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Agricultural water pollution treatment for efficient water quality improvement in linked terrestrial and marine ecosystems

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ABSTRACT

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While it is recognized that marine ecosystems are of vital importance from an ecological as well as an economic perspective, these marine ecosystems are affected by water pollution originating from coastal catchments. The delivery of water pollutants to the marine environment can be reduced through water pollution treatment and, consequently, to warrant sustainable economic development of coastal regions we need to balance the marginal costs from water pollution treatment and the associated marginal benefits from marine resource appreciation. Water pollution treatment costs are, however, significant and, consequently, the question arises to what extent marine water quality improvement can efficiently be pursued through water pollution treatment. In this paper we develop and apply an optimal control approach to explore, analytically as well as numerically, social welfare maximizing rates of water pollution treatment for efficient diffuse source water pollution management in linked terrestrial and marine ecosystems. For the case of diffuse source Dissolved Inorganic Nitrogen water pollution in the Tully-Murray catchment (Queensland, Australia), (wetland) water pollution treatment cost functions as well as marine-based environmental value reductions from marine water pollution are estimated to determine social welfare maximizing rates of water pollution treatment. Provided partial (wetland) treatment costs and positive downstream water pollution costs are considered, results show that limited social welfare gains can be obtained through diffuse source water pollution treatment (wetland restoration) in the Tully-Murray catchment.

ADITIONAL INDEX WORDS: *environmental-economic analysis; diffuse source water pollution treatment; wetland restoration; marine ecosystem (service) values.*

INTRODUCTION

Land use change and agricultural development in coastal catchments in the Great Barrier Reef (GBR) region of Australia have led to an increase in the export of diffuse-source water pollutants into the GBR lagoon over the past decades (GABRIC and BELL, 1993; FURNAS, 2003). There is growing concern that the associated elevated levels of water pollution in the GBR lagoon are one of the biggest potential causes of reef degradation (FURNAS, 2003; FABRICIUS, 2005) which, as a result, may affect the economic sectors that rely on the GBR for their income generation (Productivity Commission, 2003; Roebeling, 2006).

As to protect the environmental values of the GBR, the Australian and Queensland Governments developed the Reef Water Quality Protection Plan (STATE OF QUEENSLAND AND COMMONWEALTH OF AUSTRALIA, 2003) which aims to '*halt and reverse the decline in water quality entering the Reef within 10 years*' through the development of Water Quality Improvement Plans (WQIPs) for coastal catchments. These recently developed WQIPs focus, primarily, on (agricultural) water pollution abatement through the adoption of improved management practices and, only to a minor extent, on (wetland) water pollution treatment through wetland restoration (BINNEY, 2010).

To warrant sustainable economic development of coastal regions, we need to balance the marginal costs from reduced water pollution delivery to the marine environment and the associated marginal benefits from marine resource appreciation (see HART and BRADY, 2002; GREN and FOLMER, 2003; ROEBELING, 2006). While several studies explore efficient rates of (agricultural) water pollution abatement in linked terrestrial-marine ecosystems (GOETZ and ZILBERMAN, 2000; HART and BRADY, 2002; ROEBELING, 2006; ROEBELING *et al*., 2009a) and few studies explore social welfare maximizing rates of (municipal) wastewater treatment in linked terrestrial-marine ecosystems (GREN and FOLMER, 2003; LAUKKANEN and HUHTALA, 2008; LAUKKANEN *et al*., 2009), to the knowledge of the authors no studies are available that explore efficient rates of diffuse source (wetland) water pollution treatment in linked terrestrial-marine ecosystems.

In contribution to these earlier studies, the objective of this paper is to develop and apply an analytically tractable deterministic optimal control approach that allows us to explore social welfare maximizing rates of diffuse source (wetland) water pollution treatment in linked terrestrial and marine ecosystems. For the case of diffuse source Dissolved Inorganic Nitrogen (DIN) water pollution by the agricultural sector in the Tully-Murray catchment (Queensland, Australia), we estimate (wetland) water pollution treatment cost functions and marine-based environmental value reductions from water pollution to, in turn, explore to what extent GBR lagoon water quality improvement can efficiently be pursued through water pollution treatment (wetland restoration) in the Tully-Murray catchment.

The structure of the paper is as follows. In the next section the deterministic optimal control approach is developed and solved analytically. Next, we estimate parameter values for the (wetland) water pollution treatment cost function and the marine-based environmental benefit function to determine, in turn, social welfare maximizing rates of (wetland) water pollution treatment in the Tully-Murray catchment. Finally, we provide concluding remarks and observations.

A DETERMINISTIC MODEL OF EFFICIENT WATER POLLUTION TREATMENT

To explore social welfare maximizing rates of (wetland) water pollution treatment, we adapt the Catchment to Reef Optimal Water Pollution Abatement (CROWPA) modeling approach (see ROEBELING, 2006; ROEBELING *et al*., 2007, 2009a) to the case of DIN water pollution treatment in the Tully-Murray catchment.

Let $B_{ter}(R_0,T_t)$ denote total terrestrial benefits from agricultural and wetland land use in coastal catchments that are a function of the current rate of (agricultural) water pollution R_0 (given variable) and the rate of (wetland) water pollution treatment T_t (control variable), and let $B_{mar}(P_t)$ denote total marine benefits from economic use and non-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 $\pi(R_0,T_t,P_t)$ is given by the sum of terrestrial and marine benefits, and is given by

$$\begin{aligned}\pi(R_0,T_t,P_t) &= B_{ter}(R_0,T_t) + B_{mar}(P_t)\\ &= \left((\alpha_1+\alpha_2 R_0-\alpha_3 R_0^2)-(\alpha_4+\alpha_5 T_t+\alpha_6 T_t^2)\right)+(\beta_1-\beta_2 P_t)\end{aligned} \quad (1)$$

where α_1 represents the benefits from agricultural production without (agricultural) water pollution, α_2 and α_3 denote the (agricultural) water pollution benefit coefficients, α_4 represents the fixed costs associated with (wetland) water pollution treatment, and where α_5 and α_6 denote the (wetland) water pollution treatment cost coefficients. In turn, β_1 represents the marine benefits from economic use and non-use values of marine resources in the absence of marine water pollution, and where β_2 denotes the marginal cost from marine water pollution. The social welfare (W) maximization problem is now given by

$$\underset{T_t}{Max}\, W = \int_0^\infty [\pi(R_0,T_t,P_t)]e^{-rt}dt \quad (2)$$

subject to $$\dot{P}_t = f(R_0,T_t,P_t) = R_0 + b - T_t - aP_t \quad (3)$$

with $R_0 > 0$, $T_0 > 0$, $P_0 > 0$, $T_t \geq 0$ and $P_t \geq 0$, and where r is the time discount rate, $\dot{P}_t$ 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 marine water pollution P_t is determined by the current rate of agricultural R_0 and non-agricultural b water pollution, 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.

Following ROEBELING (2006) and dropping time notation t, it can now be shown that the steady state (*i.e.* $\dot{\lambda} = \dot{P} = 0$) social welfare maximizing rate of (wetland) water pollution treatment T^* and level of water pollution P^* are, respectively, given by

$$T^* = \frac{\beta_2 - \alpha_5(a+r)}{2\alpha_6(a+r)} \quad (4)$$

$$P^* = \frac{b + R_0 - T^*}{a} \quad (5)$$

The annual flow of (regional) net benefits π^* is obtained through substitution of R_0, T^* and P^* back into Eqn 1. It can be observed that the social welfare maximizing rate of (wetland) water pollution treatment T^* is increasing in β_2 and decreasing in α_5, α_6, a and r (Eqn 4), while the social welfare maximizing level of water pollution P^* is decreasing in T^* and a and increasing in R_0 and b (Eqn 5).

MODEL PARAMETRIZATION FOR THE TULLY-MURRAY CASE STUDY

The model described in the previous section is applied to the case of DIN (wetland) water pollution treatment in the Tully-Murray catchment in the Wet Tropics of Queensland, Australia. We estimate parameter values for total terrestrial benefits $B_{ter}(R_0,T_t)$ and total marine benefits $B_{mar}(P_t)$ to determine, in the following section, social welfare maximizing rates of (wetland) water pollution treatment T^*.

Total terrestrial benefits

Total terrestrial benefits $B_{ter}(R_0,T_t)$ are given by the sum of current (agricultural) water pollution benefits $B_{ter}(R_0)$ and (wetland) water pollution treatment costs $B_{ter}(T_t)$ (see Eqn 1).

The current (agricultural) water pollution benefits $B_{ter}(R_0)$ for the Tully-Murray catchment, are derived from ROEBELING *et al*. (2009a). In their study they use the Environmental Economic Spatial Investment Prioritization (EESIP) model to determine terrestrial 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 terrestrial (agricultural) benefit functions. Summation of these industry-specific water pollution benefit functions for the sugarcane and grazing industries, yields the (agricultural) water pollution benefit function (in 2005 million A\$ yr^{-1})

$$B_{ter}(R_0) = 54.278 + 0.0890R_0 - 0.00009R_0^2 \quad (6)$$

where R_0 = 547.5 the current rate of (agricultural) water pollution (in t DIN yr^{-1}).

The (wetland) water pollution treatment cost function $B_{ter}(T_t)$ is estimated using secondary information. While various studies estimate cost functions for intensive treatment technologies like activated sludge systems, oxidation ditches and biological contactors (*e.g.* TSAGARAKIS *et al*., 2003; CHO *et al*., 2004; FRIEDLER and PISANTY, 2006), only few studies estimate treatment cost functions for extensive technologies like constructed/restored managed wetlands (GREN *et al*., 1997; BYSTRÖM, 1998; SÖDERQVIST, 2002). Hence, we constructed a database (N=41) for wetland capacity, area, pollution concentration, treatment efficiency, construction costs (CC) and operation & maintenance costs (OC), including data from Italy (MANNINO *et al*., 2008; n=3), Spain (PUIGAGUT *et al*., 2006; NOGUEIRA *et al*., 2007; n=13), United States (BREAUX *et al*., 1994; USEPA, 1988, 1993; n=21), China (ZHANG *et al*., 2009; n=3) and Australia (LEE *et al*., 2009; n=1). Construction and operation & maintenance costs (in million A\$ yr^{-1}) were transferred to 2005 A\$ using the inflation GDP deflator and the corresponding exchange rate (WORLD BANK, 2009), while construction costs were annualized using a wetland lifetime of 50 years and a time discount rate of 5% (following SÖDERQVIST, 2002). The (wetland) water pollution treatment rates (in t DIN yr^{-1}) were calculated using DIN concentration, wetland capacity and wetland treatment efficiency data.

Using ordinary least squares estimation techniques and including all non-zero observations (CC>0 and OC>0), quadratic (wetland) treatment costs functions (see Eqn 1) are estimated for construction costs and operation & maintenance costs, respectively. Model estimation results show (Table 1) that construction costs are quadratically increasing in the rate of DIN water pollution treatment ($\alpha_6 > 0$), which is explained by costs associated with terrain leveling works and land acquisition that are exponentially increasing in wetland size. The linear coefficient (α_5) is insignificant at the 10% level and, hence, excluded. Adjusted R^2-values are relatively low for both the full and reduced model, which is explained by the fact that the explanatory variable (wetland treatment rate) does not linearly translate into wetland area and by the fact that construction costs and land prices vary considerably between countries. Operation & maintenance costs are linearly increasing in the rate of DIN water pollution treatment ($\alpha_5 > 0$), with the constant (α_4) and quadratic (α_6) coefficients insignificant at the 10% level. Adjusted R^2-values indicate that the greater part of the variation is explained by the full as well as the reduced model.

Table 1: *Full and reduced model estimation results for quadratic specification of the annual construction (CC) and operation & maintenance (OC) costs (in 2005 million A$).*

	Full models		Reduced models	
	CC	OC	CC	OC
α_4	0.0523 (1.40)	0.0342 (1.51)	0.1098 (3.11)	-
α_5	0.4513 (0.93)	0.3733 (1.80)	-	0.2438 (6.75)
α_6	0.0117 (1.76)	-0.0573 (-0.74)	0.0068 (2.86)	-
Adj. R^2	0.34	0.62	0.28	0.58
N	33	23	33	23

Note: All *t*-values in parenthesis.

Summation of the (reduced model) construction and operation & maintenance cost functions, yields the (wetland) water pollution treatment cost function (in 2005 million A$ yr^{-1})

$$B_{ter}(T_t) = 0.1098 + 0.2438T_t + 0.0068T_t^2 \qquad (7)$$

where T_t is the rate of (wetland) water pollution treatment (in t DIN yr^{-1}). For relatively small wetlands (< 5 t DIN yr^{-1}), marginal (wetland) water pollution treatment costs are estimated at between 30 and 250 thousand A$ t^{-1} DIN – in line with BYSTRÖM (1998) and GREN (2008) who estimate marginal (wetland) water pollution treatment costs at between 3 and 160 thousand A$ t^{-1} DIN. While research in temperate locations, on which our estimates are based, has been extensive and generally supports the role of managed wetlands as filters, the effectiveness of (managed) wetlands in tropical environments is largely unknown (MCJANNET, 2007; KROON, 2008). Hence, we argue that cost-effectiveness studies of (managed) tropical wetlands are needed to confirm the validity of our estimates in tropical environments.

Total marine benefits

Marine benefits $B_{mar}(P_t)$ from use and non-use values of the GBR are taken to be linearly decreasing in the level of marine water pollution P_t (see Eqn 1), in line with earlier studies from the Caribbean (RUITENBEEK *et al*., 1999; GUSTAVSON and HUBER, 2000), Hawaii (CESAR *et al*., 2002) and Australia (ROEBELING, 2006; ROEBELING *et al*., 2009a).

Estimates of current use values of marine resources in the Tully-Murray catchment, include tourism, commercial fishery and recreational fishery benefits. The marine tourism producer surplus equals ~4.7 million A$ per year, given an average expenditure of almost 115 A$ per visitor (GBRMPA, 2004), about 75,000 reef visitors to the Tully-Murray area per year (GBRMPA, 2004) and a ratio of value added to gross margin of 0.55 (Productivity Commission, 2003). The commercial and recreational fishery producer surplus equals ~8.9 million A$ per year (FENTON and MARSHALL, 2001; PRODUCTIVITY COMMISSION, 2003). Consequently, the current use value β_1 of the GBR in the Tully-Murray catchment amounts to ~13.6 million A$ per year.

While the effect of water pollution on reef health is widely recognized (FURNAS, 2003; FABRICIUS, 2005), the quantitative relationship between water pollution and indicators of reef health is less well known (WIELGUS *et al*., 2002) and, thus, so is the relationship between water pollution, reef health and marine ecosystem (service) values (ROEBELING, 2006). Thus, we perform a sensitivity analysis with respect to β_2 in the next section.

Given that the current use value β_1 is obtained at the current level of (GBR lagoon) water pollution P_0 and to allow for a sensitivity analysis with respect to β_2, the total marine benefit function becomes (in 2005 million A$ yr^{-1})

$$B_{mar}(P_t) = (13.6 + \beta_2 P_0) - \beta_2 P_t \qquad (8)$$

with P_t the level of (GBR lagoon) water pollution (in t DIN yr^{-1}). Note that the first term on the right-hand-side of Eqn 8 determines the maximum attainable marine benefit $B_{mar}(P_t)$ for specified marginal costs from marine water pollution β_2, while $B_{mar}(P_t)$ = 13.6 for all β_2 when $P_t = P_0$.

MODEL RESULTS FOR THE TULLY-MURRAY CASE STUDY

Based on the parameter estimates derived in the previous section, we determine the social welfare maximizing rates of (wetland) water pollution treatment T^* for varying values of marine water pollution costs β_2. As pollution treatment is but one of many ecosystem services provided by wetlands, estimated at about 10% of the total ecosystem service value of floodplain wetlands (COSTANZA *et al*., 1997), results are presented for full and partial (wetland) water pollution treatment costs $B_{ter}(T_t)$.

For the reference year 2005, the current Tully-Murray catchment rate of (agricultural) water pollution R_0 equals 547.5 t DIN yr^{-1} (ROEBELING *et al*., 2009a). Given that diffuse source (wetland) water pollution treatment does not take place (T_0 = 0.0 t DIN yr^{-1}) while ignoring other sources (b = 0) and re-suspension (a = 1) of water pollutants, the current level of (GBR lagoon) water pollution P_0 equals 547.5 t DIN yr^{-1} (using Eqn 3). The corresponding (regional) net benefit π_0 equals 88.3 million A$ yr^{-1} (using Eqn 6, 7 and 8; β_2 = 0). Given a time discount rate r of 5% yr^{-1}, the social welfare maximizing T^*, P^* and π^* for varying values of marine water pollution costs β_2 and (wetland) water pollution treatment costs $B_{ter}(T_t)$ are given in Table 2.

When we ignore downstream costs from DIN water pollution (i.e. β_2 = 0), we see that (wetland) DIN water pollution treatment does not contribute to social welfare (and, hence, T^* = 0) as treatment involves considerable costs (see previous section) while there are no associated benefits from water quality improvement (given that β_2 = 0). Hence, the level of (GBR lagoon) water pollution remains at P^* = 547.5 t DIN yr^{-1} and the corresponding (regional) net benefit at π^* = 88.3 million A$ yr^{-1}.

Table 2: *Social welfare maximizing rates of (wetland) water pollution treatment T^*, levels of (GBR lagoon) water pollution P^* and levels of (regional) net benefits π^*, for values of (marine) water pollution costs β_2 and (wetland) water pollution treatment costs ($B_{ter}(T_t)$ = 100%, 50%, 25% and 12.5%).*

	Treatment costs 100%			Treatment costs 50%		
	β_2 = 0.00	β_2 = 0.04	β_2 = 0.08	β_2 = 0.00	β_2 = 0.04	β_2 = 0.08
T^* (t DIN)	0.0	0.0	0.0	0.0	0.0	0.0
P^* (t DIN)	547.5	547.5	547.5	547.5	547.5	547.5
π^* (10^6 A$)	88.3	88.3	88.3	88.3	88.3	88.3

	Treatment costs 25%			Treatment costs 12.5%		
	β_2 = 0.00	β_2 = 0.04	β_2 = 0.08	β_2 = 0.00	β_2 = 0.04	β_2 = 0.08
T^* (t DIN)	0.0	0.0	4.5	0.0	4.5	27.1
P^* (t DIN)	547.5	547.5	543.0	547.5	543.0	520.4
π^* (million A$)	88.3	88.3	88.4	88.3	88.4	89.1

When we acknowledge downstream costs from DIN water pollution (i.e. $\beta_2 > 0$), we see that social welfare gains can be obtained through some (wetland) water pollution treatment. Wetland water pollution treatment only takes place when partial treatment costs are considered, with wetlands treating up to 4.5 t DIN (25% treatments costs) and 27.1 t DIN (12.5% treatments costs) per year. As a result, levels of (GBR lagoon) water pollution decrease with up to 1% (β_2 = 0.04) and 5% (β_2 = 0.08). Finally, additional welfare gains from (wetland) water pollution treatment are relatively small (< 1%).

Consequently, we've shown that limited social welfare gains can be obtained through diffuse source water pollution treatment (wetland restoration). This in contrast with studies assessing the social welfare gains from point source (municipal) water pollution treatment (LAUKKANEN and HUHTALA, 2008; LAUKKANEN *et al*., 2009), that indicate substantial welfare gains from investments in (municipal) wastewater treatment plants.

CONCLUSIONS AND DISCUSSION

A deterministic optimal control approach was developed and applied to explore, social welfare maximizing rates of (wetland) water pollution treatment for efficient diffuse source water pollution management in linked terrestrial and marine ecosystems. In contrast to earlier studies we provide an analytically tractable solution concept, while providing a first indication of the extent to which diffuse source water pollution delivery to the marine environment can efficiently be controlled by means of water pollution treatment (through wetland restoration).

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

Given that pollution treatment is estimated at about 10% of the total ecosystem service value of floodplain wetlands, we've shown that limited social welfare gains can be obtained 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, we stress the need for cost-effectiveness studies of (managed) tropical wetlands to confirm the validity of our (wetland) water pollution treatment cost estimates in tropical environments.

LITERATURE CITED

BINNEY, J., 2010. The economic and social impacts of protecting environmental values in the Great Barrier Reef catchment waterways and reef lagoon. Marsden Jacob Associates for the Department of Environment and Resource Management, Brisbane, Australia. 176 pp.

BREAUX, A., FARBER, S. and DAY, J., 1994. Using natural coastal wetlands systems for wastewater treatment: an economic benefit analysis. *Journal of Environmental Management*, 44, 285-291.

BYSTRÖM, O., 1998. The nitrogen abatement cost in wetlands. *Ecological Economics*, 26, 321-331.

CESAR, H.S.J., VAN BREUKINGEN, P., PINTZ, S. and DIERKING, J., 2002. Economic valuation of the coral reefs of Hawaii. Hawaii Coral Reef Initiative Research Program, Hawaii, USA. 123 pp.

CHO, J.H., SUNG, K.S. and HA, S.R., 2004. A river water quality management model for optimizing regional wastewater treatment using a genetic algorithm. *Journal of Environmental Management*, 73, 229-242.

COSTANZA, R., D'ARGE, R., DE GROOT, R., FARBER, S., GRASSO, M., HANNON, B., NAEEM, S., LIMBURG, K., PARUELO, J., O'NEILL, R.V., RASKIN, R., SUTTON, P. and VAN DEN BELT, M., 1997. The value of the world's ecosystem services and natural capital. *Nature*, 387, 253–260.

FABRICIUS, K. E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Marine Pollution Bulletin*, 50, 125-146.

FENTON, D.M. and MARSHALL, N.A., 2001. A guide to the fishers of Queensland, part A: TRC analysis and social profiles of Queensland's commercial fishing industry. CRC Reef Research Centre, Technical Report 36, Townsville, Australia. 207 pp.

FRIEDLER, E. and PISANTY, E., 2006. Effects of design flow and treatment level on construction and operation costs of municipal wastewater treatment plants and their implications on policy making. *Water Research*, 40, 3751-3758.

FURNAS, M., 2003. Catchments and corals: terrestrial runoff to the Great Barrier Reef. Australian Institute of Marine Science, Townsville, Australia. 334 pp.

GABRIC, A.J. and BELL, P.R.F., 1993. Review of the effects of non-point nutrient loading on coastal ecosystems. *Australian Journal of Marine and Freshwater Research*, 44, 261–283.

GBRMPA – GREAT BARRIER REEF MARINE PARK AUTHORITY, 2004. Data from environmental management charge. Web-site http://www.gbrmpa.gov.au/corp site/key issues/tourism/gbr visitation/page 02.html, viewed June 2004, GBRMPA, Townsville, Australia.

GOETZ, R.U. and ZILBERMAN, D., 2000. The dynamics of spatial pollution: the case of phosphorus runoff from agricultural land. *Journal of Economic Dynamics and Control*, 24, 143-163.

GREN, I.M., 2008. Adaptation and mitigation strategies for controlling stochastic water pollution: an application to the Baltic Sea. *Ecological Economics*, 66, 337-347.

GREN, I.M. and FOLMER, H., 2003. Cooperation with respect to cleaning of an international water body with stochastic environmental damage: the case of the Baltic Sea. *Ecological Economics*, 47, 33-42.

GREN, I.M., ELOFSSON, K. and JANNKE, P., 1997. Cost-effective nutrient reductions to the Baltic Sea. *Environmental and Resource Economics*, 10, 341-362.

GUSTAVSON, K. and HUBER, R.M., 2000. Ecological economic decision support modeling for the integrated coastal zone management of coral reefs. Pages 183-202 in Cesar, H.S.J. (Ed.) Collected essays on the economics of coral reefs. CORDIO, Department for Biology and Environmental Sciences, Kalmar University, Kalmar, Sweden. 244 pp.

HART, R. and BRADY, M., 2002. Nitrogen in the Baltic Sea: policy implications of stock effects. *Journal of Environmental Management*, 66, 91-103.

KROON, F.J., 2008. Draft Tully water quality improvement plan. CSIRO Water for a Healthy Country National Research Flagship, Australia. 117 pp.

LAUKKANEN, M. and HUHTALA, A., 2008. Optimal management of a eutrophied coastal ecosystem: balancing agricultural and municipal abatement measures. *Environmental and Resource Economics*, 39, 139-159.

LAUKKANEN, M., EKHOLM, P., HUHTALA, A., PITKÄNEN, H., KIIRIKKI, M., RANTANEN, P. and INKALA, A., 2009. Integrating ecological and economic modeling of eutrophication: toward optimal solutions for a coastal area suffering from sediment release of fhosphorus. *Ambio*, 38(4), 225-235.

LEE, C.G., FLETCHER, T.D. and SUN, G., 2009. Nitrogen removal in constructed wetland systems. *Engineering in Life Sciences*, 9(1), 11-22.

MANNINO, I., FRANCO, D., PICCIONI, E., FAVERO, L., MATTIUZZO, E. and ZANETTO, G., 2008. A cost-effectiveness analysis of seminatural wetlands and activated sludge wastewater-treatment systems. *Environmental Management*, 41, 118-129.

MCJANNET, D.L., 2007. Towards an understanding of the filter function of tropical wetlands: lessons from temperate locations, development of a conceptual model and design of a field monitoring strategy. CSIRO Water for a Healthy Country National Research Flagship, Australia. 26 pp.

NOGUEIRA, R., FERREIRA, I., JANKNECH, P., RODRÍGUEZ, J.J., OLIVEIRA, P. and BRITO, A.G., 2007. Energy-saving wastewater treatment systems: formulation of cost functions. *Water Science & Technology*, 56(3), 85-92.

PRODUCTIVITY COMMISSION, 2003. Industries, land use and water quality in the Great Barrier Reef catchment. Research Report, Canberra, Australia. 415 pp.

PUIGAGUT, J., VILLASEÑOR, J., SALAS, J.J., BÉCARES, E. and GARCÍA, J., 2006. Subsurface-flow constructed wetlands in Spain for the sanitation of small communities: a comparative study. *Ecological Engineering*, 30, 312-319.

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., VAN GRIEKEN, M.E. and WEBSTER, A.J., 2007. 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. CSIRO Sustainable Ecosystems for the FNQ-NRM Ltd, Townsville, Australia. 26 pp.

ROEBELING, P.C., HENDRIX, E.M.T. and VAN GRIEKEN, M.E., 2009. Exploring industry specific social welfare maximizing rates of water pollution abatement in linked terrestrial and marine ecosystems. *Journal of Coastal Research*, 56, 1681-1685.

RUITENBEEK, J., RIDGLEY, M., DOLLAR, S. and HUBER, R., 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. *Coral Reefs*, 18, 381-392.

SÖDERQVIST, T., 2002. Constructed wetlands as nitrogen sinks in southern Sweden: an empirical analysis of cost determinants. *Ecological Engineering*, 19, 161-173.

STATE OF QUEENSLAND AND COMMONWEALTH OF AUSTRALIA, 2003. Reef water quality protection plan for catchments adjacent to the Great Barrier Reef world heritage area. Queensland Department of Premier and Cabinet, Brisbane, Australia. 44 pp.

TSAGARAKISI, K.P., MARA, D.D. and ANGELAKISI, A.N., 2003. Application of cost criteria for selection of municipal wastewater treatment systems. *Water, Air and Soil Pollution*, 142, 187-210.

USEPA – UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, 1988. Constructed wetlands and aquatic plant systems for municipal wastewater treatment – design manual. Report EPA/625/1-88/022, USEPA Office of Research and Development, Cincinnati, USA. 92 pp.

USEPA – UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, 1993. Constructed wetlands for wastewater treatment and wildlife habitat. Report EPA832-R-93-005, USEPA Municipal Technology Branch, Washington, USA. 219 pp.

WIELGUS, J., CHADWICK-FURMAN, N.E., DUBINSKY, Z., SHECHTER, M. and ZEITOUNI, N., 2002. Dose-response modeling of recreationally important coral-reef attributes: a review and potential application to the economic valuation of damage. *Coral Reefs*, 21, 253 259.

WORLD BANK, 2009. World Development Indicators 2009. World Bank, Washington, USA. CD-ROM.

ZHANG, D., GERSBERG, R.M. and KEAT, T.S., 2009. Constructed wetlands in China. *Ecological Engineering*, 35, 1367-1378.

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