Abatement vs. treatment for efficient diffuse source water pollution management in terrestrial-marine systems

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ABSTRACT

Marine ecosystems are affected by water pollution originating from coastal catchments. The delivery of water pollutants can be reduced through water pollution abatement as well as water pollution treatment. Hence, sustainable economic development of coastal regions requires balancing of the marginal costs from water pollution abatement and/or treatment and the associated marginal benefits from marine resource appreciation. Water pollution delivery reduction costs are, however, not equal across abatement and treatment options. In this paper, an optimal control approach is developed and applied to explore welfare maximizing rates of water pollution abatement and/or treatment for efficient diffuse source water pollution management in terrestrial-marine systems. For the case of diffuse source dissolved inorganic nitrogen water pollution in the Tully-Murray region, Queensland, Australia, (agricultural) water pollution abatement cost, (wetland) water pollution treatment cost and marine benefit functions are determined to explore welfare maximizing rates of water pollution abatement and/or treatment. Considering partial (wetland) treatment costs and positive water quality improvement benefits, results show that welfare gains can be obtained, primarily, through diffuse source water pollution abatement (improved agricultural management practices) and, to a minor extent, through diffuse source water pollution treatment (wetland restoration).

Key words | abatement, diffuse source water pollution, improved agricultural management practices, marine ecosystem values, treatment, wetland restoration

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INTRODUCTION

Land use change and intensification in coastal catchments along the Great Barrier Reef (GBR) region of Australia have led to increased exports of diffuse source water pollutants into the GBR lagoon over recent decades (Furnas 2003). Among the key water pollutants, sediments, nutrients and pesticides, nitrogen (as nitrate) from agricultural fertilizer use has been identified as a priority terrestrially sourced pollutant (Brodie & Mitchell 2005; Webster *et al.* 2009). Associated levels of water pollution in the GBR lagoon are one of the biggest potential causes of reef degradation (Fabricius 2005) which, consequently, may affect economic sectors, notably tourism and commercial/recreational fishery, that rely on the GBR for their income generation (Productivity Commission 2003).

To protect the environmental values of the GBR, the Australian Government developed the Reef Water Quality Protection Plan (QDP&C 2003), which aims to halt and reverse the decline in water quality entering the Reef within 10 years through the development of catchment Water Quality Improvement Plans (WQIPs). These WQIPs aim to reduce anthropogenically sourced pollutant delivery to the GBR lagoon, through improved management practices (pollution abatement) and restoration of wetland areas (pollution treatment) (Binney 2010). While the ability of wetlands to treat water pollution is recognized (Mitsch & Gosselink 2000; McJannet *et al.* 2012), developed WQIPs mainly focus on improved management practices to abate diffuse source water pollution (Binney 2010).

The costs of reducing diffuse source water pollution in the GBR lagoon are, however, significant (Binney 2010). Sustainable economic development of coastal regions requires balancing of the marginal costs from reduced diffuse source

water pollution delivery to the marine environment and the associated marginal benefits from marine resource appreciation (see Hart & Brady 2002; Gren & Folmer 2003; Roebeling *et al.* 2009b). Yet, diffuse source water pollution delivery reduction costs are not equal across abatement and treatment options and, hence, the question arises: to what extent can marine water quality improvement be efficiently pursued through diffuse source water pollution abatement (improved agricultural management practices) and/or treatment (wetland restoration), respectively?

Numerous studies assess the cost-effectiveness of agricultural water pollution abatement options (e.g., Elofsson 2003; Yang *et al.* 2005; Roebeling *et al.* 2009a, 2014; Lescot *et al.* 2013; Liu *et al.* 2014), wetland water pollution treatment options (e.g., Byström 1998; Byström *et al.* 2000; Söderqvist 2002; Gren 2010) and both (agricultural) water pollution abatement and (diverse) water pollution treatment options (e.g., Byström 2000; Ribaudo *et al.* 2001; Veeren & Tol 2001; Gren 2008; Gren *et al.* 2013). Only a few studies explore efficient, welfare maximizing rates of (agricultural) water pollution abatement and/or water pollution treatment in terrestrial-marine systems. In particular, Goetz & Zilberman (2000), Hart & Brady (2002) and Roebeling *et al.* (2009b) explore welfare maximizing rates of (agricultural) water pollution abatement, Roebeling *et al.* (2011) explore welfare maximizing rates of (wetland) water pollution treatment, and Gren & Folmer (2003), Laukkanen & Huhtala (2008) and Laukkanen *et al.* (2009) explore welfare maximizing rates of (agricultural) water pollution abatement and (municipal) wastewater treatment.

In contribution to these earlier studies, an analytically tractable deterministic optimal control approach was developed and applied that allowed us to explore, simultaneously, welfare maximizing rates of diffuse source (agricultural) water pollution abatement as well as (wetland) water pollution treatment in terrestrial-marine systems. For the case of diffuse source dissolved inorganic nitrogen (DIN) water pollution in the Tully-Murray region in the Wet Tropics of Queensland, Australia, (agricultural) water pollution abatement cost, (wetland) water pollution treatment cost and marine benefit functions are determined to explore to what extent water quality improvement in the GBR lagoon can efficiently be pursued through water pollution abatement (improved agricultural management practices) and/or water pollution treatment (wetland restoration).

In the next section, the deterministic optimal control approach is developed and solved analytically. Next, the parameter values for (agricultural) water pollution abatement cost, (wetland) water pollution treatment cost and

marine benefit functions are determined to explore, in turn, welfare maximizing rates of (agricultural) water pollution abatement and (wetland) water pollution treatment in the Tully-Murray region. Finally, concluding remarks and recommendations are presented.

MATERIALS AND METHODS

To explore welfare (W) maximizing rates of (agricultural) water pollution abatement as well as (wetland) water pollution treatment, the Catchment to Reef Optimal Water Pollution Abatement modelling approach (see Roebeling *et al.* 2009b) was adapted to the case of DIN water pollution from fertilizer use by the key agricultural land uses, as well as DIN water pollution treatment through wetland restoration in the Tully-Murray catchment in the Wet Tropics of Queensland, Australia.

Let $B_{ter}(R_t)$ denote the benefits (net returns) from agricultural production that are a function of the rate of (agricultural) water pollution R_t (control variable); let $C_{ter}(T_t)$ denote the (wetland) water pollution treatment costs that are a function of the rate of (wetland) water pollution treatment T_t (control variable); and let $B_{mar}(P_t)$ denote the marine benefits from economic use values of marine resources that are a function of the level of water pollution P_t (stock variable). The annual flow of (regional) net benefits $\pi(R_t, T_t, P_t)$ is given by the sum of agricultural benefits $B_{ter}(R_t)$, (wetland) water pollution treatment costs $C_{ter}(T_t)$ and marine benefits $B_{mar}(P_t)$:

$$
\begin{aligned}
\pi(R_t, T_t, P_t) &= B_{ter}(R_t) - C_{ter}(T_t) + B_{mar}(P_t) \\
&= (\alpha_1 + \alpha_2 R_t - \alpha_3 R_t^2) - (\alpha_4 + \alpha_5 T_t + \alpha_6 T_t^2) \quad (1) \\
&\quad + (\beta_1 - \beta_2 P_t)
\end{aligned}
$$

This specification acknowledges: (i) decreasing marginal benefits from agricultural fertilizer use and corresponding (agricultural) water pollution R_t (i.e., $\alpha_1 \geq 0$, $\alpha_2 > 0$ and $\alpha_3 > 0$; (ii) increasing marginal costs from (wetland) water pollution treatment T_t (i.e. $\alpha_4 \geq 0$, $\alpha_5 > 0$ and $\alpha_6 > 0$); and (iii) constant marginal costs from marine water pollution P_t (i.e. $\beta_1 \geq 0$ and $\beta_2 > 0$). Note that the specification of benefits from agricultural production as a function of the rate of (agricultural) water pollution is equivalent to the commonly used abatement cost function specification (Roebeling *et al.* 2009a, b), and allows the direct relation of catchment-sourced rates of water pollution (R_t) to marine levels of water pollution (P_t) and subsequent load targets.

The corresponding optimal control welfare (W) maximization problem is given by:

$$\underset{R_t, T_t}{\text{Max}} \ W = \int_0^\infty [\pi(R_t, T_t, P_t)]e^{-rt} \, dt \tag{2}$$

subject to $\dot{P}_t = b + R_t - T_t - aP_t$ $\qquad$ (3)

with $P_0 > 0$, $R_0 > 0$, $T_0 > 0$, $P_t \geq 0$, $R_t \geq 0$ and $T_t \geq 0$, and 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 $\dot{P}_t$ Equation (3), depicting the intertemporal change in the level of marine water pollution P_t, is determined by the rate of non-agricultural water pollution b, the rate of (agricultural) water pollution R_t, the rate of (wetland) water pollution treatment T_t, and the fraction a of total water pollution P_t that is lost from the system through deposition, transport, uptake and other biophysical processes.

The current value Hamiltonian, while omitting time notation t, is now given by:

$$H = (\alpha_1 + \alpha_2 R - \alpha_3 R^2) - (\alpha_4 + \alpha_5 T + \alpha_6 T^2)$$
$$+ (\beta_1 - \beta_2 P) + \lambda(b + R - T - aP) \tag{4}$$

where λ is the costate variable. Assuming an interior solution, the necessary conditions for an optimum solution can be derived (i.e., $\delta H/\delta R = 0$; $\delta H/\delta T = 0$; $\delta P/\delta t = \delta H/\delta \lambda$; $\delta \lambda/\delta t = -\delta H/\delta P + r\lambda$), and in the steady state ($\delta \lambda/\delta t = \delta P/\delta t = 0$) this is solved for the welfare maximizing rates of (agricultural) water pollution R^*, (wetland) water pollution treatment T^* and level of water pollution P^*. These are given by:

$$R^* = (\alpha_2(a + r) - \beta_2)/2\alpha_3(a + r) \tag{5}$$

$$T^* = (\beta_2 - \alpha_5(a + r))/2\alpha_6(a + r) \tag{6}$$

$$P^* = (b + R^* - T^*)/a \tag{7}$$

Note that the welfare maximizing rate of (agricultural) water pollution R^* is decreasing in α_3 and β_2, and increasing in α_2, r and a (Equation (5)), while the welfare maximizing rate of (wetland) water pollution treatment T^* is increasing in β_2, and decreasing in α_5, α_6, a and r (Equation (6)). The welfare maximizing level of water pollution P^* is decreasing in T^* and a, and increasing in R^* and b (Equation (7)).

Empirical application

The model described in the previous section is now used to compare rates of (agricultural) water pollution abatement and (wetland) water pollution treatment as well as corresponding welfare implications in the Tully-Murray region. To this end, parameter values for agricultural benefit $B_{\text{ter}}(R_t)$, (wetland) water pollution treatment cost $C_{\text{ter}}(T_t)$ and marine benefit $B_{\text{mar}}(P_t)$ functions are determined.

The agricultural benefit function $B_{\text{ter}}(R_t)$ for the Tully-Murray catchment is derived using the Environmental Economic Spatial Investment Prioritization (EESIP) modelling approach, which integrates an agricultural production system simulation model, a catchment water quality model and a spatial environmental-economic land-use model (see Roebeling *et al.* 2009a). The agricultural production system simulation model assesses plot-level production and water pollution characteristics for hundreds of agricultural land use and management practices; the catchment water quality model assesses the relationship between local water pollution supply (i.e., gross supply of water pollutants to streams and rivers) and end-of-catchment water pollution delivery (i.e., net delivery of water pollutants to the coast); and, finally, the spatial environmental-economic land-use model allocates agricultural land use and management practices such that they contribute most to agricultural benefits given specified end-of-catchment load targets.

Roebeling *et al.* (2009b) use EESIP to estimate benefits from sugarcane and grazing production at increasing rates of allowed DIN water pollution delivery to the GBR catchment lagoon and, in turn, fit the corresponding quadratic agricultural benefit functions (see Equation (1)). Summation of these industry-specific agricultural benefit functions for the sugarcane and grazing industries, yields the agricultural benefit function (in 2014 million AUD year^{-1}).

$$B_{\text{ter}}(R_t) = 69.423 + 0.1139R_t - 0.00012R_t^2 \tag{8}$$

with R_t the rate of (agricultural) water pollution (in t DIN year^{-1}). All monetary values are updated to 2014 AUD using the consumer price index (World Bank 2015).

The (wetland) water pollution treatment cost function $C_{\text{ter}}(T_t)$ is taken from Roebeling *et al.* (2011). Based on secondary information for extensive treatment technologies (i.e., constructed/restored/managed wetlands), they construct a database ($n = 41$) for wetland capacity, area, pollution concentration, treatment efficiency, construction costs and operation and maintenance costs. Wetland water

pollution treatment rates (in t DIN year^{-1}) were calculated using DIN concentration, wetland capacity and wetland treatment efficiency data, and all cost data were transferred to 2005 AUD year^{-1}. Using ordinary least squares estimation techniques they, in turn, estimate quadratic (wetland) treatment cost functions (see Equation (1)) for construction costs and operation and maintenance costs.

Their results show that construction costs are quadratically increasing in the rate of DIN water pollution treatment, due to costs associated with terrain levelling and land acquisition that are exponentially increasing in wetland size. Adjusted R^2 values are, however, low ($R^2 = 0.3$) because: (i) the wetland treatment rate (explanatory variable) does not linearly translate into wetland area; and (ii) construction costs and land prices vary considerably between locations. Operation and maintenance costs are, as expected, linearly increasing in the rate of DIN water pollution treatment. Adjusted R^2 values are satisfactory ($R^2 = 0.6$). Summation of the construction cost and operation and maintenance cost functions yields the (wetland) water pollution treatment cost function (in 2014 million AUD year^{-1})

$$C_{\text{ter}}(T_t) = 0.1404 + 0.3118T_t + 0.0086T_t^2 \tag{9}$$

where T_t is the rate of (wetland) water pollution treatment (in t DIN year^{-1}).

The marine benefit function $B_{\text{mar}}(P_t)$ from use values of the GBR, is taken from Roebeling *et al.* (2011). In line with earlier studies and based on tourism, commercial fishery and recreational fishery values in the Tully-Murray region, they take marine benefits to be linearly decreasing in the level of marine water pollution P_t (see Equation (1)). The marine tourism producer surplus equals about 6.1 million AUD per year (based on Productivity Commission (2003) and GBRMPA (2004)), the commercial and recreational fishery producer surplus equals around 11.4 million AUD per year (based on Fenton & Marshall (2001) and Productivity Commission (2003)) and, hence, the use value of the GBR in the Tully-Murray region (in its current state) amounts to about 17.5 million AUD per year. The marine benefit function becomes (in 2014 million AUD year^{-1})

$$B_{\text{mar}}(P_t) = (17.5 + \beta_2 P_0) - \beta_2 P_t \tag{10}$$

where P_0 is the current baseline level of (GBR lagoon) water pollution (in t DIN), and noting that the first term on the right-hand side determines the maximum attainable marine benefits β_1.

While the effect of marine water pollution on reef health is widely recognized (Furnas 2003; Fabricius 2005), the marginal costs from marine water pollution β_2 are less well known (Wielgus *et al.* 2002; Keeler *et al.* 2012). Keeler *et al.* (2012) argue that there is no generic framework linking continuous changes in water quality to changes in multiple ecosystem services – thus failing to achieve full-accounting of associated changes in ecosystem service values. Thus, a sensitivity analysis with respect to β_2 is performed in the next section.

RESULTS AND DISCUSSION

Based on the abovementioned parameter values for the Tully-Murray region, first, the costs associated with (agricultural) water pollution abatement and (wetland) water pollution treatment are analysed and compared. Next, welfare maximizing rates of (agricultural) water pollution R^* and (wetland) water pollution treatment T^* for varying values of marginal marine water pollution costs β_2 are explored. As pollution treatment is one of many ecosystem services provided by wetlands (Costanza *et al.* 1997; Mitsch & Gosselink 2000), estimated at about 10% of the total ecosystem service value of floodplain wetlands (Costanza *et al.* 1997; De Groot *et al.* 2012), results are presented for full and partial (wetland) water pollution treatment costs $B_{\text{ter}}(T_t)$.

Water pollution abatement and treatment costs

To compare the costs of (wetland) water pollution treatment T_t and (agricultural) water pollution abatement A_t, the agricultural benefit function $B_{\text{ter}}(R_t)$ is rewritten in terms of the water pollution abatement cost function $C_{\text{ter}}(A_t)$. Using Equation (8), while noting that $C_{\text{ter}}(A_t) = B_{\text{ter}}(R_0) - B_{\text{ter}}(R_t)$ and $A_t = R_0 - R_t$ (with R_0 the current rate of agricultural water pollution), it can be verified that the (agricultural) water pollution abatement cost function is given by (in 2014 million AUD year^{-1})

$$C_{\text{ter}}(A_t) = -0.0183A_t + 0.00012A_t^2 \tag{11}$$

with A_t the rate of (agricultural) water pollution abatement (in t DIN year^{-1}).

Graphical representation of the (agricultural) water pollution abatement cost function (see Equation (11); Figure 1) shows that considerable DIN water quality improvements can be obtained at a negative cost and, thus, a private benefit
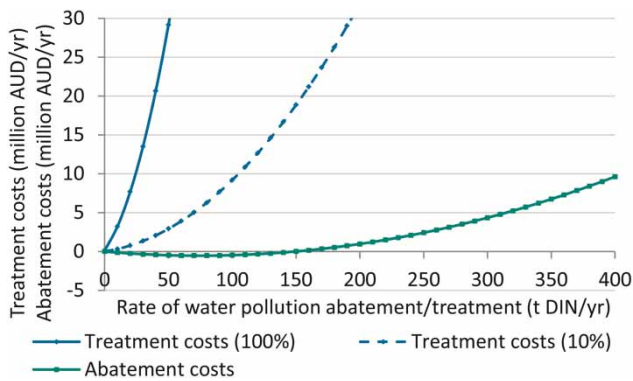
Figure 1 | Total (agricultural) DIN water pollution abatement cost function and (wetland) DIN water pollution treatment cost functions ($B_{ter}(T_t) = 100\%$ and 10%) for the Tully-Murray catchment.

to the agricultural sector. Maximum benefits are expected to be obtained through a reduction in DIN water pollution of about 15% (~75 t DIN), and are facilitated through the adoption of win-win management practices in sugarcane production. Win-win management practices in sugarcane production include the adoption of more nitrogen-efficient management practices, such as economic optimum rates of nitrogen application, split nitrogen application and nitrogen replacement (see Roebeling *et al.* 2009a, b).

While reductions in DIN water pollution beyond 15% come at a cost to the agricultural sector, reductions in DIN water pollution of up to almost 30% (~150 t DIN) are expected to come at no additional cost, as compared to the current situation. Reductions in DIN water pollution of over 30% come at a (significant) cost to the agricultural sector – up to about 10.8 million AUD year^{-1} for a 70% (~380 t DIN) decrease in DIN water pollution. This is due to the adoption of lose-win management practices in combination with a reduction in production area (see Roebeling *et al.* 2009a, b).

Graphical representation of the (wetland) water pollution treatment cost function (see Equation (9); Figure 1) shows that all treatment comes at a cost. For a 5% (~25 t DIN) decrease in DIN water pollution, (wetland) water pollution treatment costs amount to up to about 13.5 million AUD year^{-1} and 1.4 million AUD year^{-1} in case full (100%) and partial (10%) treatment costs are considered, respectively. For wetlands of relatively small capacity (<5 t DIN year^{-1}), marginal (wetland) water pollution treatment costs are estimated at between 38 and 320 thousand AUD t^{-1} DIN – in line with Byström (1998) and Gren (2008) who estimate marginal (wetland) water pollution treatment costs at between 4 and 205 thousand AUD t^{-1} DIN. Ribaudo *et al.* (2001), however, estimate average (wetland) water pollution treatment costs at only 25,000 AUD

t^{-1} DIN, although they do not consider wetland operation and maintenance costs.

Comparison of the (agricultural) water pollution abatement and (wetland) water pollution treatment cost functions shows that diffuse source (wetland) water pollution treatment options are relatively expensive. This in line with Ribaudo *et al.* (2001) and Gren (2008), who show that the unit cost of diffuse source (wetland) water pollution treatment can be up to twenty times more expensive than the unit cost of diffuse source (agricultural) water pollution abatement. For the Tully-Murray case study, these differences are even larger as, in contrast to these earlier studies, win-win (agricultural) water pollution abatement options are specifically taken into account.

Welfare maximizing rates of water pollution abatement and treatment

For the reference year 2005, the current rate of (agricultural) water pollution $R_0 = 547.5$ t DIN year^{-1} (Roebeling *et al.* 2009b). Given that diffuse source (wetland) water pollution treatment does not take place ($T_0 = 0.0$ t DIN year^{-1}) while considering no other sources ($b = 0$) and no re-suspension ($a = 1$) of water pollutants, the current level of (GBR lagoon) water pollution P_0 equals 547.5 t DIN year^{-1} (using Equation (7)). The corresponding (regional) net benefit π_0 equals 112.9 million AUD year^{-1} (using Equations (8), (9) and (10); $\beta_2 = 0$). Given a time discount rate r of 5% year^{-1}, the welfare maximizing R^*, T^*, P^* and π^* for values of marine water pollution costs β_2 and (wetland) water pollution treatment costs $B_{ter}(T_t)$ are given in Table 1.

When downstream costs from DIN water pollution (i.e., $\beta_2 = 0$) are ignored, maximum welfare gains can be obtained

Table 1 | Welfare maximizing rates of (agricultural) DIN water pollution R^*, rates of (wetland) DIN water pollution treatment T^*, levels of (GBR lagoon) DIN water pollution P^* and levels of (regional) net benefits π^*, for values of (marine) DIN water pollution costs β_2 and (wetland) DIN water pollution treatment costs ($B_{ter}(T_t) = 100\%$ and 10%) for the Tully-Murray region

	Water pollution treatment costs 100%			Water pollution treatment costs 10%		
	$\beta_2 =$ 0.00	$\beta_2 =$ 0.04	$\beta_2 =$ 0.08	$\beta_2 =$ 0.00	$\beta_2 =$ 0.04	$\beta_2 =$ 0.08
R^* (t DIN/year)	471.7	313.9	156.1	471.7	313.9	156.1
T^* (t DIN/year)	0.0	0.0	0.0	0.0	4.0	26.1
P^* (t DIN/year)	471.7	313.9	156.1	471.7	309.9	130.0
π^* (million AUD/year)	113.6	119.9	132.9	113.7	120.1	133.7

through a reduction in (agricultural) DIN water pollution of about 15% (~75 t DIN) – i.e., through the adoption of win-win management practices (see previous section). DIN water pollution treatment (wetland) does not contribute to welfare ($T^* = 0$), as treatment involves considerable costs (see previous section) while there are no associated benefits from water quality improvement (given $\beta_2 = 0$). The level of (GBR lagoon) water pollution decreases, as a result, by almost 15% and (regional) net benefit increases by about 1% to 113.6 million AUD per year.

When downstream costs from DIN water pollution (i.e., $\beta_2 > 0$) are acknowledged, welfare gains can be obtained through sizable reductions in (agricultural) water pollution and some (wetland) water pollution treatment. In the case where downstream costs from water pollution β_2 equals 40,000AUD t^{-1} DIN (i.e., $\beta_2 = 0.04$) or even 80,000AUD t^{-1} DIN (i.e., $\beta_2 = 0.08$), maximum welfare gains are obtained through a reduction in (agricultural) rates and corresponding (GBR lagoon) levels of DIN water pollution of 43% and 71%, respectively. Wetland water pollution treatment only takes place when partial treatment costs are considered, with wetlands treating up to 26.1 t DIN per year (10% treatments costs). Thus, levels of (GBR lagoon) water pollution decrease by another 1% ($\beta_2 = 0.04$) to 5% ($\beta_2 = 0.08$). Regional net benefits increase by between 6% ($\beta_2 = 0.04$) and 18% ($\beta_2 = 0.08$), while noting that additional welfare gains from (wetland) water pollution treatment are relatively small (<1%).

Hence, it is shown that welfare gains can be obtained, primarily, through diffuse source water pollution abatement (improved agricultural management practices) and, to a minor extent, through diffuse source water pollution treatment (wetland restoration). This is in contrast with studies assessing welfare gains from diffuse source (agricultural) water pollution abatement and point source (municipal) water pollution treatment, which indicate substantial welfare gains from investments in (municipal) wastewater treatment plants (e.g., Laukkanen & Huhtala 2008).

CONCLUSIONS

A deterministic optimal control approach was developed and applied to explore, simultaneously, welfare maximizing rates of (agricultural) water pollution abatement as well as (wetland) water pollution treatment for efficient diffuse source water pollution management in terrestrial-marine systems. In contrast to earlier studies, an analytically tractable solution concept is presented, while providing an indication of the extent to which diffuse source water pollution delivery to the marine environment can efficiently be controlled by means of water pollution abatement (through improved agricultural management practices) and/or water pollution treatment (through wetland restoration), respectively.

Analytical results indicate that the welfare maximizing rates of (agricultural) water pollution and (wetland) water pollution treatment are, respectively, decreasing and increasing in the downstream costs from (GBR lagoon) water pollution. The level of downstream (GBR lagoon) water pollution is increasing in the rate of (agricultural) water pollution and decreasing in the rate of (wetland) water pollution treatment. Numerical results show that (wetland) water pollution treatment only leads to welfare gains when partial treatment costs and positive downstream water pollution costs are considered, while (agricultural) water pollution abatement leads to welfare gains even when downstream costs from water pollution are ignored.

Provided that pollution treatment is estimated at about 10% of the total ecosystem service value of floodplain wetlands, it is shown that welfare gains can be obtained, primarily, through diffuse source water pollution abatement (improved agricultural management practices) and, to a minor extent, through diffuse source water pollution treatment (wetland restoration) in the Tully-Murray catchment. While wetland research in temperate locations has been extensive and generally supports the role of managed wetlands as filters for water pollution, the effectiveness of (managed) wetlands in tropical environments is largely unknown. Hence, it is stressed that cost-effectiveness studies of (managed) tropical wetlands are needed to confirm the validity of the used (wetland) water pollution treatment cost estimates.

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