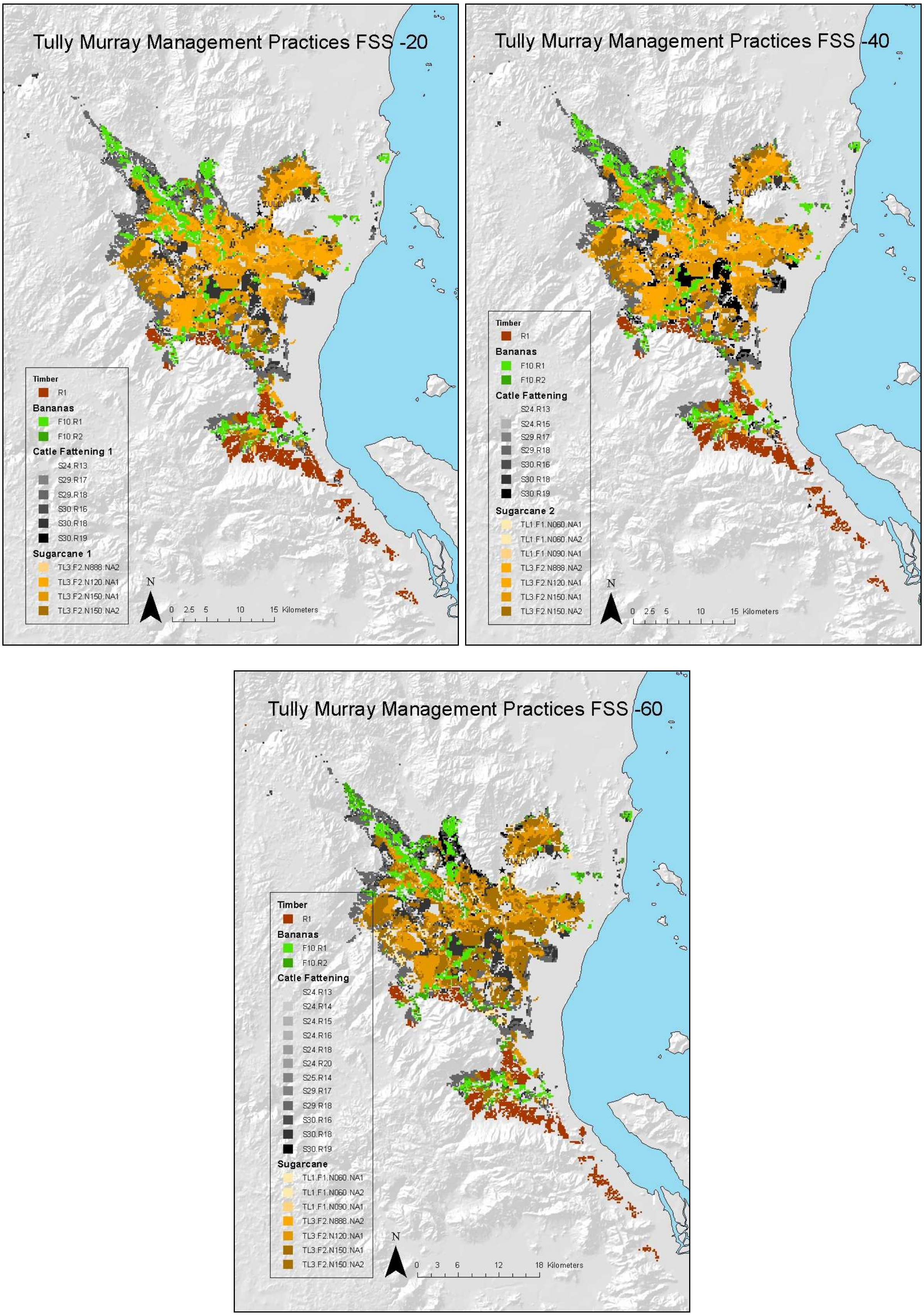
Scenario[1]	Indicator	Unit	Sugarcane	Horticulture	Grazing	Forestry	Total
Baseline	Land use	ha	36,548.0	8,064.0	22,964.0	5,784.0	73,360.0
	Regional agr. inc.	million $	65.4	48.2	8.4	4.7	126.7
	FSS delivery	kt FSS	29.7	7.5	12.3	4.9	54.4
	DIN delivery	t DIN	371.0	85.7	176.5	10.5	643.8
FSS -20%	Land use	ha	36,542.9	8,064.0	17,408.0	5,744.0	67,758.9
	Regional agr. inc.	million $	66.2	47.9	7.2	4.6	125.9
	FSS delivery	kt FSS	20.0	6.0	8.6	3.9	38.6
	DIN delivery	t DIN	245.8	85.7	111.1	10.3	452.9
FSS -40%	Land use	ha	36,501.1	8,064.0	17,401.1	5,504.7	67,470.9
	Regional agr. inc.	million $	65.2	47.6	7.2	4.3	124.3
	FSS delivery	kt FSS	17.8	4.5	7.7	2.9	32.9
	DIN delivery	t DIN	242.9	85.7	111.1	9.6	449.3
FSS -60%	Land use	ha	34,430.1	8,064.0	17,260.0	4,909.1	64,663.2
	Regional agr. inc.	million $	57.3	47.1	6.9	3.6	115.0
	FSS delivery	kt FSS	11.9	3.0	5.1	1.9	21.9
	DIN delivery	t DIN	217.7	85.7	111.1	8.0	422.5

Note: [1] Baseline scenario (Baseline), 20% reduction in FSS delivery (FSS -20%), 40% reduction in FSS delivery (FSS -40%) and 60% reduction in FSS delivery (FSS -60%). Note: scenario steps are not always 20% for all industries.

In sugarcane production, a 20% reduction in FSS delivery is expected to come at a benefit to the industry due to the adoption of win-win management practices (reduced tillage and zero tillage). A further reduction in FSS delivery would, however, come at a significant cost to the sugarcane industry and is most cost-effectively achieved through a reduction in the sugarcane area, altered fertilizer application rates and re-arrangement of land management across the landscape. In particular, for 'FSS -40%' most cost-effective fertilizer application rates are used on each soil type (150 kg N/ha on S1; 120 kg/ha on S2 and S4), while for 'FSS -60%' a significant amount of sugarcane land (on steepest slopes, on the least productive soil type S4 and furthest away from Tully) is taken out of production and fertilizer application rates on soil type S2 are increased to minimize subsequent foregone production returns.

In horticulture (banana) production, reductions in FSS delivery are expected to come at a small cost to the industry due to the gradual adoption of grassed interrows. The most cost-effective location for grassed interrows is close to rivers and/or river mouths.

Figure 3 Cost-efficient land management arrangements in the Tully-Murray catchment for a 20%, 40% and 60% reduction in fine suspended sediment (FSS) delivery



Notes: See Figure 2.

In beef production, reductions in FSS delivery are expected to come at a significant cost to the grazing industry as a result of a reduction in the grazing area in combination with the adoption of reduced stocking rates. Grazing land on the steepest slopes, on the least productive soil type (S4) and furthest away from Tully is taken out of production first, while stocking rates (and subsequent nitrogen fertilizer application rates) are most cost-effectively reduced on the most productive soil type (S1) and, again, furthest away from Tully.

Finally, in forestry production reductions in FSS delivery are expected to come at a significant cost to the industry as a result of a reduction in the forestry area. In effect, it is more cost-effective to take forestry land out of production than to adopt grassed interrows. Once again we see that forestry land on the steepest slopes, on the least productive soil type (S4) and furthest away from Tully is taken out of production first.

3.1.3 Dissolved inorganic nitrogen scenarios

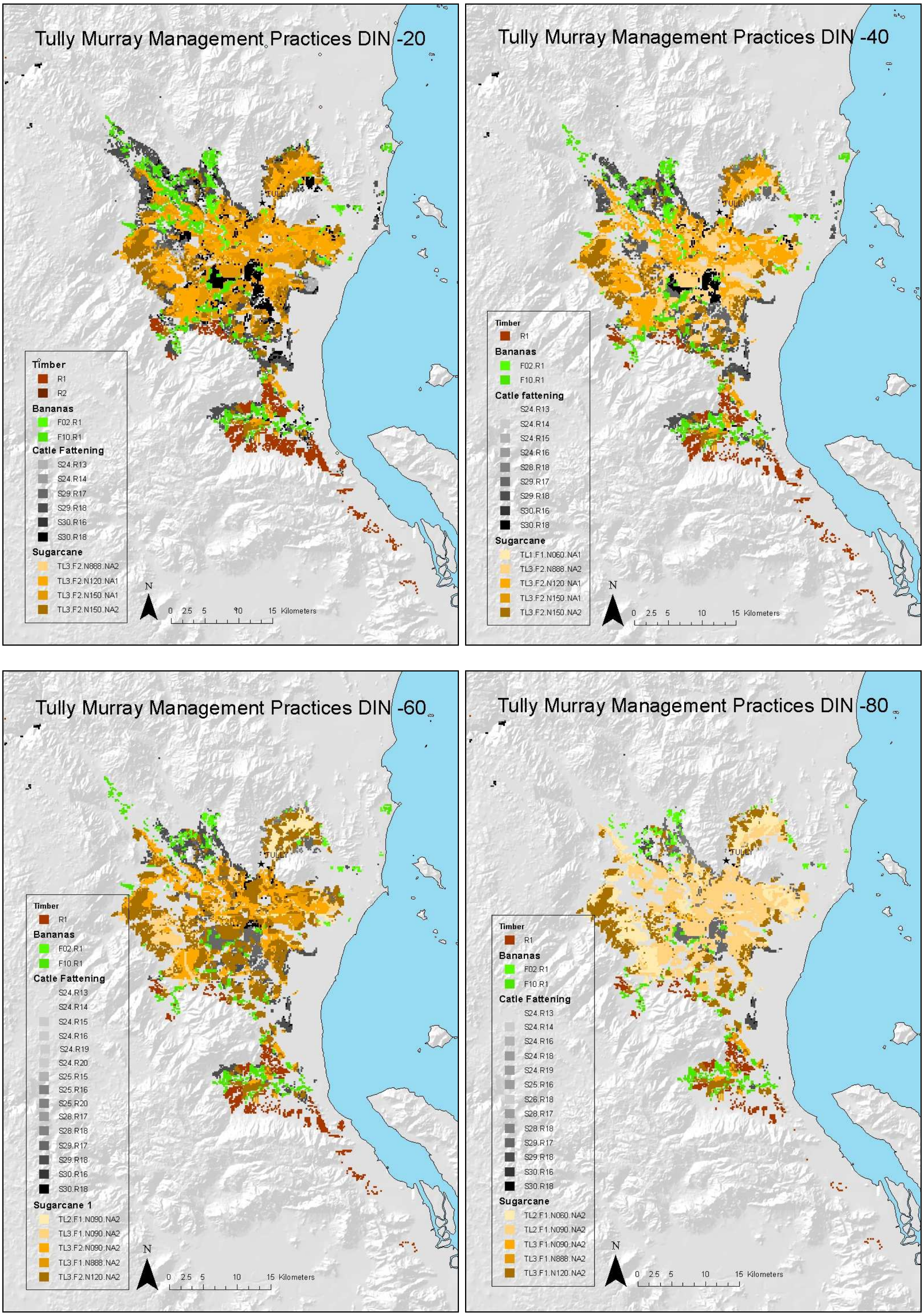
Reduced DIN delivery scenario results per industry and associated land management arrangements in the Tully-Murray catchment are shown in Table 2 and Figure 4, respectively. Like with FSS water pollution control, it can be observed from Table 2 that DIN water pollution control becomes increasingly expensive at larger rates of DIN water pollution abatement and, again, that there are large differences between industries.

Table 2 Model results per industry in the Tully-Murray catchment for the baseline and a 20%, 40%, 60% and 80% reduction in dissolved inorganic nitrogen (DIN) delivery

Scenario[1]	Indicator	Unit	Sugarcane	Horticulture	Grazing	Forestry	Total
Baseline	Land use	ha	36,548.0	8,064.0	22,964.0	5,784.0	73,360.0
	Regional agr. inc.	million $	65.4	48.2	8.4	4.7	126.7
	FSS delivery	kt FSS	29.7	7.5	12.3	4.9	54.4
	DIN delivery	t DIN	371.0	85.7	176.5	10.5	643.8
DIN -20%	Land use	ha	36,542.9	7,676.1	14,916.0	4,884.0	64,019.0
	Regional agr. inc.	million $	66.2	41.0	6.1	4.1	117.4
	FSS delivery	kt FSS	20.0	6.5	6.9	4.2	37.5
	DIN delivery	t DIN	245.8	68.6	88.8	8.4	411.6
DIN -40%	Land use	ha	36,548.0	6,185.6	12,316.7	3,520.0	58,570.3
	Regional agr. inc.	million $	66.1	33.5	4.8	3.4	107.8
	FSS delivery	kt FSS	20.0	5.5	4.8	3.1	33.5
	DIN delivery	t DIN	222.6	51.4	66.6	6.3	347.0
DIN -60%	Land use	ha	36,542.9	4,480.0	8,830.8	3,204.0	53,057.6
	Regional agr. inc.	million $	65.1	24.5	3.3	2.4	95.3
	FSS delivery	kt FSS	20.4	3.8	3.0	2.5	29.8
	DIN delivery	t DIN	148.4	34.3	44.4	4.2	231.3
DIN -80%	Land use	ha	36,542.9	3,453.7	5,113.5	2,012.0	47,122.1
	Regional agr. inc.	million $	59.7	14.4	1.8	1.2	77.1
	FSS delivery	kt FSS	24.3	2.2	1.7	1.5	29.8
	DIN delivery	t DIN	74.2	17.1	22.2	2.1	115.7

Note: [1] Baseline scenario (Baseline), 20% reduction in DIN delivery (DIN -20%), 40% reduction in DIN delivery (DIN -40%), 60% reduction in DIN delivery (DIN -60%) and 80% reduction in DIN delivery (DIN -80%). Note that scenario steps are not always 20% for all industries.

Figure 4 Cost-efficient land management arrangements in the Tully-Murray catchment for a 20%, 40%, 60% and 80% reduction in dissolved inorganic nitrogen (DIN) delivery



Notes: See Figure 2.

In sugarcane production, a reduction in DIN delivery of up to 40% is expected to come at a benefit to the industry due to the adoption of win-win management practices (economic optimum rates of fertilizer application, nitrogen replacement and split nitrogen application). A further reduction in DIN delivery would, however, come at a significant cost to the sugarcane industry and is most cost-effectively achieved through a further decrease in rates of nitrogen application, in particular on the least productive soil type (S4) and to a minor extent on the most productive soil types (S1 and S2) as the yield response to nitrogen application is largest on these most productive soil types.

In horticulture (banana) production, reductions in DIN delivery are expected to come at a large cost to the industry as a result of a reduction in the horticulture area in combination with reduced rates of fertilizer application. Horticulture land on the least productive soil type (S2 – note that there is no horticulture production on S4) and furthest away from Tully is taken out of production first, while fertilizer application rates are proportionally reduced on all soil types.

In beef production, reductions in DIN delivery are expected to come at a large cost to the grazing industry as a result of a reduction in the grazing area in combination with reduced rates of nitrogen application. Grazing land on the least productive soil type (S4) and furthest away from Tully is taken out of production first, while nitrogen application rates (and subsequent stocking rates) are most cost-effectively reduced on the most productive soil types (S1 and S2) furthest away from Tully.

Finally, in forestry production reductions in DIN delivery are expected to come at a large cost to the industry as a result of a reduction in the forestry area. Forestry income losses are larger as compared to those for the FSS scenarios, because DIN delivery is less location dependent as compared to FSS delivery. Moreover, nitrogen application best management practices in forestry production have not been assessed and included in this study.

3.2 Efficient industry water quality improvement targets

The CROWPA model presented in Section 2.2 is used to determine optimal rates of water pollution R^* for each industry and each water pollutant separately. To this end we first determine parameter estimates for the terrestrial (agricultural) benefit functions $B_{ter}(R_t)$ per industry and per water pollutant (using Eqn 8) and, in turn, (based on these parameter estimates) we determine optimal rates of (agricultural) water pollution R^* per industry and per water pollutant (using Eqn 11). As the quantitative relationship between water pollution and indicators of reef health is not well established and, thus, neither is the relationship between water pollution and marine based economic values (Roebeling et al, 2006), we perform a sensitivity analysis with respect to water pollution costs β_2 (see Eqn 8). Again, we focus on fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) water pollution in the sugarcane, horticulture, grazing and forestry industries.

Table 3 Parameter estimates for terrestrial benefit functions $B_{ter}(R_t)$ per industry and per water pollutant

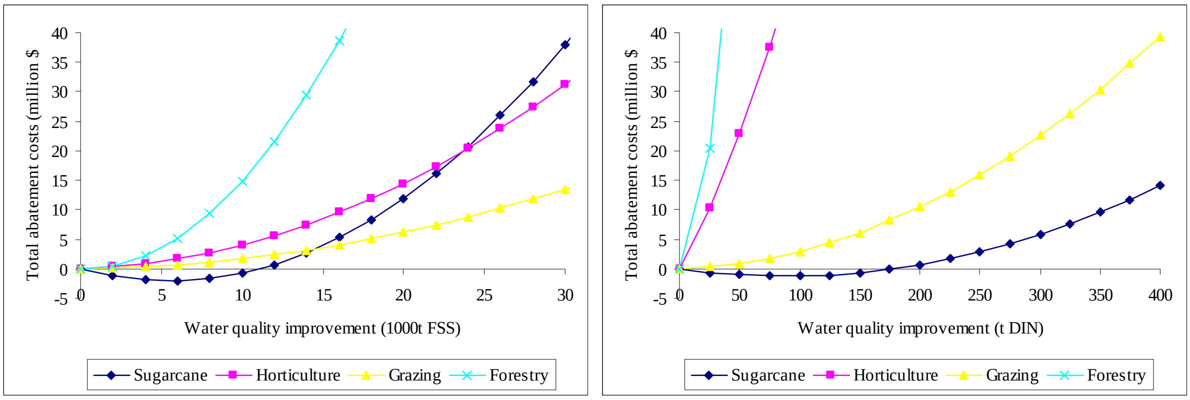
	FSS				DIN			
	Sugarcane	Horticulture	Grazing	Forestry	Sugarcane	Horticulture	Grazing	Forestry
α_1	28.4010	23.8100	3.6853	1.4097	54.4810	3.4770	-0.2035	-0.1982
α_2	3.2408	0.5682	0.3745	1.4330	0.0900	0.6646	0.0876	0.7222
α_3	-0.0672	-0.0315	-0.0142	-0.1564	-0.0002	-0.0017	-0.0002	-0.0246

Based on the EESIP model results presented in Tables 1 and 2 (see Section 3.1), we estimate the terrestrial (agricultural) benefit functions for each industry and each water pollutant by plotting the rate of water pollution R_t against the terrestrial benefits $B_{ter}(R_t)$ and fitting the quadratic terrestrial

agricultural benefit functions (see Eqn 8). Parameter estimates are given in Table 3 and corresponding total water pollution abatement cost functions are shown in Figure 5.[4]

To put the total abatement cost functions (Figure 5) into perspective, we need to bear in mind the base rates of water pollution R_0 per industry (given in Tables 1 and 2, and for convenience repeated in Table 4) which are to a large extent determined by the land use area covered by each of these industries. Some of the total abatement cost functions rise sharply in the rate of water quality improvement (particularly for FSS in the forestry industry and for DIN in the horticulture and forestry industries), as the potential for these industries to contribute to water quality improvement is limited due to their relatively small land use area within the catchment and/or the limited availability or even absence of (assessed) industry best management practices for water quality improvement. This is not to say, however, that water quality improvement should not be considered in these industries.

Figure 5 Total water pollution abatement cost functions per industry and per water pollutant



Furthermore, it can be observed from Figure 5 that in some industries water quality improvements can be obtained at a negative cost and, thus, a benefit (particularly for FSS and DIN in the sugarcane industry). These are the so-called win-win management practices that provide economic benefits to the industries as well as environmental benefits to the wider community (see also Section 3.1).

Table 4 Optimal rates of water pollution R^* per industry and per water pollutant for water pollution costs β_2

β_2	R^* (kt FSS)				β_2	R^* (t DIN)			
($/t FSS)	Sugarcane	Horticulture	Grazing	Forestry	($/t DIN)	Sugarcane	Horticulture	Grazing	Forestry
0	24.1	9.0	13.2	4.6	0	281.3	195.5	190.5	14.7
100	23.4	7.5	9.9	4.3	20,000	221.7	189.9	149.0	14.3
200	22.7	6.0	6.5	4.0	40,000	162.2	184.3	107.6	13.9
300	22.0	4.5	3.1	3.7	60,000	102.7	178.7	66.2	13.5
400	21.3	3.0	-0.2	3.4	80,000	43.2	173.1	24.8	13.1
R_0 (kt)	29.7	7.5	12.3	4.9	R_0 (t)	371.0	85.7	176.5	10.5

Based on the parameter estimates for the terrestrial (agricultural) benefit functions $B_{ter}(R_t)$ per industry and per water pollutant presented in Table 3, we determine optimal rates of (agricultural) water pollution R^* per industry and per water pollutant (using Eqn 11). Given a time discount rate r of 5%/yr and ignoring re-suspension of water pollutants (i.e. a = 1), results are given in Table 4 and corresponding marginal water pollution abatement cost functions are shown in Figure 6.[5] Note that

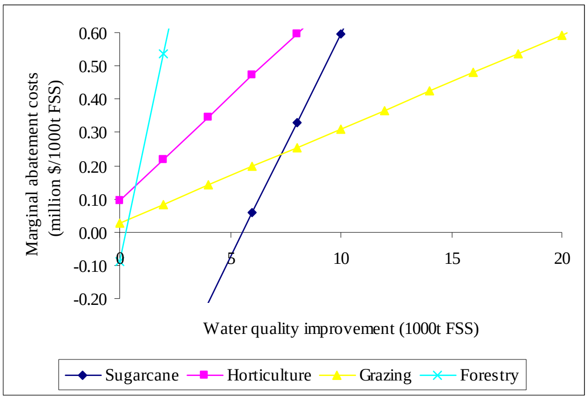
[4] Total water pollution abatement costs refer to the total costs associated with a particular rate of improvement in water quality (as compared to the current rate of water pollution).
[5] Marginal water pollution abatement costs refer to the marginal costs associated with a marginal improvement in water quality at a particular rate of improvement in water quality (as compared to the current rate of water pollution).

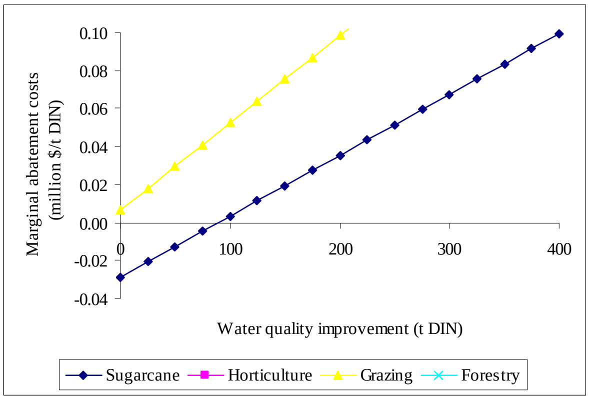
some of the industry marginal abatement cost functions don't show up in Figure 6 (particularly for DIN in the horticulture and forestry industries), as the marginal abatement costs are (well) above those provided on the scale in the figure.

In case we ignore the downstream costs from water pollution ($\beta_2 = 0$), we see that maximum welfare gains are expected to be obtained through a reduction in FSS and DIN water pollution by the sugarcane industry of about 20% and 25%, respectively. Note that these welfare gains purely accrue to the sugarcane industry. No welfare gains are expected to be obtained from a reduction in FSS and DIN water pollution by the other industries.

In case we do take into account the downstream costs from water pollution ($\beta_2 > 0$), we see that welfare gains are likely to be obtained through a reduction in water pollution not only by the sugarcane industry but also through a reduction in water pollution by some of the other industries. If the downstream costs from FSS water pollution would be 200$/t FSS, maximum welfare gains are likely to be obtained through a reduction in FSS water pollution by the sugarcane, horticulture, grazing and forestry industries of about 25%, 20%, 45% and 17%, respectively. Alternatively, if the downstream costs from DIN water pollution are 40,000$/t DIN, maximum welfare gains are expected to be obtained through a reduction in DIN water pollution by the sugarcane and grazing industries of about 55% and 40%, respectively.

Figure 6 Marginal water pollution abatement cost functions per industry and per water pollutant





The way in which these efficient, welfare maximizing water quality improvement targets for FSS and DIN can be achieved most cost-effectively within the landscape through adoption of best management practices by the industries in the Tully-Murray catchment, can be observed in Section 3.1 from Figures 3 and 4, respectively.

A number of observations should be made. First, the (total and marginal) DIN water pollution abatement costs for the horticulture and forestry industries are most likely overestimated because they are based on a limited number of best management practices (see Roebeling et al., 2007) and because they are based on a target-oriented production systems simulation model (LUCTOR) that ignores inefficiencies in input application (Hengsdijk et al., 1998). As a consequence, it is not likely that reliable welfare maximizing rates of water quality improvement have been identified for the horticulture and forestry industries. Second, the (total and marginal) water pollution abatement costs are based on the current best management practices assessed in Roebeling et al. (2007), and thus do not include any future best management practices for water quality improvement. It can be expected that (total and marginal) water pollution abatement costs would decrease if future best management practices would be taken into account, thus achieving a larger water quality outcome at the same cost. Finally, re-suspension of water pollution has not been taken into account and, as a consequence, welfare maximizing rates of water quality improvement are underestimated (see Roebeling, 2006).

3.3 Incentives for industry adoption of best management practices

The EESIP model (see Section 2.1) is now used to assess the effectiveness of various price policy instruments (taxes and subsidies) in promoting the adoption of best management practices to achieve FSS and DIN water quality improvement. Price instruments include a water pollutant delivery tax (i.e. a price on the net delivery of water pollutants to the coast), a water pollutant supply tax (i.e. a price on the gross supply of water pollutants to waterways), a water pollutant delivery abatement subsidy (i.e. a payment for the achieved reduction in net delivery of water pollutants to the coast) and a nitrogen fertilizer tax (i.e. an increase in the price of fertilizer). To this end parameter values are changed (nitrogen fertilizer tax) or additional lines are added to the objective, regional agricultural income, function (water pollutant delivery tax, water pollutant supply tax and water pollutant abatement subsidy) to reflect the changes brought about by the price policy instrument (see Section 2.1).

The following sections provide an overview of the model simulation results assessing the effectiveness of policy instruments promoting the adoption of best management practices for FSS and DIN water quality improvement, respectively.

3.3.1 Fine suspended sediment policy instruments

Baseline and price policy instrument simulation results for FSS water quality improvement by industries in the Tully-Murray catchment are shown in Table 5, assessed price policy instruments including a FSS delivery tax, a FSS supply tax and a FSS delivery abatement subsidy.

The FSS delivery tax as well as the FSS delivery abatement subsidy of 200$/t FSS are chosen equivalent to the downstream costs from FSS water pollution used in Section 3.2, to show that both the delivery tax and the delivery abatement subsidy are likely to lead to industry adoption of best management practices at locations in the catchment that result in welfare maximizing rates of FSS water pollution (i.e. cost-efficient). Consequently, and in line with environmental-economic theory (see for example Perman et al., 1999), both the delivery tax as well as the delivery abatement subsidy can be used to achieve the optimal rates of water pollution in the Tully-Murray catchment identified in Section 3.2 (Table 4), implying a reduction in FSS delivery of about 30%.[6]

Industries in the Tully-Murray catchment respond differently to the FSS delivery tax and the FSS delivery abatement subsidy of 200$/t FSS. In sugarcane production FSS delivery is reduced by about 30% due to industry adoption of win-win management practices (reduced tillage and zero tillage), in horticulture (banana) production FSS delivery is reduced by about 20% through industry adoption of grassed interrows, in beef production FSS delivery is reduced by over 40% through a reduction in the grazing area as well as a reduction in stocking rates and, finally, in forestry production FSS delivery is reduced by almost 25% through a reduction in the forestry area. For further details on the location of land use and land management change in the landscape, please refer to Section 3.1.2.

The costs involved in the FSS delivery tax and the FSS delivery abatement subsidy are either carried by the involved industries (delivery tax) or by the government (delivery abatement subsidy), and amount to about 7.3 m$/yr and 3.6 m$/yr, respectively. While the costs associated with the FSS delivery tax may be relatively small at the catchment level (regional agricultural income decreases by about 5%), they can be relatively large for some industries in the Tully-Murray catchment (about 20% decrease in agricultural income from grazing and forestry production, respectively).

[6] The small differences in CROWPA and EESIP model outcomes for optimal rates of FSS and DIN water pollution are explained by the fact that EESIP model simulation results are used to determine parameter estimates for functional forms used in the CROWPA model (see Section 3.2).

Table 5 Policy simulation results per industry in the Tully-Murray catchment for the baseline and incentives for fine suspended sediment (FSS) delivery abatement

Scenario[1]	Indicator	Unit	Sugarcane	Horticulture	Grazing	Forestry	Total
Baseline	Land use	ha	36,548.0	8,064.0	22,964.0	5,784.0	73,360.0
	Regional agr. inc.	million $	65.4	48.2	8.4	4.7	126.7
	FSS delivery	kt FSS	29.7	7.5	12.3	4.9	54.4
	DIN delivery	t DIN	371.0	85.7	176.5	10.5	643.8
FSS	Land use	ha	36,548.0	8,064.0	21,304.0	5,620.0	71,536.0
delivery tax	Regional agr. inc.	million $	62.2	46.8	6.6	3.8	119.4
($200/t FSS)	FSS delivery	kt FSS	20.0	6.0	7.0	3.7	36.8
	DIN delivery	t DIN	245.8	85.7	165.7	10.3	507.5
FSS	Land use	ha	36,168.0	8,064.0	18,404.0	5,264.0	68,260.0
supply tax	Regional agr. inc.	million $	56.3	44.6	4.9	2.8	108.7
($200/t FSS)	FSS delivery	kt FSS	18.0	5.2	4.2	2.9	30.3
	DIN delivery	t DIN	243.1	85.7	142.8	9.6	481.3
FSS delivery	Land use	ha	36,548.0	8,064.0	21,304.0	5,620.0	71,536.0
abatement	Regional agr. inc.	million $	68.1	48.3	9.0	4.8	128.4
subsidy	FSS delivery	kt FSS	20.0	6.0	7.0	3.7	36.8
($200/t FSS)	DIN delivery	t DIN	245.8	85.7	165.7	10.3	507.5

The FSS supply tax differs from the FSS delivery tax in the sense that it is charged on the (gross) supply of FSS to waterways rather than on the (net) delivery of FSS to the coast – thus ignoring that FSS delivery is time and spatially dependent (see for example Prosser et al., 2001).[7] An FSS supply tax of 200$/t FSS is likely to lead to industry adoption of best management practices that result in rates of FSS water pollution that are below the welfare maximizing rates of FSS water pollution in the Tully-Murray catchment identified in Section 3.2 (Table 4), implying a reduction in FSS delivery of about 45% as best management practices are adopted throughout the catchment independent of their actual effectiveness in reducing FSS delivery (i.e. not cost-efficient).[8]

Industry response to the FSS supply tax of 200$/t FSS is as follows. In addition to the management practices adopted under the FSS delivery tax and the FSS delivery abatement subsidy (see above), FSS delivery in sugarcane production is reduced by another 10% through a reduction in the sugarcane area and altered fertilizer application rates, FSS delivery in horticulture production is reduced by an additional 10% through further adoption of grassed interrows, FSS delivery in beef production is reduced by another 25% through a further reduction in grazing area as well as stocking rates and, finally, FSS delivery in forestry production is reduced by an additional 15% through a further reduction in the forestry area.

The costs associated with the FSS supply tax are relatively large (18 m$/yr or about 15% of regional agricultural income) and carried by the involved industries. Costs are (relatively) largest for the grazing, forestry and sugarcane industry (41%, 40% and 15% decrease in agricultural income from grazing, forestry and sugarcane production, respectively). Finally note that, at an average FSS

[7] Although the same land use in two particular locations may be characterized by the same supply of FSS or DIN to waterways, the associated net delivery of FSS or DIN to the coast may differ significantly.
[8] This result is in line with environmental-economic theory, which states that a uniform tax will only lead to cost-efficient (i.e. most cost-effective) reduction in pollution if the impact of pollution emission is independent of time and place (see Perman et al., 1999). As FSS and DIN water pollutant delivery are time and spatially dependent (Prosser et al., 2001), a water pollutant delivery tax will but a water pollutant supply tax will not lead to cost-efficient (i.e. most cost-effective) reduction in water pollutant delivery.

delivery reduction cost of 0.75 m$/kt FSS for the supply tax versus 0.41 m$/kt FSS for the delivery tax, the FSS supply tax is far less cost-effective in reducing FSS delivery to the coast.

3.3.2 Dissolved inorganic nitrogen policy instruments

Baseline and price policy instrument simulation results for DIN water quality improvement by industries in the Tully-Murray catchment are shown in Table 6. Assessed instruments include a DIN delivery tax, a DIN supply tax, a DIN delivery abatement subsidy and a nitrogen (N) fertilizer tax.

Analogous to the FSS delivery tax and the FSS delivery abatement subsidy, we see that both the DIN delivery tax and the DIN delivery abatement subsidy of 40$/kg DIN are likely to lead to industry adoption of best management practices at locations in the catchment that result in welfare maximizing rates of DIN water pollution in the Tully-Murray catchment (i.e. cost-efficient) – implying a reduction in DIN delivery of about 45% (see Table 4, Section 3.2).[9]

Industries in the Tully-Murray catchment respond in a number of ways to the DIN delivery tax and the DIN delivery abatement subsidy of 40$/kg DIN. In sugarcane production DIN delivery is reduced by almost 60% due to industry adoption of win-win management practices (economic optimum rates of fertilizer application, nitrogen replacement and split nitrogen application) as well as adoption of some lose-win management practices (rates of fertilizer application below the economic optimum rate of application). In beef production DIN delivery is reduced by about 35% through a reduction in the grazing area as well as a reduction in the nitrogen application rate. Finally, in horticulture (banana) and forestry production, DIN delivery is not reduced as neither the DIN delivery tax nor the DIN delivery abatement subsidy provide a sufficiently large incentive to change land use and/or land management. For further details on the location of land use and land management change in the landscape, please refer to Section 3.1.3.

The costs involved in the DIN delivery tax and the DIN delivery abatement subsidy, carried by the involved industries or government, amount to about 15.6 m$/yr and 10.1 m$/yr, respectively. The costs associated with the DIN delivery tax are (relatively) largest for the grazing, sugarcane and forestry industry, leading to a decrease in agricultural income from grazing, sugarcane and forestry production of about 65%, 10% and 10%, respectively.

The DIN supply tax is, like the FSS supply tax, charged on the supply of DIN to waterways and thus ignores that DIN delivery is time and spatially dependent (Prosser et al., 2001).[10] A DIN supply tax of 40$/kg DIN is likely to lead to industry adoption of best management practices that result in rates of DIN water pollution that are well below the welfare maximizing rates of DIN water pollution in the Tully-Murray catchment (see Table 4, Section 3.2), implying a reduction in DIN delivery of almost 90% as, again, best management practices are adopted throughout the catchment independent of their actual effectiveness in reducing DIN delivery (i.e. not cost-efficient).[11]

Industry response to the DIN supply tax of 40$/kg DIN is, as a consequence, fairly extreme. While grazing and forestry production are abandoned, DIN delivery in sugarcane production is reduced by almost 90% due to further industry adoption of lose-win management practices (fertilizer application rates below the economic optimum application rate) and DIN delivery in horticulture production is reduced by about 60% through a reduction in the horticulture area in combination with reduced fertilizer application rates.

The costs associated with the DIN supply tax are very large (95 m$/yr or about 75% of regional agricultural income) and carried by the involved industries, thereby noting that the grazing and

[9] See footnote 6.
[10] See footnote 7.
[11] See footnote 8.

forestry industry would have to close down as a consequence of the DIN supply tax of 40$/kg DIN. Also here we see that, at an average DIN delivery reduction cost of 0.17 m$/t DIN for the supply tax versus 0.06 m$/t DIN for the delivery tax, the DIN supply tax is less cost-effective in reducing DIN delivery to the coast.

Table 6 Policy simulation results per industry in the Tully-Murray catchment for the baseline and incentives for dissolved inorganic nitrogen (DIN) delivery abatement

Scenario[1]	Indicator	Unit	Sugarcane	Horticulture	Grazing	Forestry	Total
Baseline	Land use	ha	36,548.0	8,064.0	22,964.0	5,784.0	73,360.0
	Regional agr. inc.	million $	65.4	48.2	8.4	4.7	126.7
	FSS delivery	kt FSS	29.7	7.5	12.3	4.9	54.4
	DIN delivery	t DIN	371.0	85.7	176.5	10.5	643.8
DIN	Land use	ha	36,548.0	8,064.0	17,576.0	5,784.0	67,972.0
delivery tax	Regional agr. inc.	million $	59.3	44.7	2.8	4.3	111.1
($40/kg DIN)	FSS delivery	kt FSS	20.4	7.5	9.5	4.9	42.3
	DIN delivery	t DIN	155.9	85.7	116.0	10.5	368.1
DIN	Land use	ha	36,548.0	3,252.0	0.0	0.8	39,800.8
supply tax	Regional agr. inc.	million $	28.8	2.9	0.0	0.0	31.7
($40/kg DIN)	FSS delivery	kt FSS	24.5	4.1	0.0	0.0	28.7
	DIN delivery	t DIN	43.1	33.2	0.0	0.0	76.3
DIN delivery	Land use	ha	36,548.0	8,064.0	17,576.0	5,784.0	67,972.0
abatement	Regional agr. inc.	million $	74.1	48.2	9.9	4.7	136.8
subsidy	FSS delivery	kt FSS	20.4	7.5	9.5	4.9	42.3
($40/kg DIN)	DIN delivery	t DIN	155.9	85.7	116.0	10.5	368.1
N-fertilizer	Land use	ha	36,548.0	8,064.0	18,532.0	5,784.0	68,928.0
tax	Regional agr. inc.	million $	59.4	42.8	4.5	3.9	110.6
(+150%)	FSS delivery	kt FSS	20.0	7.5	10.1	4.9	42.6
	DIN delivery	t DIN	159.6	85.7	131.6	10.5	387.4

The nitrogen (N) fertilizer tax of 150% is likely to lead to industry adoption of best management practices that result in rates of DIN water pollution that are just above the welfare maximizing rates of DIN water pollution in the Tully-Murray catchment identified in Section 3.2 (Table 4), implying a reduction in DIN delivery of about 40%. Like with the DIN supply tax, we see that best management practices are adopted throughout the catchment independent of their actual effectiveness in reducing DIN delivery (i.e. not cost-efficient).[12]

Industry response to the N-fertilizer tax of 150% varies widely across industries. While the horticulture (banana) and forestry industry are not likely to respond to the fertilizer tax, in sugarcane production DIN delivery is reduced by almost 60% due to industry adoption of win-win management practices (economic optimum rates of fertilizer application, nitrogen replacement and split nitrogen application) and in beef production DIN delivery is reduced by about 25% due to a reduction the grazing area as well as a reduction in the nitrogen application rate.

The costs involved in the N-fertilizer tax are carried by the involved industries, and amount to about 16.1 m$/yr (~ 15% of regional agricultural income). The costs associated with the N-fertilizer tax are likely to be (relatively) largest for the grazing and forestry industries in the Tully-Murray catchment

[12] See footnote 8.

(about 45% and 15% decrease in agricultural income from beef and forestry production, respectively) and about equally large for the sugarcane and horticulture industry (about 10% decrease in agricultural income from sugarcane and horticulture production, respectively). At an average DIN delivery reduction cost of 0.07 m$/t DIN for the N-fertilizer tax versus 0.06 m$/t DIN for the delivery tax, we see that the N-fertilizer tax is less cost-effective in reducing DIN delivery to the coast.

4. Discussion and conclusions

In this report we apply and link the EESIP model (based on Roebeling et al., 2006) and the CROWPA model (based on Roebeling, 2006) to: i) explore cost-efficient industry land management arrangements for water quality improvement, ii) explore efficient water quality improvement targets, and iii) assess incentives for industry adoption of best management practices for water quality improvement.[13] The Environmental Economic Spatial Investment Prioritization (EESIP) model integrates a land use and value chain model (see Smith et al., 2005) with the water quality model SedNet/ANNEX (see Bartley et al., 2004). It is not only used to explore cost-efficient industry specific land management arrangements for water quality improvement and to assess the effectiveness of price policy instruments in promoting industry best management practice adoption, but also to determine terrestrial (agricultural) benefit functions for use in the Catchment to Reef Optimal Water Pollution Abatement (CROWPA) model. The CROWPA model relates economic benefits from terrestrial agricultural activities and associated water pollution to changes in marine based economic values in order to explore efficient water quality improvement targets (see Roebeling, 2006). Based on preceding program and project reports, literature and expert knowledge, this approach allows us to assess incentives for industry best management practice adoption that lead to efficient water quality improvement targets and corresponding cost-effective land use and land management arrangements for fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) water pollution in sugarcane, horticulture, grazing and forestry production in the Tully-Murray catchment.

Results from the explorative industry land management arrangement analysis (based on EESIP) show that FSS and DIN water pollution control becomes increasingly expensive at larger rates of FSS and DIN water pollution abatement. It is important to note, however, that there are large differences between industries:

- In sugarcane production, a 20% reduction in FSS delivery is expected to come at benefit to the industry due to the adoption of reduced tillage and zero tillage, while a reduction in DIN delivery of up to 40% is expected to come at benefit to the industry due to the adoption of economic optimum rates of fertilizer application, nitrogen replacement and split nitrogen application. A further reduction in FSS and DIN delivery would come at a significant cost to the industry as a result of a reduction in the sugarcane area and a further decrease in nitrogen application rates.
- In horticulture (banana) production, reductions in FSS delivery are expected to come at a small cost to the industry due to the adoption of grassed interrows, while reductions in DIN delivery are expected to come at a large cost to the industry as a result of a reduction in the horticulture area in combination with reduced rates of fertilizer application.
- In beef production, reductions in FSS delivery are expected to come at a significant cost to the grazing industry as a result of a reduction in the grazing area in combination with the adoption of reduced stocking rates, while reductions in DIN delivery are expected to come at a large cost to the grazing industry as a result of a reduction in the grazing area in combination with reduced rates of nitrogen application.
- In forestry production, reductions in FSS as well as DIN delivery are expected to come at a significant/large cost to the industry as a result of a reduction in the forestry area.

Furthermore, it is shown that FSS delivery is most cost-effectively reduced on paddocks that are located on the steepest slopes, on the least productive soil types and furthest away from Tully, while DIN delivery is most cost-effectively reduced on paddocks that are located on the least productive soil types and furthest away from Tully.

Results from the explorative water quality improvement target analysis (based on CROWPA) have been generated for a range of water pollution costs as the quantitative relationship between water

[13] The terms water quality, water pollution and water quality improvement refer to water pollutant delivery to the coast.

pollution and indicators of reef health and, in turn, marine based economic values, is not well established (Roebeling et al, 2006). It is shown that:

- If we ignore the downstream costs from water pollution, welfare gains are only likely to be obtained through a reduction in water pollution by the sugarcane industry. Maximum welfare gains are expected to be gained through a reduction in FSS and DIN water pollution by the sugarcane industry of about 20% and 25%, respectively. Note that these welfare gains purely accrue to the sugarcane industry.
- If we account for the downstream costs from water pollution, welfare gains are likely to be obtained through a reduction in water pollution by the sugarcane industry as well as by some of the other industries. If downstream costs from FSS water pollution equal 200$/t FSS, maximum welfare gains are likely to be obtained through a reduction in FSS delivery by the sugarcane, horticulture, grazing and forestry industries of about 25%, 20%, 45% and 17%, respectively. If downstream costs from DIN water pollution total 40,000$/t DIN, maximum welfare gains are expected to be obtained through a reduction in DIN delivery by the sugarcane and grazing industries of about 55% and 40%, respectively

Results from the price policy instrument assessment (using EESIP), which have been generated for a water pollutant delivery tax, a water pollutant supply tax, a water pollutant delivery abatement subsidy and a nitrogen (N) fertilizer tax, show that:

- A water pollutant delivery tax as well as a water pollutant delivery abatement subsidy are likely to lead to industry adoption of best management practices at locations in the Tully-Murray catchment that result in welfare maximizing rates of water pollution (i.e. cost-efficient). The costs involved in the delivery tax and the delivery abatement subsidy are carried by the involved industries and the government, respectively, and result to be between 50% (DIN) and 100% (FSS) larger for the delivery tax. Relatively largest agricultural income losses from a water pollutant delivery tax can be observed in the grazing and forestry industries.
- A water pollutant supply tax (which is charged on the gross supply of water pollutants rather than on the net delivery of water pollutants to the coast) is not likely to lead to industry adoption of best management practices at locations in the catchment that result in welfare maximizing rates of water pollution, as best management practices are adopted throughout the catchment independent of their actual effectiveness in reducing water pollutant delivery to the coast (i.e. not cost-efficient). As compared to the water pollutant delivery tax, an equivalent water pollutant supply tax comes at a three (FSS) to six (DIN) times larger cost to the involved industries (agricultural income losses again being relatively largest amongst the grazing and forestry industries) and is on average between two (FSS) and three (DIN) times less cost-effective in reducing water pollutant delivery to the coast.
- A nitrogen (N) fertilizer tax is, similarly, not likely to lead to industry adoption of best management practices at locations in the catchment that result in welfare maximizing rates of water pollution, as best management practices are adopted throughout the catchment independent of their actual effectiveness in reducing water pollutant delivery to the coast (i.e. not cost-efficient). Agricultural income losses are relatively largest amongst the grazing and forestry industries and, as compared to the DIN delivery tax, a N-fertilizer tax results to be about 10% less cost-effective in reducing water pollutant delivery to the coast.

Summarizing, based on the assessed current best management practices and actual land use pattern in the Tully-Murray catchment, this study shows that total FSS and DIN delivery from the Tully-Murray catchment can be reduced by about 10% and 15%, respectively, through the adoption of current win-win best management practices – i.e. management practices that benefit the industry as well as the wider community. In case there are beneficial spillovers from reduced water pollution, further welfare gains can be obtained through a reduction in the industry production area in combination with industry adoption of current lose-win best management practices – i.e. management practices that cost

the industry though benefit the wider community. In case beneficial spillovers from reduced FSS and DIN delivery from the Tully-Murray catchment amount to 200$/t FSS and 40,000$/t DIN, this study shows that maximum welfare gains can be obtained by reducing total FSS and DIN delivery from the Tully-Murray catchment by another 20% and 30%, respectively.

Incentives for industry adoption of best management practices for water quality improvement can be provided through various price policy instruments. Water pollutant delivery taxes as well as water pollutant delivery abatement subsidies provide cost-efficient incentives for water quality improvement, though associated costs need to be carried by the involved industries or the government, respectively. In contrast, water pollutant supply taxes as well as a N-fertilizer tax provide non-cost-efficient incentives for water quality improvement because best management practices are adopted throughout the catchment independent of their actual effectiveness in reducing water pollution (i.e. water pollutant delivery to the coast). Although emission based taxes and subsidies are cost-efficient, it is generally hard and costly to measure actual diffuse source emissions (i.e. water pollutant deliveries) and, consequently, it may be more practical to base taxes and subsidies on (non-cost-efficient) diffuse source emission proxies (water pollutant supplies), inputs (N-fertilizers) or management practices (Perman et al., 1999).

Future research needs to address a number of limitations associated with this study. First, the industry (total and marginal) water pollution abatement costs are based on the current best management practices assessed in Roebeling et al. (2007) and, thus, do not include any future best management practices for water quality improvement. It can be expected that the industry (total and marginal) water pollution abatement costs are lower if future best management practices would be taken into account, thus achieving a larger water quality outcome at the same cost. To this end industry future best management practices for water quality improvement need to be identified,[14] assessed and trailed, which requires investment from the corresponding industry R&D organizations.

Second, and related to the previous point, the industry (total and marginal) water pollution abatement costs are based on the current land use pattern and, consequently, do not include land use change between industries. It can be expected that the aggregate (total and marginal) water pollution abatement costs are lower if land use change would be taken into account, thus achieving a larger water quality outcome at the same cost. This may imply, however, that for some industries (total and marginal) water pollution abatement costs increase as to allow for a decrease in the (total and marginal) water pollution abatement costs for other (more cost-effective) industries.

Third, the (total and marginal) DIN water pollution abatement costs for the horticulture and forestry industries are most likely overestimated because they are based on a limited number of best management practices (see Roebeling et al., 2007) and because they are based on a target-oriented production systems simulation model (LUCTOR) that ignores inefficiencies in input application (Hengsdijk et al., 1998).[15] As a consequence, less reliable welfare maximizing rates of water quality improvement have been identified for the horticulture and forestry industries.

Fourth, we evaluated the sensitivity of the model with respect to the downstream costs from water pollution as the quantitative relationship between water pollution and indicators of reef health is not well established and, thus, neither is the relationship between water pollution and marine based

[14] For a review of current and future best management practices for water quality improvement in the Wet Tropics of Australia, please refer to Roebeling and Webster (2007).

[15] Roebeling et al. (2007) argue that as compared to the production system simulation models LUCTOR (for horticulture and forestry production; Hengsdijk et al., 1998) and PASTOR (for beef production; Bouman et al., 1998), APSIM (for sugarcane production; Keating et al., 1999) resulted to be best suited for best management practice cost-effectiveness assessment as it contains the most sophisticated routines for the calculation of C-factors and DIN concentrations (which are used in the calculation of water pollutant supply and delivery using SedNet/ANNEX – see Bartley et al., 2004) while it also allows for the assessment of the largest range of current and future best management practices.

economic values (Roebeling et al, 2006). Moreover, we assumed marine benefits to be linearly decreasing in the level of water pollution, which implies that the cost per unit of downstream water pollution is constant. If we desire to aim for efficiency in water pollution control through the development of policies and incentives, we need more detailed and quantitative estimates for the marginal downstream costs from water pollution.

Fifth, re-suspension of water pollutants has not been taken into account. Roebeling (2006) shows that the optimal (welfare maximizing) rate of water pollution is sensitive to and decreasing in the rate of water pollutant re-suspension and, as a consequence, the welfare maximizing rates of water quality improvement presented in this study are most likely underestimated.

Finally, the used approach is deterministic and is, as a result, likely to lead in biased outcomes. When marine benefits from Great Barrier Reef (GBR) conservation are uncertain while GBR degradation is to a certain extent irreversible, deterministic cost-benefit analyses result in biased outcomes as they don’t take the quasi-option value of the GBR into account (Dixit and Pindyck, 1994). Accounting for uncertainty in marine benefits from GBR conservation will lead to lower optimal rates of (agricultural) water pollution and, consequently, improved levels of water quality in the GBR lagoon.

Consequently and self-evidently, care should be taken when using the figures presented in this study for policy and planning purposes. Presented results provide an indication of the gross direction and magnitude of change – not an exact recipe for change.

References

Bartley, R., A. Henderson, G. Baker, M. Bormans and S. Wilkinson, 2004. Patterns of erosion and sediment nutrient transport in the Douglas Shire catchments (Daintree, Saltwater, Mossman and Mowbray), Queensland. CSIRO Land and Water Client Report, Atherton, Australia. 61pp.

Bouman, B.A.M., A. Nieuwenhuyse and H. Hengsdijk, 1998. PASTOR: a technical coefficient generator for pasture and livestock systems in the humid tropics, version 2.0. Quantitative Approaches in Systems Analysis No.18. AB-DLO/C.T. de Wit Graduate school for Production Ecology. Wageningen, The Netherlands. 59 pp., plus appendices.

Brooke, A., D. Kendrick, A. Meeraus and R. Raman, 1998. GAMS User's Guide. GAMS Development Corporation, Washington, DC, US, 262 pp.

Cesar, H., P. van Breukingen, S. Pintz and J. Dierking, 2002. Economic Valuation of the Coral Reefs of Hawaii. Hawaii Coral Reef Initiative Research Program, Hawaii, USA, 123pp.

Dixit, A.K. and R.S. Pindyck, 1994. Investment under Uncertainty. Princeton University Press, Princeton, USA.

Gustavson, K. and R.M. Huber, 2000. Ecological Economic Decision Support Modelling for the Integrated Coastal Zone Management of Coral Reefs, in Collected Essays on the Economics of Coral Reefs (H.S.J. Cesar, ed.), CORDIO, Dept. for Biology and Environ. Science, Kalmar University, Kalmar, pp. 183-202.

Hajkowicz, S., J.M. Perraud, W. Daves and R. DeRose, 2005. The strategic investment model: a tool for mapping optimal environmental expenditure. Environmental Modelling and Software 20: 1251-1262.

Hengsdijk, H., A. Nieuwenhuyse and B.A.M. Bouman, 1998. LUCTOR: Land crop technical coefficient generator. A model to quantify cropping systems in the northern Atlantic Zone of Costa Rica. Version 2.0. Quantitative Approaches in Systems Analysis No.17. AB-DLO/C.T. de Wit Graduate School for Production Ecology. Wageningen, The Netherlands. 65 pp., plus appendices.

Hodgson, G. and J.A. Dixon, 1988. Logging versus fisheries and tourism in Palawan, East-West Environment Insitute (EAPI) Occasional Paper 7, Hawaii, USA.

Jansen, H.G.P., B.A.M. Bouman, R.A. Schipper, H. Hengsdijk and A. Nieuwenhuyse, 2005. An interdisciplinary approach to regional land use analysis using GIS, with application to the Atlantic Zone of Costa Rica. Agricultural Economics 32(1): 87-104.

Keating, B.A., M.J. Robertson, R.C. Muchow and N.I. Huth, 1999. Modelling sugarcane production systems I. Development and performance of the sugarcane module. Field Crops Research 61: 253-271.

Khanna, M., W. Yang, R. Farnswoth and H. Onal, 2003. Cost-effective targeting of land retirement to improve water quality with endogenous sediment deposition coefficients. American Journal of Agricultural Economics 85(3): 538-553.

Murtha, G.G. and C.D. Smith, C.D., 1994. Key to the soils and land suitability of the wet tropical coast: Cardwell – Cape Tribulation. CSIRO Division of Soils and Queensland Department of Primary Industries.

Nelson, G.C., 2002. Introduction to the special issue on spatial analysis for agricultural economists. Agricultural Economics 27: 197-200.

Perman, R., Y. Ma, J. McGilvray and M. Common, 1999. Natural resource and environmental economics – 2nd edition. Pearson Education Limited, Harlow, UK. 564 pp.

Prosser, I. A. Hughes, P. Rustomji and C. Moran, 2001. Predictions of the sediment regime of Australian rivers. Pages 529-533 in: Rutherfurd, I., G. Brierley, S. Bunn, F. Sheldon and C. Kenyon (Eds) The proceedings of the third Australian stream management conference. Cooperative Research Centre for Catchment Hydrology, Melbourne, Australia.

QLUMP, 2004. Queensland Land Use Mapping Program (QLUMP). Queensland Department of Natural Resources and Mines (QDNR&M), Australia.

Roebeling, P.C., 2006. Efficiency in Great Barrier Reef water pollution control: a case study for the Douglas Shire. Natural Resource Modeling 19(4): 539-556.

Roebeling, P.C., D.M. Smith, J. Biggs, A.J. Webster, and P. Thorburn, 2005. Private-economic analysis of drivers promoting the adoption of best management practices for water quality improvement in the Douglas Shire: Report on the cost-effectiveness of BMP implementation for water quality improvement. Report prepared for the Douglas Shire Water Quality Improvement Program, CSIRO-Sustainable Ecosystems, Townsville, Australia. 95 pp.

Roebeling, P.C., D.M. Smith and M.E. van Grieken, 2006. Exploring environmental-economic benefits from agri-industrial diversification in the sugar industry: an integrated land use and value chain approach. Contributed paper prepared for presentation at the 26th Conference of the International Association of Agricultural Economists (IAAE), Gold Coast, Australia, 12-18 August, 2006.

Roebeling, P.C. and A.J. Webster, 2007. Review of current and future best-management-practices for sugarcane, horticulture, grazing and forestry industries in the Tully-Murray catchment. Report to FNQ-NRM Ltd, CSIRO Sustainable Ecosystems, Townsville, Australia. 58 pp.

Roebeling, P.C., A.J. Webster, J. Biggs and P. Thorburn, 2007. Financial-economic analysis of current best-management-practices for sugarcane, horticulture, grazing and forestry industries in the Tully-Murray catchment. Report to MTSRF and FNQ-NRM Ltd, CSIRO Sustainable Ecosystems, Townsville, Australia. 48 pp.

Rounsevell, M.D.A., J.E. Annetts, E. Audsley, T. Mayr and I. Reginster, 2003. Modelling the spatial distribution of agricultural land use at the regional scale. Agriculture, Ecosystems and Environment 95: 465-479.

Ruitenbeek, J., M. Ridgley, S. Dollar and R. Huber, 1999. Optimization of Economic Policies and Investment Projects using a Fuzzy logic based cost-effectiveness model of coral reef quality: Empirical results for Montego Bay, Jamaica. World Bank Project RPO# 680-08, Washington, DC, 85 pp. plus Appendices.

Ruitenbeek, J. and C. Cartier, 1999. Issues in applied coral reef biodiversity valuation: Results for Montego Bay, Jamaica. World Bank Project RPO# 682-22, Washington, DC, 149 pp. plus Appendices.

Smith, D.M., P.C. Roebeling, T. Parker, A.J. Webster, K.J. Williams and G. Antony, 2005. Financial assessment of CAPS at regional scale: A case study for Tully. Report prepared for the Bio-industries Alliance of North Queensland (BioNQ), CSIRO-Sustainable Ecosystems, Townsville, Australia, 23pp.

Sadoulet, S., and A. De Janvry, 1995. Quantitative development policy analysis. The Johns Hopkins University Press, Baltimore, USA. 397 pp.

Wielgus, J., N.E. Chadwick-Furman, Z. Dubinsky, M. Shechter and N. Zeitouni, 2002. Dose-response modelling of recreationally important coral-reef attributes: a review and potential application to the economic valuation of damage. Coral Reefs 21: 253-259.