Financial-economic analysis of current best management practices for sugarcane, horticulture, grazing and forestry industries in the Tully-Murray catchment

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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 3.3b,c,d and Task 2.15 of the Water Quality Improvement Program (WQIP) for the Tully-Murray catchment.

This study analyses the cost-effectiveness of most promising best-management-practices (BMPs) for water quality improvement in sugarcane, horticulture, grazing and forestry production in the Tully-Murray catchment. More specifically, the objectives of this study are to:

- Determine the (plot level) financial-economic consequences of BMP implementation in sugarcane, horticulture, grazing and forestry production;
- Determine the effectiveness of these BMPs in reducing fine suspended sediment, dissolved inorganic nitrogen and persistent herbicide delivery; and
- Assess the impact of climate change and population growth on BMP cost-effectiveness and attainment of water quality targets

We therefore apply and extend the approach developed by Roebeling *et al*. (2005), which uses production system simulation models (APSIM, LUCTOR and PASTOR) and a hydrological model (SedNet/ANNEX) in combination with sound cost-benefit analysis, while the impact of population growth on attainment of water quality targets is assessed using a classic urban economic model with environmental amenities (see Roebeling *et al.* 2007).

Scenarios for BMPs are based on the compilation of practices identified in Task 3.3(a) (see Roebeling and Webster, 2007), and include tillage management, fallow management, nitrogen application rate, nitrogen application method and herbicide application rate in the case of sugarcane production; inter-row management and fertiliser application rate in the case of (banana) horticulture production; stocking rate and nitrogen application rate in the case of grazing production; and finally inter-row management in the case of forestry production.

Production system	Management practice	Gross margin	FSS delivery	DIN delivery	HER delivery
Sugarcane	Tillage management	(+)	++	0	0
	Fallow management	+	0	–	0
	Nitrogen application rate ~ requirements	+	(0)	++	0
	Nitrogen application method	(0)	0	(+)	0
	Herbicide application rate	(–)	0	0	++
Horticulture	Interrow management	(–)	++	0	0
	Fertiliser application rate ~ requirements	–	(0)	+	0
Grazing	Stocking rate ~ carrying capacity	+	(+)	(0)	0
	Nitrogen application rate ~ requirements	+	(0)	(+)	0
Forestry	Interrow management	(–)	(+)	0	0

- In sugarcane production, moving towards a zero tillage system as well as moving towards a legume (rather than a bare) fallow are attractive from a financial-economic perspective, while only zero tillage leads to a reduction in water pollutant (fine suspended sediment – FSS) delivery. Matching nitrogen application rates to crop requirements is attractive from a financial-economic as well as a water pollutant (dissolved inorganic nitrogen – DIN) delivery perspective, while split (rather than single) application of nitrogen leads to minor changes in profitability and water pollutant delivery. Reduced herbicide application comes at a small cost while leading to a considerable reduction water pollutant (persistent herbicide – HER) delivery.
- In (banana) horticulture production, maintenance of grassed (rather than bare) interrows leads to a small reduction in profitability though does lead to a considerable reduction in water pollutant (FSS) delivery. Matching fertiliser application rates to crop requirements rates lead to a decrease in water pollutant (DIN) delivery and gross margins, unless efficiency gains can be made through re-composition of fertiliser application ratios.
- In grazing production, matching stocking rates to pasture carrying capacity leads to a small reduction in water pollutant (FSS) delivery as well as an increase in profitability. Matching nitrogen application rates to pasture requirements is attractive from a financial-economic perspective and leads to small reductions in water pollutant (DIN) delivery.
- In (hard timber) forestry production, maintenance of grassed (rather than bare) interrows leads to a small reduction in water pollutant (FSS) delivery and profitability.

Consequently, options for cost-effective water quality improvement are largest in sugarcane production (tillage management, nitrogen application rate and herbicide application rate) and (banana) horticulture production (interrow management in (banana), while options for cost-effective water quality improvement in grazing and forestry production are limited.

Climate change and population growth are shown to potentially impact on the attainment of water quality targets. While climate change does not seem to affect, for an example of the sugarcane industry, BMP cost-effectiveness, it may lead to a significant increase in levels of water pollutant (DIN) delivery under some climate change projections for 2070. In case water pollution from residential land uses exceeds water pollution from the land uses it replaces, it can be expected that water pollution increases with population size and that the potential for water quality improvement through BMP adoption in agriculture is reduced due to population growth.

A number of caveats to this study must be mentioned. First, this BMP cost-effectiveness assessment is a plot-level study and, consequently, does not include costs associated with BMP implementation at the farm and community level. Second, not all of the used production system simulation models are equally suited for BMP cost-effectiveness assessment – APSIM resulted to be best suited as it contains the most sophisticated routines for the calculation of *C*-factors and DIN concentrations while it also allows for the assessment of the largest range of current and future BMPs. Third, persistent herbicide (HER) delivery calculations are fairly simplistic as there is no hydrological model available that accurately describes the relationship between plot level persistent herbicide concentrations and persistent herbicide delivery. Finally, it must be noted that the figures in this document are generated for the Tully-Murray catchment and, consequently, care should be taken when transferring these figures to other catchments.

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 Program (WQIP) for the Tully-Murray catchment.

The overall objective of this particular 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 Water Quality Improvement Program (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 focuses on Task 3.3b,c,d and Task 2.15, analysing the cost-effectiveness of most promising best-management-practices (BMPs) for water quality improvement in sugarcane, horticulture, grazing and forestry production in the Tully-Murray catchment (as identified in Task 3.3a – see Roebeling and Webster, 2007) and assessing the impact of climate change and population growth on BMP cost-effectiveness and attainment of water quality targets. We determine the plot level financial-economic consequences of BMP implementation in sugarcane, horticulture, grazing and forestry production, as well as the effectiveness of these BMPs in reducing fine suspended sediment (FSS), dissolved inorganic nitrogen (DIN) and persistent herbicide (HER) delivery – which are considered the most important water pollutants in the Tully-Murray catchment (Mitchell *et al.* 2007). We therefore apply and extend the approach developed by Roebeling *et al*. (2005) that uses production system simulation models (APSIM, LUCTOR and PASTOR) and a hydrological model (SedNet/ANNEX) in combination with sound cost-benefit analysis. The impact of climate change on BMP cost-effectiveness and attainment of water quality targets is assessed using the above mentioned approach in combination with climate change projections for 2030 and 2070 (see for example Park *et al.* 2007), while the impact of population growth on attainment of water quality targets is assessed using a classic urban economic model with environmental amenities (see Roebeling *et al.* 2007).

The structure of this report is as follows. Chapter 2 describes the methodology applied in this study, which links production system simulation models, water quality models and costs-benefit analysis to assess the plot level financial-economic cost-effectiveness of management practices in sugarcane, horticulture, grazing and forestry production. In Chapter 3 results are presented and analysed for the identified management practices, thereby looking at annuity gross margins and average annual water pollutant deliveries. In Chapter 4 the potential impacts of climate change and population growth on the effectiveness of BMPs for water quality improvement are discussed. Finally, Chapter 5 summarises key results and offers concluding remarks and observations.

2. Approach to financial-economic analysis of industry current best management practices

Agricultural production systems can be implemented using a wide variety of management practices (MPs), *i.e.* ways in which soils are prepared, crops are treated and cattle are managed. To analyse the cost-effectiveness of these MPs for water quality improvement, we apply an approach that uses production system simulation models (APSIM, LUCTOR and PASTOR) and an hydrological model (SedNet/ANNEX) in combination with sound cost-benefit analysis (see Roebeling *et al.* 2005). The effects of different management practices on sugarcane, horticulture, grazing and forestry production at the plot level, are estimated using production system simulation models (Keating *et al.* 2003; Hengsdijk *et al*. 2000; Bouman *et al.* 1998; see Section 2.1). In turn, the contribution of these management practices to fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) delivery is estimated using the water quality model SedNet/ANNEX (Bartley *et al.* 2004; Hateley *et al.* 2006; see Section 2.2), while persistent herbicide (HER) is estimated by assigning a fixed delivery coefficient to Diuron application based on literature and expert knowledge. Finally, the financial-economic implications of management practice implementation are determined using standard cost-benefit analysis (Zerbe and Dively, 1994; see Section 2.3).

2.1 Production system simulation models

2.1.1 Sugarcane crop growth model – APSIM

Sugarcane input-output data for different management practices (MPs) are generated using the APSIM crop growth model (see for example Robertson *et al.* 1995; Keating *et al.* 1999, 2003). The APSIM sugar module simulates, for a uniform block of cane, per hectare long term dry cane and sucrose weight, ground cover, soil water balance and nitrogen uptake and partitioning to leaf and cane stem. Model simulation results are determined by soil factors such as depth, water holding capacity and nitrogen availability, management factors such as planting date, harvesting date, crop residue management and fertiliser use, genetic factors such as sugarcane variety, and climatic factors like rainfall, radiation and temperature.

For the analysis of sugarcane BMPs in the Tully-Murray catchment, we identify the following soil, management, genetic and environmental factors:

- One set of soil factors is considered, thereby differentiating between four soil classes. The soil classification is based on the soils and land use suitability study of Murtha and Smith (1994). Soil classes include well drained sandy loam soils from granite origin (S1), well drained medium to heavy clay soils from alluvial origin (S2), slowly drained gradational or duplex textured (S3), and poorly drained loam soils from alluvial origin (S4).
- Seven sets of management factors are considered, including three tillage management practices, two fallow management practices, six nitrogen application rates, two nitrogen application methods, two herbicide application rates, one headland type, one trash management practice and one harvest strategy.

  Tillage management practice has been identified as an important management factor by industry and experts in the Tully-Murray catchment (Roebeling and Webster, 2007), determining ground cover and, thus, erosion and sediment delivery from sugarcane systems. Tillage levels are defined for actual (TL1), minimum (TL2) and zero (TL3) tillage. Actual tillage refers to double rotary hoeing and disking-rolling, and single ripping, cross ripping and disking. Minimum tillage refers to single rotary hoeing, disking and disking-rolling. Zero tillage refers to spraying (instead of plowing) out the sugarcane by applying glyphosphate.

Fallow management practice is another management factor considered important by industry and experts in the Tully-Murray catchment (Roebeling and Webster, 2007), determining ground cover and nutrient availability and, thus, sediment and nutrient delivery from sugarcane systems. Fallow management practices are defined for bare (F1) and legume (F2) fallow. Bare fallow implies that the field is left idle after the fourth ratoon harvest until sugarcane is planted in the second week of June the following year and harvested as of the year after that. Legume fallow implies that the field is planted with a legume crop in December after the fourth ratoon harvest before sugarcane is planted in the second week of June the following year (legume sprayed out second week of May and ploughing starts the first week of June) and harvested as of the year after that.

Nitrogen (N) application rate has also been identified as an important management factor in the Tully-Murray catchment (Roebeling and Webster, 2007), determining inorganic nitrogen addition and, thus, inorganic nutrient delivery from sugarcane systems. Defined N-application rates range from below recommended N-application rates (N060 = 60 kg/ha) to frequently observed and perceived high N-application rates (N210 = 210 kg/ha), in five steps of 30 kg N/ha, as well as the nitrogen replacement strategy (NREPL) which aims at a fertiliser application rate matching nitrogen removed or lost from the soil during a crop (Thorburn *et al.* 2007). A differentiation is made by fallow strategy, to distinguish between N-application rates in the plant crop stage.[1]

Nitrogen (N) application method is, potentially, an important management practice to reduce nutrient delivery from sugarcane systems (Chapman, 1994). Defined N-application methods include single (NA1) and split (NA2) application of nitrogen.

Herbicide application rate is considered an important management practice determining chemical delivery from sugarcane systems. Defined herbicide application rates include current (H1) and reduced (H2) herbicide application rates. In the reduced herbicide application option (H2), persistent herbicides like Diuron are only applied on the plant row and non-persistent herbicides like Round-up in the interrow using a hooded sprayer (common in the Douglas Shire area). Alternatively, a knock-down herbicide is used on the plant row and Diuron is used on the interrow using a hooded sprayer (more common in the Cardwell Shire). In both cases, persistent herbicide use is halved using a hooded sprayer, while assuming no yield impacts.

Headland type refers to the establishment of bare or grassed headlands, the latter functioning as a sediment sink (Roth and Visser, 2003; Visser, 2003). As about 80% of the sugarcane growers in Tully-Murray catchment makes use of grassed headlands (Roebeling and Webster, 2007), we take all headlands to be grassed.

Trash management practices include burning cane prior to harvest or leaving green crop residue on the field after harvesting (green cane trash blanketing – GCTB). As the majority (90%) of sugarcane growers in the Tully-Murray catchment apply GCTB (Roebeling and Webster, 2007), we take all crop residue to be left on the field after harvest.

Harvest strategy refers to the timing of harvest during the harvest season. For this study we take all harvests to occur in the middle of the harvest season (August-September).

- One combination of genetic factors is considered, which implies the use of a sugarcane variety that is characterized by a CCS-peak in the middle of the harvesting season (August-September). Other varieties might be considered and may have important yield effects (see for example Jackson et al. 1999), though variety has not been identified as

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[1] When a bare fallow is used, the N-application rate to the plant cane is 75% of the N-application rate to the ratoon cane. When a legume fallow is used, no nitrogen is applied to plant cane.

an important management practice for water quality improvement by industry and experts in the Tully-Murray catchment (Roebeling and Webster, 2007).

- One combination of environmental factors is considered, which encompasses historical rainfall, radiation and temperature patched-point data for the Tully-Murray catchment over the last 95 years (SILO, 2006). Consequently, APSIM simulates sugarcane growth over this 95 year period thereby taking into account climate variability as well as soil N depletion over time.

APSIM is used to generate input and output data for all of the combinations of the defined soil, management, genetic and environmental factors. In total, 1152 unique combinations of inputs and corresponding outputs are assessed[2]. Inputs include fertilisers, herbicides, labour and machinery, and outputs include sugarcane yield, CCS content, ground cover, dissolved inorganic nitrogen (DIN) concentration, and persistent herbicide concentration. The net contribution to total sediment and nutrient delivery is based on ground cover and DIN concentration, and determined using SedNet/ANNEX (see Section 2.2.1 and 2.2.2), while the net contribution to total persistent herbicide delivery is taken as a proportion of persistent herbicide concentration (see Section 2.2.3).

2.1.2 Horticulture crop growth model – LUCTOR

Horticulture input-output data for different management practices (MPs) are generated using the LUCTOR crop growth model (see for example Hengsdijk *et al.* 1998; Hengsdijk *et al.* 2000). The perennial production system module simulates, for a uniform block of land, per hectare long term sustainable yield, crop biomass, ground cover and nutrient balances. Model simulation results are determined by soil factors such as depth, water holding capacity and nutrient availability, management factors such as herbicide use, pesticide use, crop residue management and fertiliser use, genetic factors such as crop variety, and climatic factors like rainfall, radiation and temperature.

For the analysis of banana BMPs in the Tully-Murray catchment, we identify the following soil, management, genetic and environmental factors:

- One set of soil factors is considered, thereby differentiating between three soil classes. The soil classification is based on the soils and land use suitability study by Murtha and Smith (1994), as described in Section 2.1.1. Poorly drained loam soils from alluvial origin (S4) are not suitable for banana production without proper drainage systems in place (Murtha and Smith, 1994), and are thus excluded from the analysis.
- Two sets of management factors are considered, including two interrow management practices and nine fertiliser application rates.

  Interrow management is an important management factor identified by industry and experts in the Tully-Murray catchment (Roebeling and Webster, 2007), determining ground cover and, thus, erosion and sediment delivery from horticulture systems. Defined interrow management practices include bare (R1) and grassed (R2) interrows. Under R1 the interrow is maintained through regular non-persistent herbicide application (e.g. Roundup), while under R2 the interrow is maintained through regular slashing.

  Fertiliser application rate has also been identified as an important management factor by industry and experts in the Tully-Murray catchment (Roebeling and Webster, 2007), determining inorganic nutrient addition and, thus, inorganic nutrient delivery from

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[2] Four soil classes, times three tillage management practices, times two fallow management practices, times six N-application rates, times two post-fallow N-application rates, times two N-application methods, times two herbicide application rates, times one headland type, times one trash management practice, times one harvest strategy, times one combination of genetic and environmental factors, yields 1152 combinations.

horticulture systems. Defined nutrient (N, P and K) application rates range from 20% (F02) to 100% (F10) of the application rate that is required to realize the maximum attainable production, in eight steps of 10%.

- One combination of genetic factors is considered, which implies the use of banana variety Cavendish 'Williams' AAA – the predominant commercial variety in Australia (Hamill, 2005).
- One combination of environmental factors is considered, which encompasses historical average annual rainfall, radiation and temperature patched-point data for the Tully-Murray catchment over the last 95 years (SILO, 2006).

LUCTOR is used to generate input and output data for all of the combinations of the defined soil, management, genetic and environmental factors. In total, 54 unique combinations of inputs and corresponding outputs are assessed[3]. Inputs include fertilisers, herbicides, pesticides, labour and machinery, and outputs include banana yield, ground cover and nutrient concentrations. The net contribution to total water pollutant delivery is based on ground cover and DIN concentration, and determined using SedNet/ANNEX (see Section 2.2).

2.1.3 Grazing production model – PASTOR

Grazing input-output data for different management practices (MPs) are generated using the PASTOR beef cattle modelling tool (see for example Bouman *et al.* 1998; Hengsdijk *et al*. 2000) which simulates, for a uniform block of grazed land, long term sustainable beef production, ground cover and nutrient balances given the complex interaction between pasture growth and stocking rate. Consequently, PASTOR contains separate modules for the calculation of input-output figures for pasture, herd and feed supplement systems.

The pasture module quantifies input-output figures for fertilised, grass-legume and unfertilised pastures. This module simulates, for a uniform block of pasture, maximum attainable metabolizable energy (ME), crude protein (CP) and phosphorus (P) production as a function of stocking rate and nitrogen (N) application rate. Pasture input costs and labour requirements calculations are based on items such as fences, equipment, herbicides and fertilisers. For the Tully-Murray catchment case study, a signal grass (*Brachiaria decumbens*) fertilised pasture system is considered as this is the most widespread pasture production system in the area.

The herd module quantifies input-output figures for breeding, fattening and dual purpose systems. Breeding refers to a system where calves are bred and sold at a specified age, fattening refers to a system where calves are bought, fattened and sold at a specified weight, and dual purpose refers to a system where milk and calves are produced and sold. This module simulates cattle feed requirements (in terms of ME, PC and P) as well as beef and milk production for a stationary herd[4] on the basis of the specified herd structure, target animal growth rates, and target buying and selling strategy. Input costs and labour requirements of the herd are calculated for items like animal health care, yard and fence maintenance, and equipment. For the Tully-Murray catchment case study, a Brahman cross fattening system is considered – the prevalent cattle production system in the area (Teitzel, 1992).

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[3] Three soil classes, times two interrow management practices, times nine nutrient application rates, times one combination of genetic and environmental factors, yields 54 combinations.

[4] A stationary herd refers to a stable herd size and composition over time (see Hengsdijk *et al.* 1998; 2000).

The feed supplement module converts supplement data into feed characteristics (ME, CP and P), input costs and labour application requirements. For the Tully-Murray catchment case study, supplements include sugarcane molasses and a P mineral salt.

For the analysis of grazing BMPs in the Tully-Murray catchment, we identify the following soil, management, genetic and environmental factors:

- One set of soil factors is considered, thereby differentiating between four soil classes. The soil classification is based on the soils and land use suitability study by Murtha and Smith (1994), as described in Section 2.1.1.
- Two sets of management factors are considered, including fifteen stocking rates and eleven nitrogen application rates.

  Stocking rate (or carrying capacity) is an important management factor identified by industry and experts in the Tully-Murray catchment (Roebeling and Webster, 2007), determining ground cover and, thus, soil erosion and sediment delivery from grazing systems. Defined stocking rates range from 0.5 AU/ha (R11) to 4.0 AU/ha (R25) in fourteen steps of 0.25 AU, and where one animal unit (AU) equals 400 kg live weight.

  Nitrogen (N) application rate has also been identified as an important management factor by industry and experts in the Tully-Murray catchment (Roebeling and Webster, 2007), determining inorganic nitrogen addition and, thus, inorganic nutrient delivery from grazing systems. Defined N-application rates range from 0% (S20) to 100% (S30) of the N-application rate that is required to realize the maximum attainable production, in ten steps of 10%.
- One combination of genetic factors is considered, which implies the use of fertilised signal grass (Brachiaria decumbens) and Brahman cattle.
- One combination of environmental factors is considered, which encompasses historical average annual rainfall, radiation and temperature patched-point data for the Tully-Murray catchment over the last 95 years (SILO, 2006).

PASTOR is used to generate input and output data for all of the combinations of the defined soil, management, genetic and environmental factors. In total, 660 unique combinations of inputs and corresponding outputs are assessed.[5] Inputs include cattle, fertilisers, herbicides, labour, equipment and machinery, and outputs include beef production, ground cover and nutrient concentrations. The net contribution to total water pollutant delivery is based on ground cover and DIN concentration, and determined using SedNet/ANNEX (see Section 2.2).

2.1.4 Forestry crop growth model – LUCTOR

Forestry input-output data for different management practices (MPs) are generated using the LUCTOR crop growth model (see for example Hengsdijk *et al.* 2000). The timber plantation production system module simulates, for a uniform block of land, per hectare long term sustainable yield, crop biomass, ground cover and nutrient balances. Model simulation results are determined by soil factors such as depth, water holding capacity and nutrient availability, management factors such as crop residue management, genetic factors such as timber specie, and climatic factors like rainfall, radiation and temperature.

For the analysis of tropical hard timber BMPs in the Tully-Murray catchment, we identify the following soil, management, genetic and environmental factors:

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[5] Four soil classes, times fifteen stocking rates, times eleven N-applications rates, times one combination of genetic and environmental factors, yields 660 combinations.

- One set of soil factors is considered, thereby differentiating between three soil classes. The soil classification is based on the soils and land use suitability study by Murtha and Smith (1994), as described in Section 2.1.1. Slowly drained gradational or duplex textured soils (S3) are generally not suitable for teak production (Kashio and White, 1998) and thus not included in thus study.
- One set of management factors is considered: two interrow management practices.

  Interrow management is an important management factor in the Tully-Murray catchment (Roebeling and Webster, 2007), determining ground cover and, thus, erosion and sediment delivery from forestry systems. Interrow management practices include bare (R1) and grassed (R2) interrows. Under R1 the interrow is maintained through regular non-persistent herbicide application (e.g. Roundup), while under R2 the interrow is maintained through regular slashing.
- One combination of genetic factors is considered, which implies the use of the tropical hard timber specie Tectona Grandis (Teak).
- One combination of environmental factors is considered, which encompasses historical average annual rainfall, radiation and temperature patched-point data for the Tully-Murray catchment over the last 95 years (SILO, 2006).

LUCTOR is used to generate input and output data for all of the combinations of the defined soil, management, genetic and environmental factors. In total, 6 unique combinations of inputs and corresponding outputs are assessed.[6] Inputs include fertilisers, herbicides, pesticides, labour and machinery, and outputs include timber yield, ground cover and nutrient concentrations. The net contribution to total water pollutant delivery is based on ground cover and DIN concentration, and determined using SedNet/ANNEX (see Section 2.2), while the net contribution to total persistent herbicide delivery is taken as a proportion of persistent herbicide concentration (see Section 2.2.3).

2.2 Water quality model – SedNet / ANNEX

The hydrological model SedNet/ANNEX (Sediment River Network model/Annual Network Nutrient Export) is used to estimate the net contribution from production systems (PSs) and management practices (MPs) to total fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) delivery which, together with persistent herbicide (HER) delivery, are considered the most important water pollutants in the Tully-Murray catchment (Mitchell *et al.* 2007). SedNet/ANNEX was originally developed as part of the National Land and Water Resources Audit (NLWRA) by CSIRO Land and Water (see for example Prosser *et al.* 2001a, 2001b; Young *et al.* 2001; DeRose *et al.* 2002, 2003; Bartley *et al.* 2003, 2004). The SedNet/ANNEX model calculates the mean annual supply, within catchment deposition and subsequent downstream delivery of sediments and nutrients through the construction of sediment and nutrient budgets for river networks.

2.2.1 Fine suspended sediment delivery

A sediment budget is an account of the most important sources and sinks for eroded material (Wilkinson *et al.* 2004). Sources of sediment include hillslope erosion, erosion of gullies, erosion of stream and river banks, and erosion of drains. Sinks for sediment include fine sediment floodplain deposition, coarse sediment river bed deposition, and fine and coarse sediment reservoir deposition. Total fine and coarse sediment delivery at the river mouth is

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[6] Three soil classes, times two herbicide application rates, times one combination of genetic and environmental factors, yields 6 combinations.

the net result of sediment erosion and deposition originating from upstream internal watersheds and connecting gullies, streams and rivers.

The net contribution of PSs and MPs to total fine suspended sediment (FSS) delivery at the river mouth is determined in four steps:

1. *C*-factors for PSs and MPs are estimated using crop growth simulation models based on the ground cover of each MP (see Section 2.1).
2. Minimum and maximum plot level *C*-factor values, as determined by the different MPs, are identified for each PS.
3. SedNet simulations are performed for *C*-factors in between these minimum and maximum values, to determine the corresponding total fine suspended sediment delivery for each PS.
4. A relationship between plot level *C*-factor and fine suspended sediment delivery is quantified for each PS, and the net contribution of different MPs to fine suspended sediment delivery is calculated.

On the basis of the plot level *C*-factor values of PSs and MPs, we thus estimate the per hectare contribution of these PSs and MPs to fine suspended sediment (FSS) delivery. Note that it is implicitly assumed that the land use pattern in the catchment remains unchanged.

2.2.2 Dissolved inorganic nitrogen delivery

Similar to the sediment budget, a nutrient budget is an account of the most important sources and sinks for physical nutrients (Young *et al.* 2001). Sources of nutrients include sediment associated nutrients, dissolved organic and inorganic nutrient loads in runoff water, and point sources of nutrients. Sinks for nutrients are associated with sediment deposition, denitrification and phosphorus adsorption-desorption. Total nutrient delivery at the river mouth is the net result of the above processes in upstream internal watersheds and connecting gullies, streams and rivers.

The net contribution of PSs and MPs to dissolved inorganic nitrogen (DIN) delivery at the river mouth is determined in four steps:

1. Plot level DIN-concentrations for PSs and MPs are estimated using crop growth simulation models based on nitrogen application rate and crop nitrogen uptake (see Section 2.1).
2. Minimum and maximum plot level DIN-concentrations, as determined by the different MPs, are identified for each PS.
3. ANNEX simulations are performed for DIN-concentrations in between these minimum and maximum values, to determine the corresponding total DIN delivery for each PS.
4. A relationship between plot level DIN-concentration and dissolved inorganic nitrogen delivery is quantified for each PS, and the net contribution of different MPs to dissolved inorganic nitrogen delivery is calculated.

On the basis of the plot level DIN-concentrations of PSs and MPs, we can thus estimate the per hectare contribution of these PSs and MPs to dissolved inorganic nitrogen delivery. Again note that it is implicitly assumed that the land use pattern in the catchment remains unchanged.

2.2.3 Herbicide delivery

There is no hydrological module available in SedNet/ANNEX that accurately describes the relationship between plot level persistent herbicide concentrations and persistent herbicide delivery (Lewis *et al.* 2006). Based on discussions with Brodie (2006, personal communication) and Green and Young (2006), we take 5% of the plot level rate of herbicide (Diuron) application to be delivered to the river mouth.

2.3 Cost benefit analysis

All analysed production systems (PSs) and management practices (MPs) have a duration exceeding one year. These PSs and MPs occupy the land for a number of years and require (considerable) investments during startup. As values that occur later in time are worth less at present than those occurring earlier in time, a time discount rate r is used to value future costs and benefits streams in present-day terms.

To compare PSs and MPs with varying life-spans and outlay bases, annuities of net present values are calculated for each of them. The net present value *NPV* of a project is defined as the discounted sum of differences between benefits B_t and costs C_t that are attributable to the installation of the project and that occur in each period t over the entire lifetime of the project T (Zerbe and Dively, 1994). The *NPV* is given by:

$$NPV = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{1}$$

where r is the time discount rate. The *NPV* rule states that investment in a project should take place in case $NPV > 0$. To be able to compare projects with different lifetimes T, net present values are converted into annuities (Schipper *et al.* 2000). The annuity A of a net present value is calculated using the capital recovery factor, which is given by (Zerbe and Dively, 1994):

$$A = NPV \left[\frac{r}{1-(1+r)^{-T}} \right] \tag{2}$$

where T is the project lifetime (generally in years). Eq. (2) states that an annual amount A needs to be obtained at the end of each period over the life span of the project T to recover the net present value *NPV* at the end of the seventh period at discount rate r. Using the *NPV* approach in combination with the capital recovery factor to determine the annuity A produces correct financial decisions in all cases (Zerbe and Dively, 1994).

This procedure is not only applied to determine the annuity gross margin of PSs and MPs, but also to determine intermediate annuity figures for, for example, yields and sediment supply (indeed, in physical terms) as well as annuity labour use and input costs (Schipper *et al.* 2000).

For the calculation of costs and benefits of PSs and MPs, constant 2005 prices are used for input, labour and machinery use, and average 2003 to 2005 prices are used for outputs. Input and machinery use prices are based on Mossman Agricultural Services (MAS) data, output prices are based on Queensland Sugar Limited (2006), FAOSTAT (2006) and ITTO (2004), and agricultural wages are extrapolated from 2000-2001 ATO income tax data. The time discount rate r is set at 5% per year, which is between the suggested 3% that is used in long-term environmental studies (Kaya and Yokobori, 1997) and the 8% geometric mean of real interest rates in Australia over the period 1982 to 1999 (World Bank, 1999). Taxes, non-production system specific fixed asset depreciation and maintenance costs, and capital costs are not considered in the gross margin figures at the plot level.

3. Financial-economic analysis of industry current best management practices

This chapter summarises the results of the cost-effectiveness of management practices (MPs) in sugarcane, horticulture, grazing and forestry production in the Tully-Murray catchment. As there are hundreds of MPs, each of these MPs cannot be discussed separately and in great detail. Consequently, for the analysis of the cost-effectiveness of MPs in sugarcane, horticulture, grazing and forestry production we will look at two indicators: annuity gross margin (in AU$/ha/yr) and average annual water pollutant delivery (in t, kg or ml per ha/yr) per MP at the plot level. Gross margin is defined as the production value net of variable input, labour and machinery costs as well as production system specific fixed asset maintenance and depreciation costs. Finally, it is important to note that taxes, non-production system specific fixed asset depreciation and maintenance costs (*e.g.* machinery, barns and sheds), and capital costs (*i.e.* opportunity or finance costs of fixed assets) are not considered in the gross margin figures at the plot level as these costs are determined at the farm level[7].

3.1 Sugarcane

As outlined in Section 2.1.1, 1152 different MP combinations for sugarcane production are identified according to soil, management, genetic and environmental factors. Before we proceed to the analysis of BMPs in sugarcane production, we provide a concise overview of average annual yield and water pollutant delivery as well as annuity input costs and gross margin figures for a typical current MP in sugarcane production (see Table 1)[8]. The simulated average annual sugar yield is, at 13.6 t/ha, just above the 2005 average sugar yield of 12.2 t/ha for the Tully-Murray mill area (Queensland Sugar Limited, 2006) and the sugar yield of 10.1 t/ha taken by Sing (2003). This difference can be explained by the fact that we use a crop growth model that simulates potential sugarcane growth, thereby accounting for all limitations on yield though excluding the effects of weeds, pests and diseases.

Table 1: Average annual yield and water pollutant delivery as well as annuity input costs and gross margin for typical current management practice in sugarcane production.

	Sugar yield (t/ha)	**Input costs (AU$/ha)**	**Gross margin[1] (AU$/ha)**	**Water pollutant delivery**		
				FSS (t/ha)	**DIN (kg/ha)**	**HER (ml/ha)**
Average	13.6	969.5	1,201.2	0.79	38.17	35.00
Std. dev.	*2.2*	*186.4*	*244.7*	*0.02*	*7.59*	*0.00*

[1] Sugarcane transport and milling costs, which are about one-third of the production value, are taken into account in the gross margin calculation.

Annuity variable input costs (including variable input and labour costs as well as sugarcane specific maintenance and depreciation costs) are, at 970 AU$/ha, about 10% lower than the per hectare input costs taken by Sing (2003). The (annuity) gross margin per hectare seems

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[7] Farm level costs can be quite substantial. For example, the opportunity or finance cost of 1 ha of land that is worth AU$ 10,000 would be AU$ 500 yr^{-1} given an interest rate of 5% yr^{-1}. Consequently, this would lead to an almost 50% reduction in gross margin per hectare.

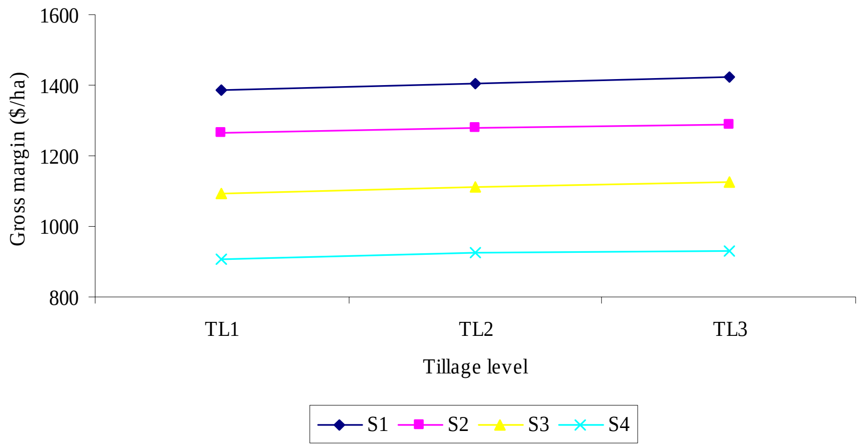
[8] A typical current management practice in sugarcane production is represented by: current tillage (TL1), bare fallow (F1), N-application rate of 180 kg N/ha (N180), single N-application (NA1) and current herbicide application rate (H1).

relatively high at just over 1,200 AU$/ha, which is a result of the above mentioned higher yield and lower variable input costs.

Fine suspended sediment (FSS), dissolved inorganic nitrogen (DIN) and persistent herbicide (HER) delivery from sugarcane production in the Tully-Murray catchment are estimated at around 0.8 t/ha, 38 kg/ha and 35 ml/ha, respectively. These figures are consistent with the predicted mean annual FSS and DIN delivery values of 1.1 t/ha and 43 kg/ha from the short term modelling project (Hateley *et al.* 2006).

Tillage management

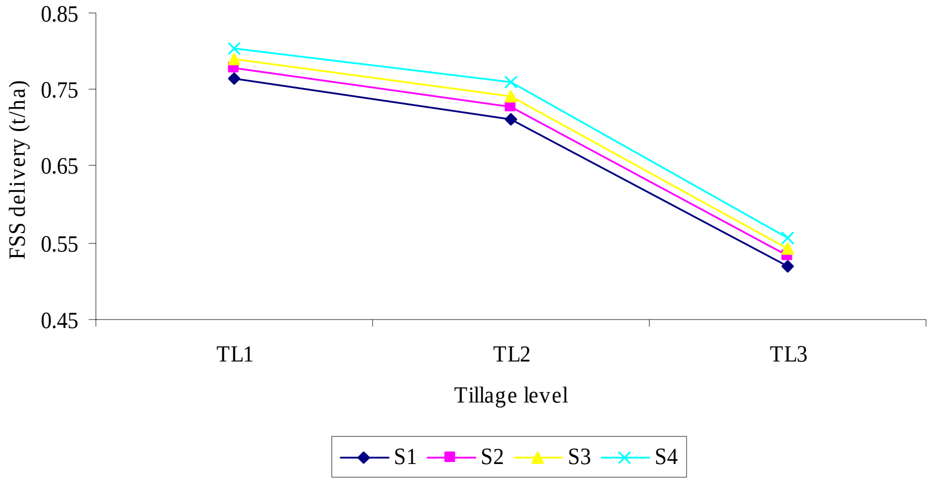
Tillage management practiced by sugarcane growers in the wet tropics of Australia is often considered too high. Major disadvantages of intensive soil preparation is that it leads to sub-soil compaction and increased soil run-off, as any disturbance of the crop residue cover leads to an increase in sediment run-off (Roth and Visser, 2003; Garside, 2004). Moreover, Roth and Visser (2003) state that there is very little agronomic justification for intensive tillage.



[1] Actual (TL1), minimum (TL2) and zero (TL3) tillage.

Figure 1: Annuity gross margin for tillage management practices per soil class in sugarcane production[1].

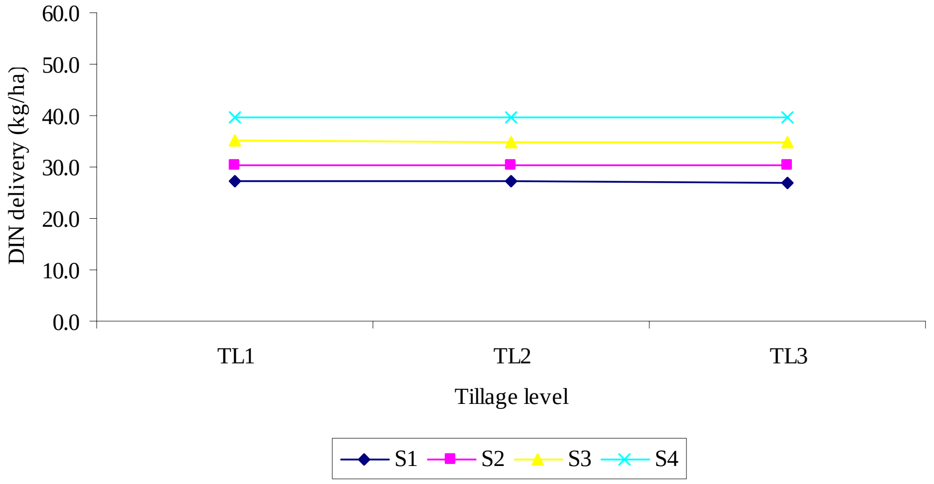
As already mentioned in Section 2.1.1, defined tillage management practices include actual (TL1), minimum (TL2) and zero (TL3) tillage. Figure 1 provides an overview of (annuity) gross margins for these tillage management practices, while differentiating between soil types. Gross margins increase with between 2% and 3% when moving from actual to zero tillage, as yields increase due to reduced soil degradation and larger soil organic matter availability (Garside, 2004) while at the same time land preparation costs decrease.



[1] Actual (TL1), minimum (TL2) and zero (TL3) tillage.

Figure 2: Average annual fine suspended sediment (FSS) delivery for tillage management practices per soil class in sugarcane production[1].

Figures 2 and 3 provide, respectively, an estimation of average annual FSS and DIN deliveries for the assessed tillage management practices. A shift from actual (TL1) to zero (TL3) tillage leads to a considerable reduction in FSS delivery (for all soil types FSS delivery decreases with about 30%), while there is no significant change in DIN delivery. Finally, HER delivery is, at 35 ml/ha, the same for all tillage management practices and soil types.



[1] Actual (TL1), minimum (TL2) and zero (TL3) tillage.

Figure 3: Average annual dissolved inorganic nitrogen (DIN) delivery for tillage management practices per soil class in sugarcane production[1].

Fallow management

Fallow management practices improve soil health and, in the case of a legume fallow, provide sufficient organic nitrogen for the subsequent plant cane (Garside, 2004). While there has been considerable research on the benefits of fallow management practices in sugarcane production (see for example Garside *et al.* 1998; Bell *et al.* 2003; Sing, 2003), legume fallows are not widely applied by sugarcane growers in the Tully-Murray catchment (Roebeling and Webster, 2007).

Fallow management practices are defined for a bare (F1) and legume (F2) fallow (see Section 2.1.1). Annuity gross margins and average annual water pollutant deliveries per soil class for these fallow management practices are given in Table 2. In line with Sing (2003), our results indicate that a legume fallow may have a small positive impact on gross margins (between 1% and 3% increase). Returns obtained from improved yields and reduced fertiliser requirements for the plant cane (Garside *et al.* 1998; Garside, 2004), outweigh the costs at the plot level resulting from legume fallow management.

Table 2: Annuity gross margin and average annual water pollutant delivery for fallow management practices per soil class in sugarcane production[1].

Soil class	Gross margin (AU$/ha)		Water pollutant delivery					
			FSS (t/ha)		DIN (kg/ha)		HER (ml/ha)	
	F1	F2	F1	F2	F1	F2	F1	F2
S1	1,374.1	1,439.0	0.67	0.66	24.14	28.86	35.00	35.00
S2	1,254.2	1,307.6	0.68	0.68	27.42	32.29	35.00	35.00
S3	1,090.3	1,1127.3	0.69	0.69	32.11	37.52	35.00	35.00
S4	899.4	942.8	0.71	0.71	36.89	42.30	35.00	35.00

[1] Bare (F1) and legume (F2) fallow.

While the adoption of a legume fallow (instead of a bare fallow) has a negligible impact on FSS delivery, it leads to an increase in DIN delivery on all soil classes (up to 20%) suggesting that nitrogen application in the first ratoon crop may be reduced after a legume fallow. Again, HER delivery is, at 35 ml/ha, the same for all legume management practices and soil types.

Nitrogen application rate

Nitrogen (N) application in sugarcane production has been extensively studied over the last decade (see for example Chapman, 1994; Keating et al. 1997; Thorburn et al. 2003, 2004). Most of these studies are, however, concerned with the technical instead of the economic optimum rate of nitrogen application[9], while few looked at externalities (like sediment and nutrient delivery) resulting from the use of nitrogen. In general, the economic optimum rate of nitrogen application lies below the technical optimum rate. Even so, nitrogen application rates applied by sugarcane growers are frequently claimed to exceed the standard industry recommendations that are based on technical optima.

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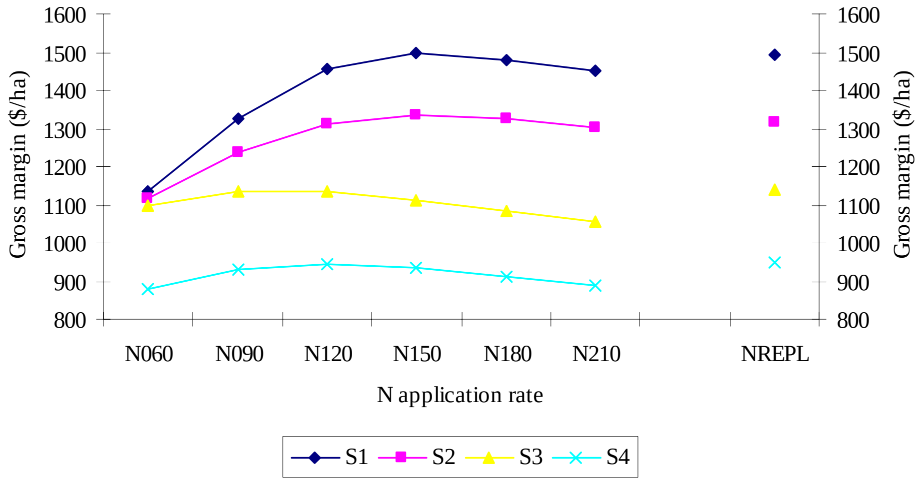
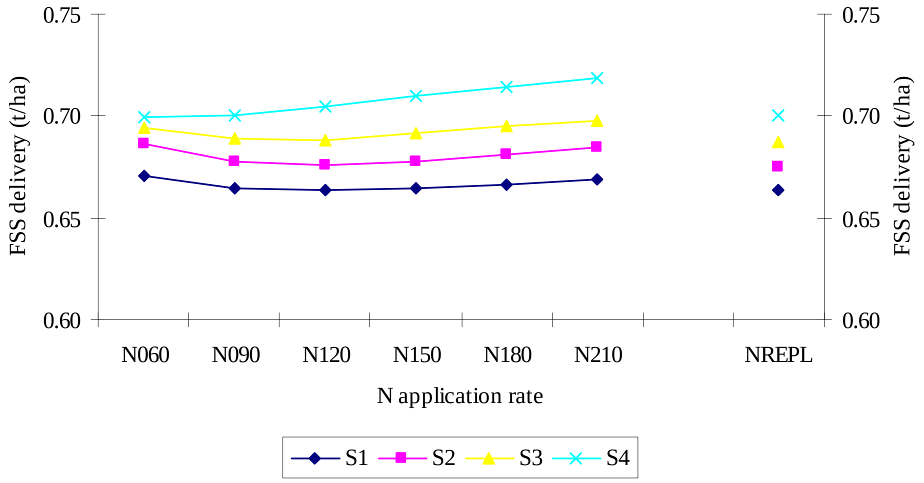
[9] Technical optimum refers to the level of nitrogen application that results in the highest yield. Economic optimum refers to the level of nitrogen application that results in the highest gross margin, which is the case when the extra costs of nitrogen use equal the extra benefits from the yield increase resulting from that extra nitrogen use.



[1] Nitrogen application rates of 60 kg (N060), 90 kg (N090), 120 kg (N120), 150 kg (N150), 180kg (N180) and 210 kg (N210) per hectare per year, as well as nitrogen replacement (NREPL).

Figure 4: Annuity gross margin for nitrogen application rates per soil class in sugarcane production[1].

Nitrogen application rates are defined for below recommended rates (N060 = 60 kg/ha) to perceived high nitrogen application rates (N210 = 210 kg/ha), in five steps of 30 kg/ha. In addition, the nitrogen replacement concept (NREPL) is considered, which aims at a nitrogen application rate that matches nitrogen removed or lost from the soil during a crop (Thorburn *et al.* 2007). Figure 4 shows the relationship between nitrogen application rate and (annuity) gross margin for each soil class.

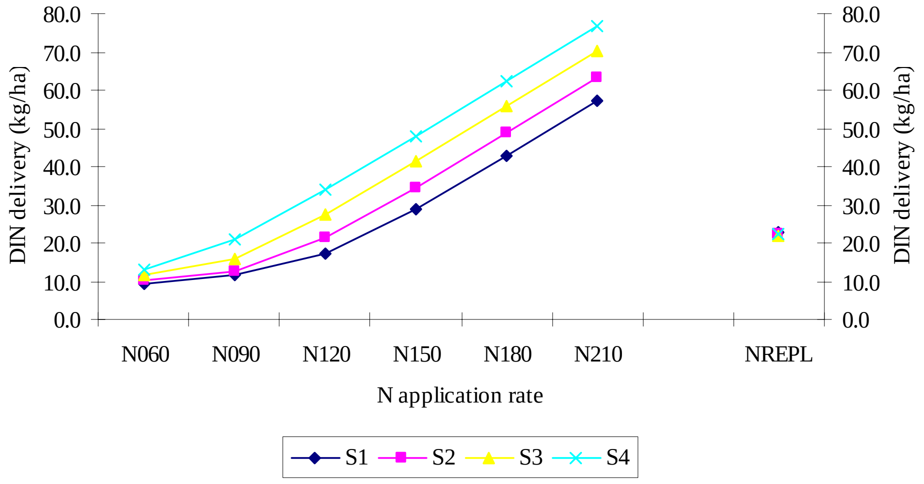


[1] Nitrogen application rates of 60 kg (N060), 90 kg (N090), 120 kg (N120), 150 kg (N150), 180kg (N180) and 210 kg (N210) per hectare per year, as well as nitrogen replacement (NREPL).

Figure 5: Average annual fine suspended sediment (FSS) delivery for nitrogen application rates per soil class in sugarcane production[1].

The economic optimum rate of nitrogen application is about 150 kg/ha for soil class S1 and S2, about 90 kg/ha for soil class S3, and about 120 kg/ha for soil class S4. Nitrogen application rates applied by sugarcane growers in the Tully-Murray catchment are around 170 kg/ha (Hateley *et al.* 2006), which is slightly above the economic optimum for soil class S1 and S2 though well above the economic optimum for soil class S3 and S4. The nitrogen replacement strategy leads to gross margins at or just below the economic optimum.

Increased nitrogen application has a marginal impact on FSS delivery (see Figure 5). The simulations suggest that a decrease in the nitrogen application rate from the current 180 kg/ha to 150 kg/ha would lead to a less than 1% decrease in FSS delivery. Note that the economic optimum rate of nitrogen application as well as the nitrogen replacement strategy generally coincides with the lowest FSS delivery levels.



[1] Nitrogen application rates of 60 kg (N060), 90 kg (N090), 120 kg (N120), 150 kg (N150), 180kg (N180) and 210 kg (N210) per hectare per year, as well as nitrogen replacement (NREPL).

Figure 6: Average annual dissolved inorganic nitrogen (DIN) delivery for nitrogen application rates per soil class in sugarcane production[1].

Increased nitrogen application leads to an increase in DIN delivery, in particular above 120 kg/ha for soil class S1 and S2 and above 90 kg/ha for soil class S3 and S4, while the nitrogen replacement strategy leads to relatively low and constant levels of DIN delivery (Figure 6). A decrease in the nitrogen application rate from the current 180 kg/ha to 150 kg/ha would lead to a more than 40% decrease in DIN delivery, while adoption of the nitrogen replacement strategy would lead to a decrease in DIN delivery of up to 60%. Again, HER delivery is, at 35 ml/ha, the same for all nitrogen application rates and soil types.

Nitrogen application method

Nitrogen application method refers to single or split application of nitrogen. It is believed that split application of nitrogen may potentially lead to a reduction in nutrient delivery from sugarcane systems (Chapman, 1994).

Nitrogen application methods are defined for single (NA1) and split (NA2) nitrogen application (see Section 2.1.1). Annuity gross margins and average annual water pollutant deliveries per soil class for these nitrogen application methods are given in Table 3. Our results indicate that split nitrogen application has a small and variable impact on gross margins (between 2% increase and 1% decrease). Returns obtained from improved yields (between 1% and 3% increase) outweigh the additional application costs only on the S1 and S2 soil classes.

Table 3: Annuity gross margin and average annual water pollutant delivery for nitrogen application methods per soil class in sugarcane production[1].

Soil class	Gross margin (AU$/ha)		Water pollutant delivery					
			FSS (t/ha)		DIN (kg/ha)		HER (ml/ha)	
	NA1	NA2	NA1	NA2	NA1	NA2	NA1	NA2
S1	1,393.6	1,419.5	0.67	0.67	27.03	25.97	35.00	35.00
S2	1,280.5	1,281.3	0.68	0.68	30.12	29.59	35.00	35.00
S3	1,113.3	1,104.4	0.69	0.69	35.09	34.55	35.00	35.00
S4	925.8	916.4	0.71	0.71	39.79	39.40	35.00	35.00

[1] Single (NA1) and split (NA2) nitrogen application.

The adoption of split nitrogen application, instead of single nitrogen application, would have a small and variable impact on water pollutant delivery. While there is no noticeable impact on FSS delivery, DIN delivery decreases with between 1% (soil class S4) and 4% (soil class S1). Finally, HER delivery is, at 35 ml/ha, the same for all nitrogen application methods and soil types.

Herbicide application rate

Herbicide application rate has been identified by experts as an important management factor mitigating chemical delivery from sugarcane production systems. Defined herbicide application rates include current (H1) and reduced (H2) herbicide application rates (see Section 2.1.1). In the reduced herbicide application option (H2), the use of persistent herbicides (like Diuron) is halved and applied using a hooded sprayer while non-persistent herbicides are used to assure effective weed control.

In case of a new hooded sprayer costing 12,000 AU$, while assuming a 10 year lifetime on a 50ha property, reduced herbicide application leads to a 50 AU$/ha decrease in gross margin given an additional non-persistent herbicide application costing 20 AU$/ha. The adoption of reduced instead of current rates of herbicide application, has no impact on FSS and DIN delivery while it is assumed to lead to a 50% decrease in HER delivery to 17.5 ml/ha.

3.2 Horticulture

As outlined in Section 2.1.2, 54 different MP combinations for banana production are identified according to soil, management, genetic and environmental factors. An overview of average annual yield and water pollutant delivery as well as annuity input costs and gross margin figures for a typical current MP in banana production is given in Table 4[10]. The simulated average annual banana yield is, at almost 30 t/ha, within the range given in Lindsay *et al.* (1998), about 20% above the average annual observed national yield of 25 t/ha

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[10] A typical current management practice in banana production is represented by: high herbicide application (H2), bare interrows (R1) and 100% nutrient application rate (F10).

in 2005 (FAOSTAT, 2006), and about 30% below the average annual field trial yield reported by Lindsay *et al*. (2005). Note that there are large differences in yields between soil types, that persistent herbicide (HER) delivery is not considered an issue in banana production (Roebeling and Webster, 2007), and that soil class S4 is not suitable for banana production unless drainage systems have been established (see Section 2.1.2).

Annuity variable input costs (including variable input and labour costs as well as banana specific maintenance and depreciation costs) are, at almost 17,000 AU$/ha, about 15% lower than those presented in Lindsay *et al.* (1998). Consequently, the (annuity) gross margin per hectare is, at just over 6,000 AU$/ha, within the range given in Lindsay *et al.* (1998). Note that levies, commissions and freight costs are not included in the gross margin figures (farm gate gross margins).

Table 4: Average annual yield and water pollutant delivery as well as annuity input costs and gross margin for typical current management practice in banana production.

	Banana yield (t/ha)	**Input costs (AU$/ha)**	**Gross margin (AU$/ha)**	**Water pollutant delivery**		
				FSS (t/ha)	**DIN (kg/ha)**	**HER (ml/ha)**
Average	28.4	16,955.6	6,200.6	1.34	7.21	n.a.
Std. dev.	*3.1*	*1,388.4*	*1,164.3*	*0.08*	*1.53*	*n.a.*

Fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) delivery from banana production in the Tully-Murray catchment are estimated at around 1.3 t/ha and 7.2 kg/ha, respectively. These figures are consistent with the predicted mean annual FSS and DIN delivery values of 1.2 t/ha and 6.6 kg/ha from the short term modelling project (Hateley *et al.* 2006).

Interrow management

Interrow management, in particular maintaining grassed interrows, has been identified as an important management practice for water quality improvement (Roebeling and Webster, 2007), increasing ground cover and thus reducing erosion and sediment delivery (Roth and Visser, 2003; Visser, 2003).

Table 5: Annuity gross margin and average annual water pollutant delivery for interrow management practices per soil class in banana production[1].

Soil class	**Gross margin (AU$/ha)**		**Water pollutant delivery**					
			FSS (t/ha)		**DIN (kg/ha)**		**HER (ml/ha)**	
	R1	**R2**	**R1**	**R2**	**R1**	**R2**	**R1**	**R2**
S1	2,001.1	1,950.5	1.44	0.42	4.69	4.69	n.a.	n.a.
S2	1,077.7	1,027.1	1.49	0.47	4.58	4.58	n.a.	n.a.
S3	571.1	520.5	1.57	0.55	3.12	3.12	n.a.	n.a.
S4	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

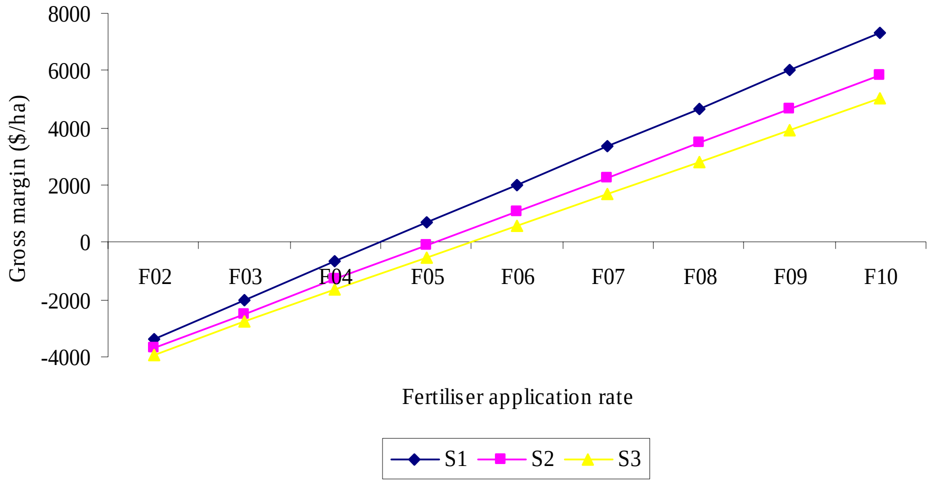
[1] Bare (R1) and grassed (R2) interrow.

Defined interrow management practices include bare (R1) and grassed (R2) interrows. Under R1 the interrow is maintained through regular non-persistent herbicide application (e.g. Roundup), while under R2 the interrow is maintained through regular slashing. Annuity gross margins and average annual water pollutant deliveries per soil class for these interrow practices are given in Table 5.

Our results indicate that maintaining grassed, instead of bare, interrows leads to a small decrease in gross margin (between 3% and 9% decrease). Additional costs of maintaining grassed interrows are about 50 AU$/ha. The adoption of grassed, instead of bare, interrows does, however, lead to a 60% decrease in FSS delivery, in line with Cattan *et al*. (2006), while it has no impact on DIN delivery.

Fertiliser application rate

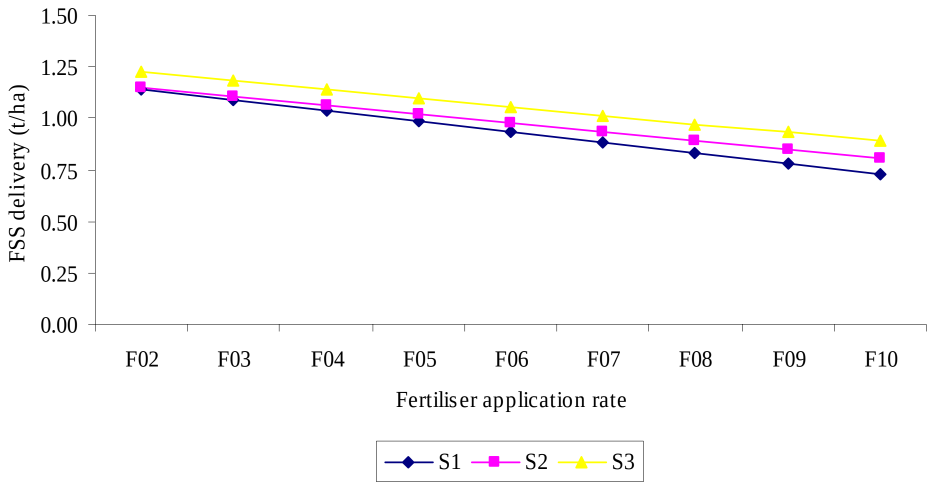
Fertiliser application rates have been identified as an important management factor for water quality improvement by industry and experts in the Tully-Murray catchment (Roebeling and Webster, 2007). Enhanced efficiency in fertiliser application leads to a reduction in inorganic nutrient addition, thus mitigating inorganic nutrient delivery (see for example Keating et al. 1997; Bartley et al. 2004). Defined fertiliser (N, P and K) application rates range from 20% (F02) to 100% (F10) of the application rate required to realize the maximum attainable yield, in eight steps of 10%.



[1] Fertiliser application rates achieving 20% (F02), 30% (F03), 40% (F04), 50% (F05), 60% (F06), 70% (F07), 80% (F08), 90% (F09) and 100% (F10) of potential yield per year.

Figure 7: Annuity gross margin for fertiliser application rates per soil class in banana production[1].

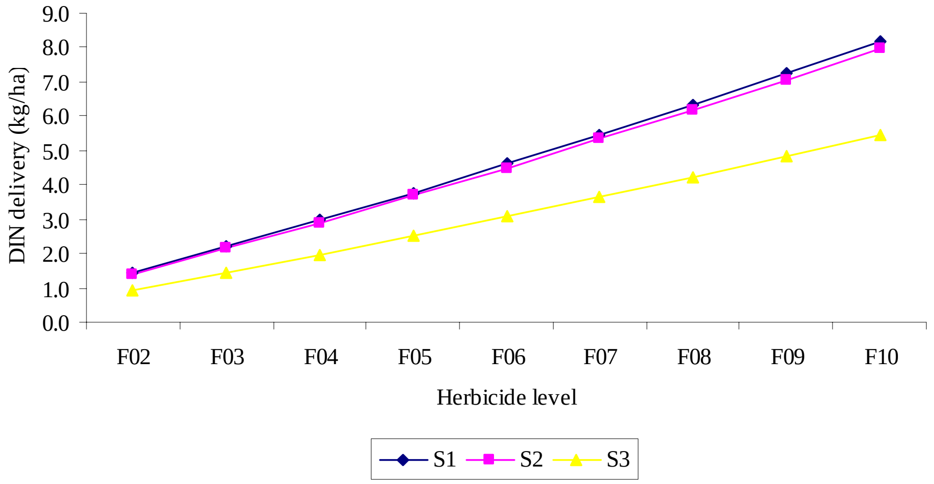
Figure 7 shows the relationship between fertiliser application rate and (annuity) gross margin for each soil class. Two things must be noted. First, in contrast with nitrogen application in sugarcane production (see Section 3.1), we do not see strong diminishing returns from increased fertiliser application. This is explained by the fact that N, P as well as K application change with the fertiliser application rate, rather than the N application rate alone (most limiting nutrient argument – see for example Hengsdijk *et al.* 1998). Second, the potential yield is attained under fertiliser application rate F10 and, thus, further fertiliser application will not lead to a further increase in yield.



[1] Fertiliser application rates achieving 20% (F02), 30% (F03), 40% (F04), 50% (F05), 60% (F06), 70% (F07), 80% (F08), 90% (F09) and 100% (F10) of potential yield per year.

Figure 8: Average annual fine suspended sediment (FSS) delivery for fertiliser application rates per soil class in banana production[1].

Largest gross margins are attained at N, P and K application rates of around 308 kg/ha, 21 kg/ha and 728 kg/ha (F10), respectively, thereby noting that nutrient requirements and ratios vary considerably per soil class. Nitrogen application rates applied by banana growers in the Great Barrier Reef catchments can be over 400 kg/ha (Brodie *et al.* 2003), indicating that re-composition of N, P and K ratios may provide options for a decrease in nitrogen requirements.



[1] Fertiliser application rates achieving 20% (F02), 30% (F03), 40% (F04), 50% (F05), 60% (F06), 70% (F07), 80% (F08), 90% (F09) and 100% (F10) of potential yield per year.

Figure 9: Average annual dissolved inorganic nitrogen (DIN) delivery for fertiliser application rates per soil class in banana production[1].

Increased fertiliser application leads to a small decrease in FSS delivery (Figure 8), as increased fertiliser application stimulates plant growth, canopy cover and crop residue cover, while it leads to a considerable increase in DIN delivery, with some notable differences between soil classes (Figure 9).

3.3 Grazing

As outlined in Section 2.1.3, 660 different MP combinations for beef cattle production are identified according to soil, management, genetic and environmental factors. An example of average annual yield and water pollutant delivery as well as annuity input costs and gross margin figures for a typical current MP in grazing production on soil class S1 is given in Table 6.[11] Note that persistent herbicide (HER) delivery is not considered an issue in grazing production (Roebeling and Webster, 2007).

Table 6: Average annual yield and water pollutant delivery as well as annuity input costs and gross margin for typical current management practice in grazing production.

	Weight gain (kg/ha)	Input costs (AU$/ha)	Gross margin (AU$/ha)	Water pollutant delivery		
				FSS (t/ha)	DIN (kg/ha)	HER (ml/ha)
Average	380.8	1,567.3	215.3	0.32	3.47	n.a.

The simulated average annual cattle weight gain is about 380 kg/ha, which is equivalent to 190 kg/AU given a stocking rate of 2.0 AU/ha. This result is consistent with animal growth rates from experiments conducted in the South Johnstone Research Station, where weight gains varied between about 170 kg ha^{-1} yr^{-1} and 210 kg ha^{-1} yr^{-1} on fertilised Signal grass (see Teitzel, 1992). Again note that yields are generally overestimated using a production systems simulation model like PASTOR that simulates potential integrated pasture-beef production, thereby accounting for all limitations on yield though excluding effects of weeds, pests and diseases. Annuity variable input costs (including variable input and labour costs as well as grazing specific maintenance and depreciation costs) are just over 1,500 AU$/ha, while (annuity) gross margins are relatively low at almost 215 AU$/ha.

Fine suspended sediment (FSS) and dissolved inorganic nitrogen (DIN) delivery from grazing production in the Tully-Murray catchment are estimated at around 0.3 t/ha and 3.5 kg/ha, respectively. These figures are consistent with the predicted mean annual FSS and DIN delivery values of 0.5 t/ha and 2.6 kg/ha from the short term modelling project (Hateley *et al.* 2006).

Stocking rate

Stocking rates in the Tully-Murray catchment vary between 1.5 AU/ha and 2.5 AU/ha. Normal practice is to adjust the stocking rate to the ability of the pasture to carry the cattle through the relatively cool and dry winter season, or to adjust the stocking rate according to the season (Teitzel, 1992). Most important disadvantages of maintaining high stocking rates are that it leads to sub-soil compaction (trampling), reduced vegetation cover (overgrazing) and, consequently, increased soil erosion (Teitzel, 1992; Bouman et al. 1998).

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[11] A typical current management practice in grazing production is represented by: stocking rate of 2.0 AU/ha (R17) and N-application rate of 59 kg N/ha (S27).

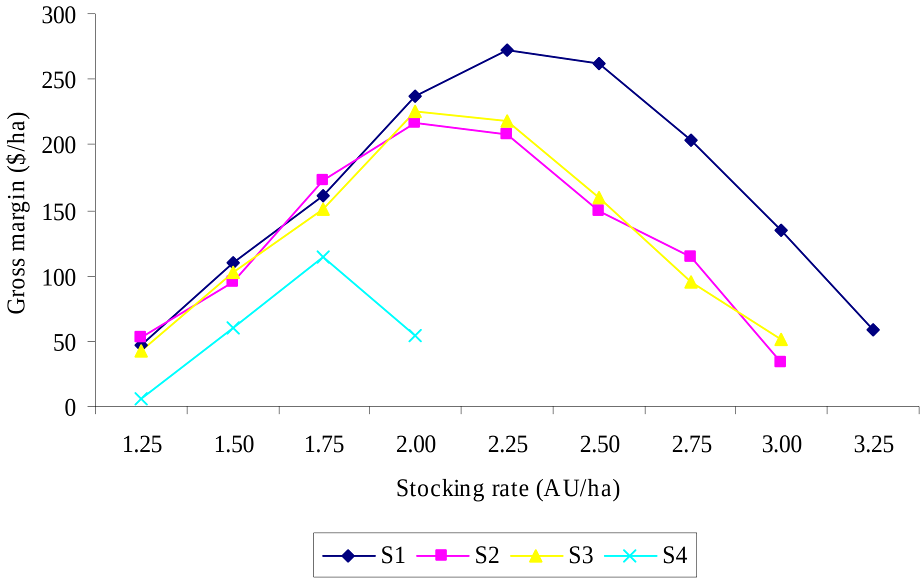

Figure 10: Annuity gross margin for stocking rates per soil class in grazing production.

Defined stocking rates range from 0.5 AU/ha to 4.0 AU/ha, in fourteen steps of 0.25 AU. The relationship between (annuity) gross margins and stocking rates for each of the identified soil classes is given in Figure 10. The economic optimum stocking rate is about 2.25 AU/ha for soil class S1, about 2.00 AU/ha for soil class S2 and S3, and about 1.75 AU/ha for soil class S4. Consequently, gross margins are lower for pastures with a lower carrying capacity, *i.e.* in particular for pastures on soils where pasture growth is affected by water logging.

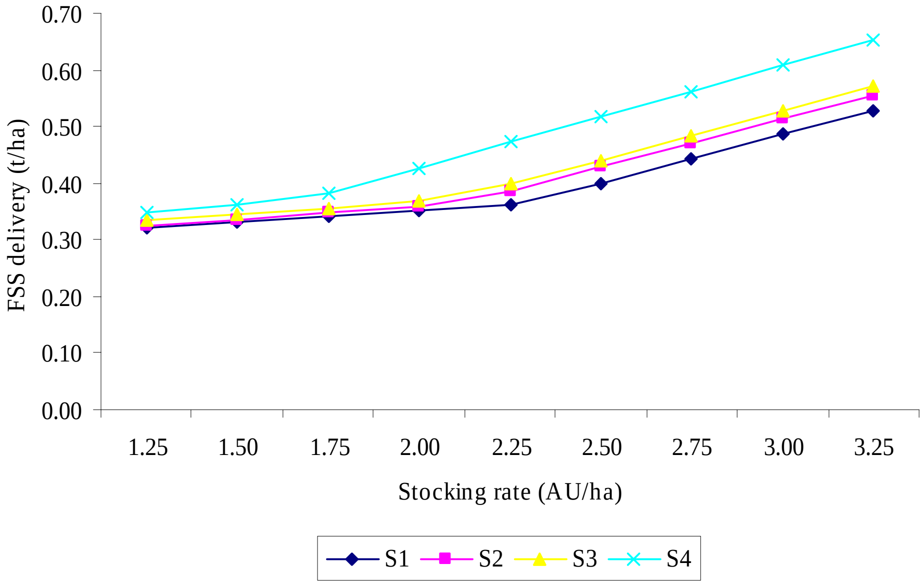

Figure 11: Average annual fine suspended sediment (FSS) delivery for stocking rates per soil class in grazing production.

Higher stocking rates lead to an increase in FSS delivery (Figure 11), due to increased trampling and reduced vegetation cover. The 'kink' in the curves indicates where the pasture can no longer sustain the corresponding cattle stock and, consequently, where feed supplements are provided to the cattle stock[12]. At stocking rates beyond this kink, pastures are increasingly overgrazed, trampling increasingly becomes a problem and, as a result, FSS delivery increases more rapidly. Note that this kink occurs at a lower stocking rate for soil types that are more susceptible to water logging. Summarizing, a lower stocking rate corresponds to a larger vegetation cover, reduced trampling and, consequently, a lower level of FSS delivery.

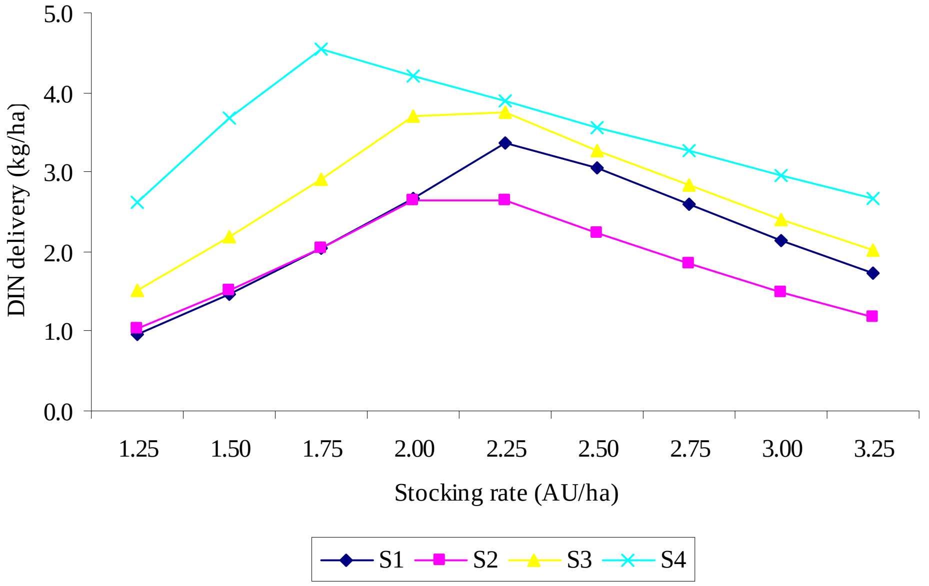

Figure 12: Average annual dissolved inorganic nitrogen (DIN) delivery for stocking rates per soil class in grazing production.

An increase in stocking rate first leads to an increase and then to a decrease in DIN delivery (see Figure 12), because feed supplements for cattle (rather than additional nitrogen to pasture) are provided to meet cattle feed requirements at stocking rates that exceed pasture carrying capacity. Note that the economic optimum stocking rate generally coincides with the highest DIN delivery levels. Again, HER delivery is not an issue in grazing production. Summarizing, choosing stocking rates below the carrying capacity of the pasture leads to a reduction in DIN delivery.

Nitrogen application rate

Nitrogen (N) application in beef cattle production has been extensively studied over the last decades (see Teitzel, 1992). As with sugarcane nitrogen research, most of these studies are concerned with the technical rather than the economic optimum rate of nitrogen application, while none of these studies looked at externalities (like sediment and nutrient delivery) resulting from the use of nitrogen.

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[12] The kink can be observed at a stocking rate of 2.25 AU/ha (soil class S1), 2.00 AU/ha (soil class S2 and S3) and 1.50 AU/ha (soil class S4).

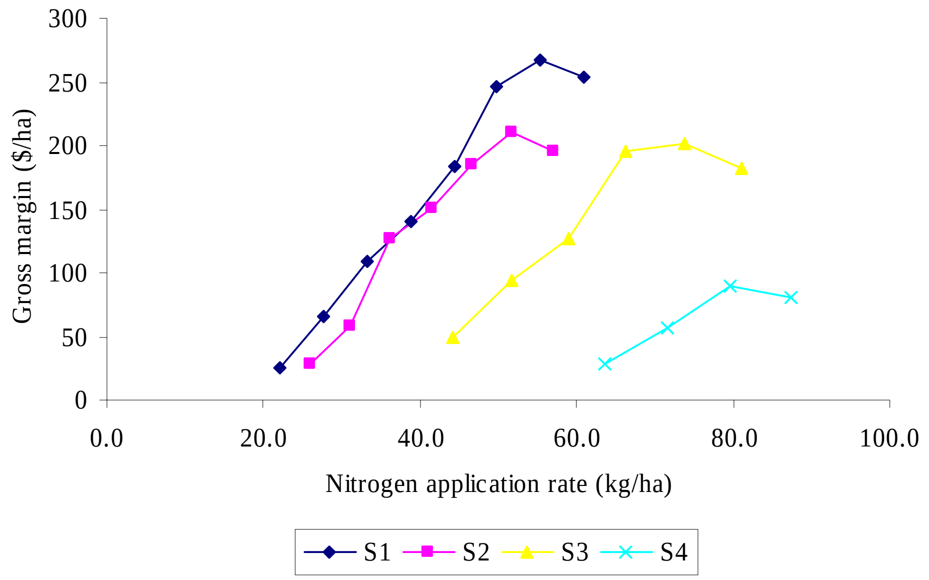

Figure 13: Annuity gross margin for nitrogen application rates per soil class in grazing production.

Defined nitrogen application rates range from 0% to 100% of the rate that is required to realize the maximum attainable production, in ten steps of 10%. Given our focus on MPs with positive gross margins, this corresponds to nitrogen application rates ranging from 20 kg/ha to 90 kg/ha.

Figure 13 shows the relationship between nitrogen application rate and (annuity) gross margin for each of the identified soil classes. The economic optimum rate of nitrogen application is around 50 to 55 kg/ha for soil class S1 and S2, around 75 kg/ha for soil class S3 and about 80 kg/ha for soil class S4. The lower returns from nitrogen application on poorly drained soils are explained by the restricted carrying capacity of these poorly drained soils.

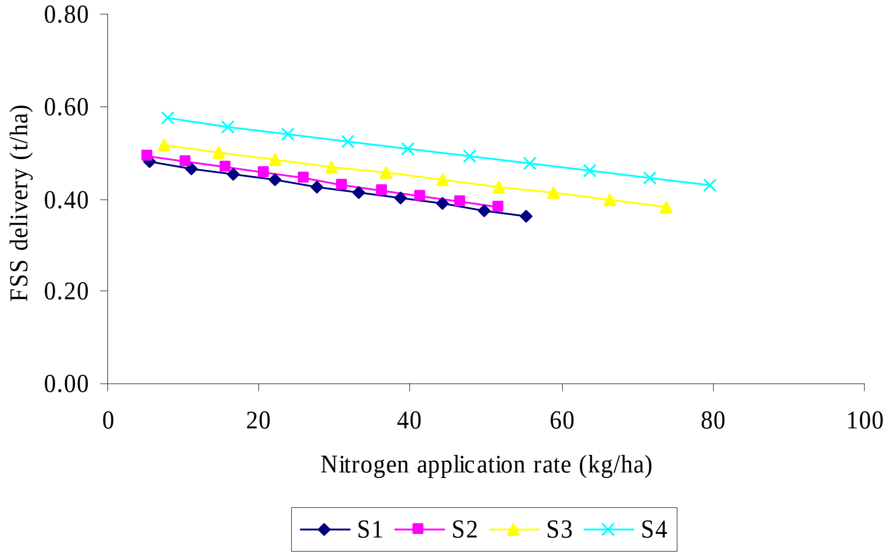

Figure 14: Average annual fine suspended sediment (FSS) delivery for nitrogen application rates per soil class in grazing production.

Increased nitrogen application leads to a small decrease in FSS delivery because increased nitrogen application stimulates pasture growth and subsequent vegetation cover, while noting that the rate of reduction in FSS delivery is fairly similar amongst soil classes (see Figure 14). An increase in nitrogen application does, however, lead to strong increase in DIN delivery, while there are no significant differences between soil classes (see Figure 15).

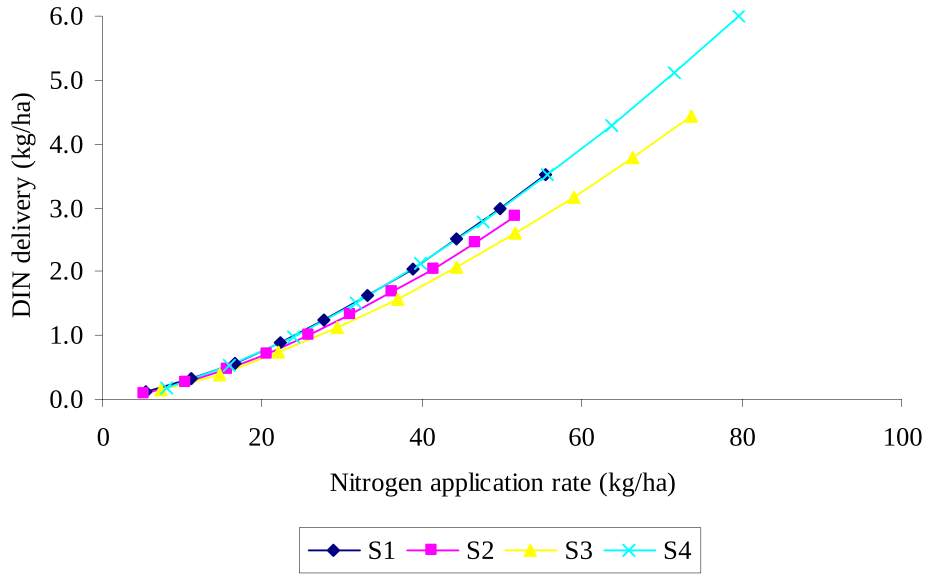

Figure 15: Average annual dissolved inorganic nitrogen (DIN) delivery for nitrogen (N) application rates per soil class in grazing production.

3.4 Forestry

As outlined in Section 2.1.4, 6 different MP combinations for hard timber forestry production are identified according to soil, management, genetic and environmental factors. An overview of annuity yield, input costs and gross margin as well as average annual water pollutant delivery for a typical current MP in (hard timber) forestry production is given in Table 7[13]. Note that soil class S3 is not suitable for teak production (see Section 2.1.4).

Table 7: Average annual yield and water pollutant delivery as well as annuity input costs and gross margin for typical current management practice in forestry production.

	Timber yield (m^3/ha)	Input costs (AU$/ha)	Gross margin (AU$/ha)	Water pollutant delivery		
				FSS (t/ha)	DIN (kg/ha)	HER (ml/ha)
Average	13.5	1,808.6	805.1	0.40	1.43	21.00
Std. dev.	*0.9*	*79.4*	*226.3*	*0.01*	*0.14*	*0.00*

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[13] A typical current management practice in forestry production is represented by: bare interrow management (R1).

The simulated average annual timber yield is, at 13.5 m^3/ha, about 15% higher than the yields reported by Kashio and White (1998) and, as already mentioned before, can be explained by the fact that we use a crop growth model that simulates potential timber growth. Annuity variable input costs (including variable input and labour costs as well as forestry specific maintenance and depreciation costs) are estimated at around 1,800 AU$/ha and subsequent gross margins at around 800 AU$/ha.

Fine suspended sediment (FSS), dissolved inorganic nitrogen (DIN) and persistent herbicide (HER) delivery from forestry production in the Tully-Murray catchment are estimated at around 0.4 t/ha and 1.4 kg/ha and 21 ml/ha, respectively. These figures are consistent with predicted mean annual FSS and DIN delivery values of 0.5 t/ha and 1.4 kg/ha from Hateley *et al*. (2006).

Interrow management

Interrow management (i.e. maintaining grassed interrows) in forestry production has been identified as an important practice for water quality improvement (Roebeling and Webster, 2007), increasing ground cover and thus reducing erosion and sediment delivery (Roth and Visser, 2003; Visser, 2003).

Table 8: Annuity gross margin and average annual water pollutant delivery for interrow management practices per soil class in forestry production[1].

Soil class	Gross margin (AU$/ha)		Water pollutant delivery					
			FSS (t/ha)		DIN (kg/ha)		HER (ml/ha)	
	R1	R2	R1	R2	R1	R2	R1	R2
S1	1,053.0	1,002.4	0.40	0.39	1.55	1.55	21.00	21.00
S2	880.1	829.5	0.40	0.39	1.25	1.25	21.00	21.00
S3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	21.00	21.00
S4	558.1	507.5	0.41	0.40	1.48	1.48	21.00	21.00

[1] Bare (R1) and grassed (R2) interrow.

Defined interrow management practices include bare (R1) and grassed (R2) interrows. Under R1 the interrow is maintained through regular non-persistent herbicide application (e.g. Roundup), while under R2 the interrow is maintained through regular slashing. Annuity gross margins and average annual water pollutant deliveries per soil class for these interrow practices are given in Table 8.

Results indicate that maintaining grassed, instead of bare, interrows leads to a small decrease in gross margin (between 5% and 10% decrease) given the additional costs of about 50 AU$/ha for maintaining grassed interrows. The adoption of grassed, instead of bare, interrows leads to only a small decrease (3%) in FSS delivery (as ‘bare’ interrows are generally covered in weeds or weed trash blankets) while it has no impact on DIN and HER delivery.

4. Climate change and population growth

Agricultural industries in the Wet Tropics area of the GBR region in Australia face a number of future challenges, including climate change and population growth (Howden *et al.* 2006). While many other factors may influence the long term cost-effectiveness of agricultural land use and management options for water quality improvement, these issues are considered of a nature and scale that need to be addressed explicitly.

4.1 Climate change

Climate change, generally reflected in higher temperatures, increased CO_2 concentrations and altered patterns of rainfall, will have a substantial impact on agricultural production worldwide (IPCC, 2001). The agricultural sector in Australia is considered particularly vulnerable, with potential for negative impacts on the amount and quality of produce, reliability of production, and the environment (Howden *et al.* 2006). The purpose of this section is not to discuss whether or not climate change will eventuate, but to assess the potential impact of climate change on the cost-effectiveness of best-management-practices (BMPs) for water quality improvement in the Tully-Murray catchment should there be a change in climate. An example is given for sugarcane production.

Table 9: Climate projections for Tully in 2030 and 2070 (source: Cai *et al.* 2005).

Season	2030		2070	
	Rainfall	Temperature	Rainfall	Temperature
Summer	-7% to +13%	+0.2°C to +1.6°C	-20% to +40%	+0.7°C to +4.8°C
Autumn	-13% to +7%	+0.2°C to +1.3°C	-40% to +20%	+0.7°C to +4.8°C
Winter	-20% to 0%	+0.2°C to +1.3°C	-60% to 0%	+0.7°C to +4.0°C
Spring	-20% to 0%	+0.2°C to +1.6°C	-60% to 0%	+0.7°C to +4.8°C

Like before, we use the production system simulation model APSIM and the hydrological model SedNet/ANNEX in combination with cost-benefit analysis, to assess the cost-effectiveness of BMPs in sugarcane production (see Chapter 2). In line with Park *et al.* (2007), the impact of rainfall, temperature and CO_2 changes on input-output data for BMPs in sugarcane production is assessed with APSIM by altering the historic climate data according to the climate change projections for 2030 and 2070 presented in Table 9 (Cai *et al.* 2005). Climate scenarios are defined for low (#1), average (#2) and high (#3) projections of rainfall (R#) and temperature (T#), with atmospheric CO_2 concentrations of 437 ppm in 2030 and 610 ppm in 2070 (IPCC, 2001), thus resulting in 9 climate scenarios for 2030 and 9 climate scenarios for 2070. For the BMP cost-effectiveness analysis we will look at plot level annuity gross margin (in AU$/ha/yr) and average annual water pollutant delivery (in t, kg or ml per ha/yr), comparing baseline values (Base; see Chapter 3) with values for the least (R1T3) and most (R3T1) favourable 2070 climate scenarios.

Tillage management

Baseline climate and 2070 climate scenario results for actual, minimum and zero tillage management practices, are provided in Table 10. Under the least favourable 2070 climate scenario (R1T3), and as compared to the baseline climate scenario, we can observe a 20% decrease in gross margin due to reduced yield potentials, while dissolved inorganic nitrogen (DIN) delivery increases with almost 20% as a result of reduced cane growth. There is no significant change in fine suspended sediment (FSS) delivery. Reduced and zero tillage remain equally cost-effective in managing FSS delivery, leading to a significant decrease in FSS delivery and a small increase in gross margin.

Table 10: Base and 2070 climate scenarios' annuity gross margin and average annual water pollutant delivery for tillage management practices in sugarcane production[1,2].

	Gross margin (AU$/ha)			Water pollutant delivery					
				FSS (t/ha)			DIN (kg/ha)		
	Base	R1T3	R3T1	Base	R1T3	R3T1	Base	R1T3	R3T1
TL1	1,164.0	933.2	1,254.1	0.78	0.79	0.78	32.72	38.87	31.27
TL2	1,181.7	934.3	1,255.9	0.74	0.74	0.74	32.70	38.82	31.25
TL3	1,192.3	940.3	1,257.9	0.54	0.55	0.54	32.65	38.95	31.22

[1] Actual (TL1), minimum (TL2) and zero (TL3) tillage.

[2] Baseline climate (Base), and 2070 least favourable (R1T3) and most favourable (R3T1) climate scenarios.

Under the most favourable 2070 climate scenario (R3T1), we see an almost 10% increase in gross margin (due to enhanced yield potentials) and a less than 5% decrease in DIN delivery (due to increased cane growth). Again, there is no significant change in FSS delivery while tillage management remains equally cost-effective in managing FSS delivery.

Fallow management

In Table 11, baseline climate and 2070 climate scenario results are presented for bare and legume fallow management practices. Under the least favourable 2070 climate scenario (R1T3) we see an almost 20% decrease in gross margin (due to reduced yield potentials), an almost 20% increase in DIN delivery and no significant change in FSS delivery. Compared to a bare fallow, the legume fallow still results in slightly higher gross margins as well as levels of DIN delivery.

Table 11: Base and 2070 climate scenarios' annuity gross margin and average annual water pollutant delivery for fallow management practices in sugarcane production[1,2].

	Gross margin (AU$/ha)			Water pollutant delivery					
				FSS (t/ha)			DIN (kg/ha)		
	Base	R1T3	R3T1	Base	R1T3	R3T1	Base	R1T3	R3T1
F1	1,154.5	921.0	1,230.8	0.69	0.70	0.69	30.14	36.01	28.75
F2	1,204.2	950.9	1,281.1	0.69	0.70	0.69	35.24	41.74	33.75

[1] Bare (F1) and legume (F2) fallow.

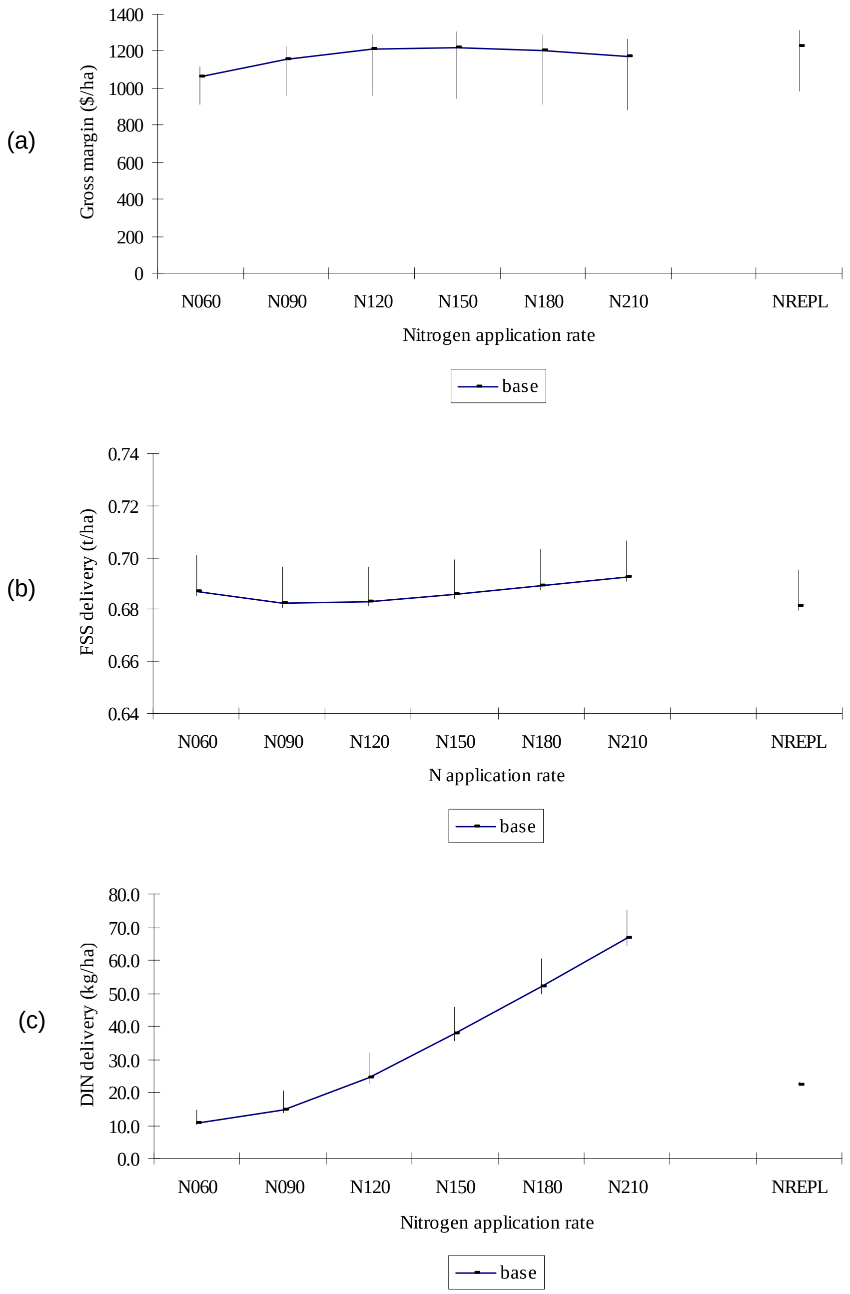
[2] Baseline climate (Base), and 2070 least favourable (R1T3) and most favourable (R3T1) climate scenarios.

Under the most favourable 2070 climate scenario (R3T1), gross margin increases with just over 5% due to enhanced yield potentials and, as a result, we see a less than 5% decrease in DIN delivery. Again, there is no significant change in FSS delivery.

Nitrogen application rate

Figure 16 provides baseline climate and 2070 climate scenario results for six nitrogen application rates and the nitrogen replacement concept. The vertical bars represent the range of results from the simulations for all of the modelled climate scenarios. Under the least favourable 2070 climate scenario (R1T3) we see, like before, a 20% decrease in gross margin, a 20% increase in DIN delivery and no significant change in FSS delivery. Reduced nitrogen application and, in particular, nitrogen replacement remain cost-effective in managing DIN delivery, leading to a significant decrease in DIN delivery at a small increase in gross margin.

Under the most favourable 2070 climate scenario (R3T1), we see a more than 5% increase in gross margin, a less than 5% decrease in DIN delivery and no significant change in FSS delivery. Again, it can be observed that reduced nitrogen application as well as nitrogen replacement remain equally cost-effective in managing DIN delivery.



[1] Nitrogen application rates of 60 kg (N060), 90 kg (N090), 120 kg (N120), 150 kg (N150), 180kg (N180) and 210 kg (N210) per hectare per year, as well as nitrogen replacement (NREPL).
[2] Baseline climate (solid line), and 2070 least favourable and most favourable climate scenarios (vertical bars).

Figure 16: Base and 2070 climate scenarios' annuity gross margin (a) and average annual water pollutant delivery (b,c) for nitrogen application rates in sugarcane production[1,2].

Nitrogen application method

Table 12 presents baseline climate and the minimum and maximum 2070 climate scenario results for single and split nitrogen application methods. Under the least favourable 2070 climate scenario (R1T3) we see an almost 20% decrease in gross margin, a 20% increase in DIN delivery and no significant change in FSS delivery. As compared to single nitrogen application, split nitrogen application remains equally cost-effective in managing DIN delivery – leading to only a small decrease in DIN delivery at no additional costs.

Table 12: Base and 2070 climate scenarios' annuity gross margin and average annual water pollutant delivery for nitrogen application methods in sugarcane production[1,2].

	Gross margin (AU$/ha)			Water pollutant delivery					
				FSS (t/ha)			DIN (kg/ha)		
	Base	R1T3	R3T1	Base	R1T3	R3T1	Base	R1T3	R3T1
NA1	1,178.3	945.2	1,253.6	0.69	0.70	0.69	33.01	39.00	31.59
NA2	1,180.4	926.6	1,258.3	0.69	0.70	0.69	32.38	38.75	30.90

[1] Single (NA1) and split (NA2) nitrogen application.

[2] Baseline climate (Base), and 2070 least favourable (R1T3) and most favourable (R3T1) climate scenarios.

Under the most favourable 2070 climate scenario (R3T1) we see a 5% increase in gross margin, a 5% decrease in DIN delivery and, again, no significant changes in FSS delivery. Split nitrogen application remains equally cost-effective in managing DIN delivery.

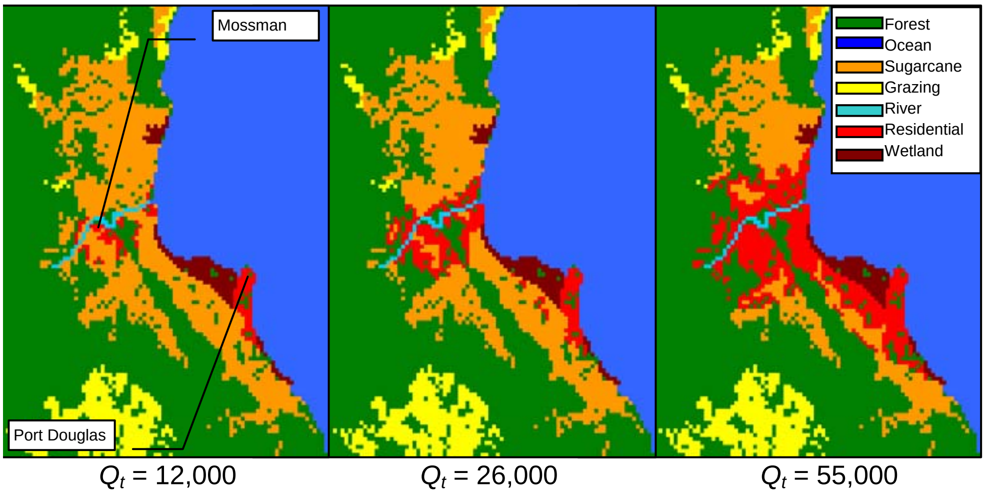
4.2 Population growth

Population growth in the GBR region is amongst the highest in Australia, the agricultural sector thus experiencing land use pressures while associated residential developments are expected to lead to a decline in water quality (Zipperer *et al.* 2000). Although residential development does not influence the plot-level cost-effectiveness of land use and management options, it does influence the location and the extent to which these can be implemented (given the conversion from agricultural to residential land use) and may also lead to significant agricultural land use changes (e.g. closing down of sugar mills due to insufficient feedstock). The net effect of population growth on water pollution and the potential for water quality improvement thus depends on the type of water pollution, the land use specific water quality characteristics and the population growth induced land use change patterns.

In a recent paper by Roebeling *et al*. (2007), a classic urban economic model with environmental amenities (see for example Wu, 2006) is used to explore land use patterns for a range of catchment population growth scenarios which they, in turn, relate back to terrestrial benefits, associated water pollution and subsequent marine costs to explore welfare gains that can be obtained from population growth in a linked terrestrial and marine ecosystem (see Appendix 1 for a detailed description of the methodology). Generated population size specific land use patterns for a case study of the Douglas Shire (see Figure 17) indicate that: i) residential development first takes place near urban centres (Mossman and Port Douglas), waterways (ocean and river) and hillside areas (forest), ii) the rate of land use conversion is increasing in population size, and iii) the rate of nitrogen water pollution is increasing in population size.

Based on these findings and assuming that water pollution from residential land uses exceeds water pollution from the agricultural land uses it replaces, it can be expected that: i) water pollution increases with population size at an increasing rate, and ii) the potential for water quality improvement through BMP adoption in agricultural land uses is reduced due to population growth induced residential development. Hence, to attain and maintain water quality targets under population growth it is crucial to be able to implement BMPs for agricultural land uses as well as for residential land uses. Alternatively, population growth and associated residential development may be constrained and is shown to provide welfare gains in case downstream costs from water pollution are taken into account Roebeling *et al*. (2007).

Figure 17: Terrestrial benefit maximizing land use patterns in Douglas Shire for three catchment population scenarios Qt (source: Roebeling et al. 2007).



5. Discussion and conclusions

In this report we apply and extend the approach developed by Roebeling *et al*. (2005), to the analysis of the (plot-level) financial-economic cost-effectiveness of best-management-practices (BMPs) for water quality improvement in sugarcane, horticulture, grazing and forestry production. The approach is based on linkage of the specialized production system simulation models APSIM, LUCTOR and PASTOR (see Keating *et al.* 1999; Hengsdijk *et al.* 2000; Bouman *et al.* 1998) and the water quality model SedNet/ANNEX (see Bartley *et al.* 2004), in combination with sound cost-benefit analysis (Zerbe and Dively, 1994). Based on literature data, field observations and expert knowledge, this approach allows us to assess the cost-effectiveness of current and future BMPs (in sugarcane, horticulture, grazing and forestry production) for water quality improvement (fine suspended sediment, dissolved inorganic nitrogen and persistent herbicides) in the Tully-Murray catchment.

Table 9 summarizes the cost-effectiveness of BMPs in sugarcane, horticulture, grazing and forestry production in the Tully-Murray catchment. Analysed BMPs in sugarcane production include tillage management, fallow management, nitrogen application rate, nitrogen application method and herbicide application rate. Results show that tillage management (*i.e.* moving towards a zero tillage system) and fallow management (*i.e.* moving from a bare towards a legume fallow) are both attractive from a financial-economic perspective while only tillage management leads to a reduction in water pollutant (fine suspended sediment – FSS) delivery. Nitrogen application rates matched to crop requirements are shown to be attractive from a financial-economic and a water pollutant (dissolved inorganic nitrogen – DIN) delivery perspective. Nitrogen application method (*i.e.* moving towards split nitrogen application) is shown to lead to marginal changes in profitability and water pollutant delivery. Finally, reduced herbicide application, using a hooded sprayer, leads to a small decrease in gross margin and to a considerable reduction in water pollutant (persistent herbicide – HER) delivery.

Table 9: Cost-effectiveness of best-management-practices for water quality improvement in sugarcane, horticulture, grazing and forestry production systems.

Production system	Management practice	Gross margin	FSS delivery	DIN delivery	HER delivery
Sugarcane	Tillage management	(+)	++	0	0
	Fallow management	+	0	–	0
	Nitrogen application rate ~ requirements	+	(0)	++	0
	Nitrogen application method	(0)	0	(+)	0
	Herbicide application rate	(–)	0	0	++
Horticulture	Interrow management	(–)	++	0	0
	Fertiliser application rate ~ requirements	–	(0)	+	0
Grazing	Stocking rate ~ carrying capacity	+	(+)	(0)	0
	Nitrogen application rate ~ requirements	+	(0)	(+)	0
Forestry	Interrow management	(–)	(+)	0	0

Analysed BMPs in (banana) horticulture production include interrow management and fertiliser application rate. Results show that interrow management (*i.e.* maintaining grassed interrows) leads to a considerable reduction in water pollutant (FSS) delivery though also to a small reduction in profitability. Reduced fertiliser application rates lead to a decrease in water pollutant (DIN) delivery and gross margins, unless efficiency gains can be made through re-composition of N, P and K ratios. Analysed BMPs in grazing production include stocking rate and nitrogen application rate. Stocking rates matched to pasture carrying capacity are shown to lead to a small reduction in water pollutant (FSS) delivery as well as an increase in profitability. Nitrogen application rates matched to pasture requirements are shown to be attractive from a financial-economic perspective and lead to small reductions in water pollutant (DIN) delivery. Finally, the analysed BMP in (hard timber) forestry production involves interrow management (*i.e.* maintaining grassed interrows), which leads to a small reduction in water pollutant (FSS) delivery and gross margins.

Thus, most of the assessed BMPs lead to a reduction in water pollutant delivery while either providing a financial-economic benefit or coming at a small financial-economic cost. Options for cost-effective water quality improvement are largest in sugarcane and (banana) horticulture production, including BMPs like tillage management, nitrogen application rate and herbicide application rate in sugarcane production, and interrow management in (banana) horticulture production. Options for cost-effective water quality improvement in grazing and forestry production are limited.

The impact of climate change on BMP cost-effectiveness and attainment of water quality targets has been assessed for an example of the sugar industry. Results indicate that BMP cost-effectiveness is generally not affected by climate change – *i.e.* BMPs remain proportionally equally effective in reducing water pollutant delivery. Levels of water pollutant (DIN) delivery may, however, increase significantly under climate change projections for 2070 (up to 20% increase in DIN delivery), thus potentially jeopardizing the attainment of water quality targets.

The impact of population growth on the attainment of water quality targets has been assessed based on a study in the Douglas Shire. In case water pollution from residential land uses exceeds water pollution from the land uses it replaces, it can be expected that: i) water pollution increases with population size at an increasing rate, and ii) the potential for water quality improvement through BMP adoption in agriculture is reduced due to residential development. Consequently, attaining water quality targets under population growth requires implementation of BMPs for agricultural as well as residential land uses. Alternatively, population growth and associated residential development may need to be constrained.

A number of caveats to this study must be mentioned. First, this BMP cost-effectiveness assessment is a plot-level study and, consequently, does not include costs associated with BMP implementation at the farm and community level. While production technologies may be cost-effective at the plot level, they may not be at the farm or community level due to, for example, labour or capital constraints, market (Sadoulet and De Janvry, 1995). Second, we can conclude that not all of the used production system simulation models are equally suited for BMP cost-effectiveness assessment. As compared to LUCTOR (Hengsdijk *et al*. 2000) and PASTOR (Bouman *et al.* 1998), APSIM (Keating *et al.* 1999) resulted to be best suited 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 run-off 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 BMPs. Third, persistent herbicide (HER) delivery calculations are fairly simplistic (*i.e.* fixed share of persistent herbicide application) as there is no hydrological module available in SedNet/ANNEX that accurately describes the relationship between plot level persistent herbicide concentrations and persistent herbicide delivery (Lewis *et al.* 2006). Finally, it must be noted that the figures in this document are generated for the Tully-Murray catchment and, consequently, care should be taken when transferring these figures to other catchments. This not only holds for yield, input cost and gross margin figures, which are dependent on locally specific bio-physical and socio-economic conditions, but also for water pollutant delivery figures, which are dependent on locally specific bio-physical conditions and land use patterns.

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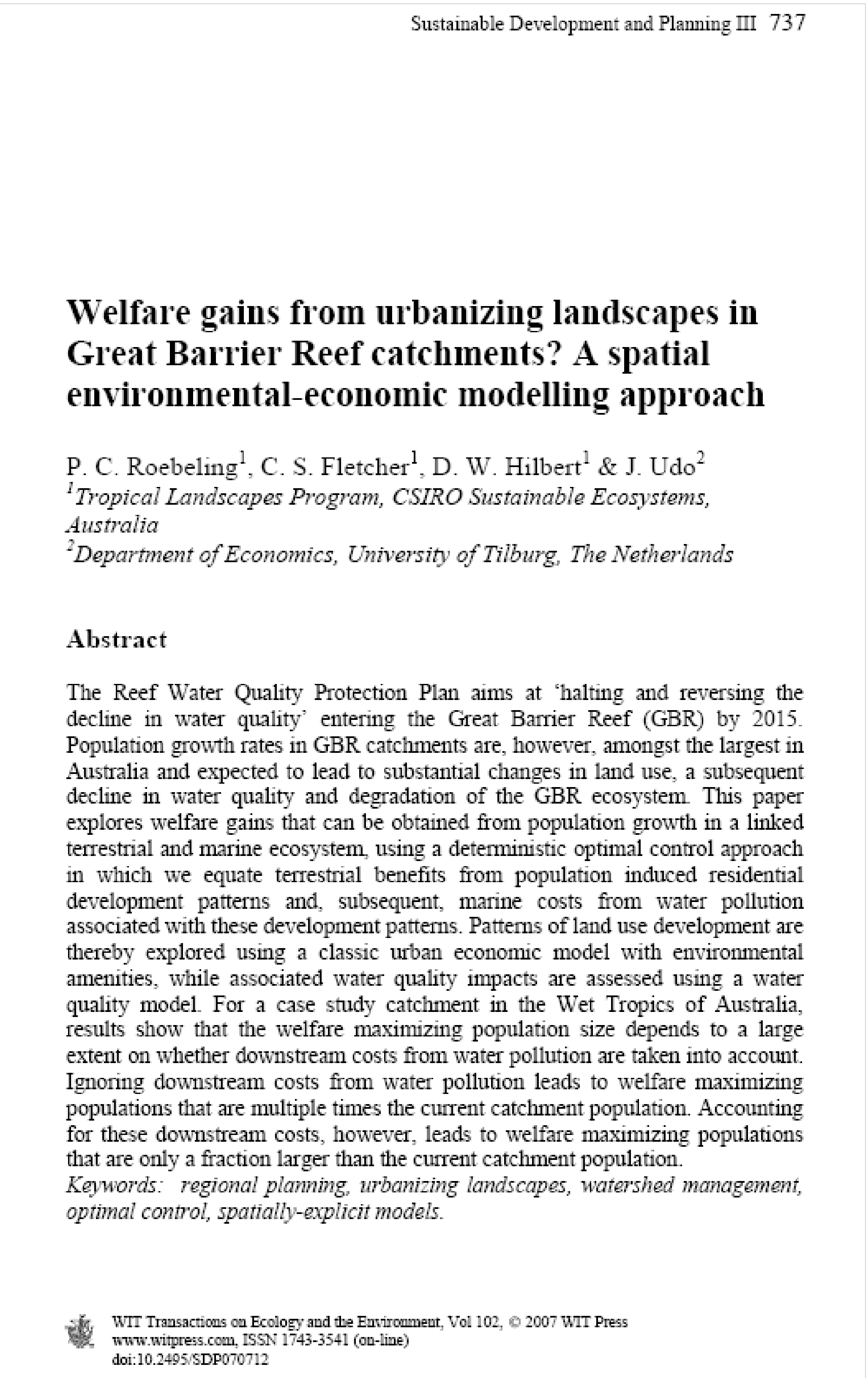
Appendix 1

Welfare gains from urbanising landscapes in Great Barrier Reef Catchments? A spatial environmental-economic modelling approach

P. C. Roebeling, C. S. Fletcher, D. W. Hilbert and J. Udo



Welfare gains from urbanizing landscapes in Great Barrier Reef catchments? A spatial environmental-economic modelling approach

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Abstract

The Reef Water Quality Protection Plan aims at 'halting and reversing the decline in water quality' entering the Great Barrier Reef (GBR) by 2015. Population growth rates in GBR catchments are, however, amongst the largest in Australia and expected to lead to substantial changes in land use, a subsequent decline in water quality and degradation of the GBR ecosystem. This paper explores welfare gains that can be obtained from population growth in a linked terrestrial and marine ecosystem, using a deterministic optimal control approach in which we equate terrestrial benefits from population induced residential development patterns and, subsequent, marine costs from water pollution associated with these development patterns. Patterns of land use development are thereby explored using a classic urban economic model with environmental amenities, while associated water quality impacts are assessed using a water quality model. For a case study catchment in the Wet Tropics of Australia, results show that the welfare maximizing population size depends to a large extent on whether downstream costs from water pollution are taken into account. Ignoring downstream costs from water pollution leads to welfare maximizing populations that are multiple times the current catchment population. Accounting for these downstream costs, however, leads to welfare maximizing populations that are only a fraction larger than the current catchment population.

Keywords: regional planning, urbanizing landscapes, watershed management, optimal control, spatially-explicit models.

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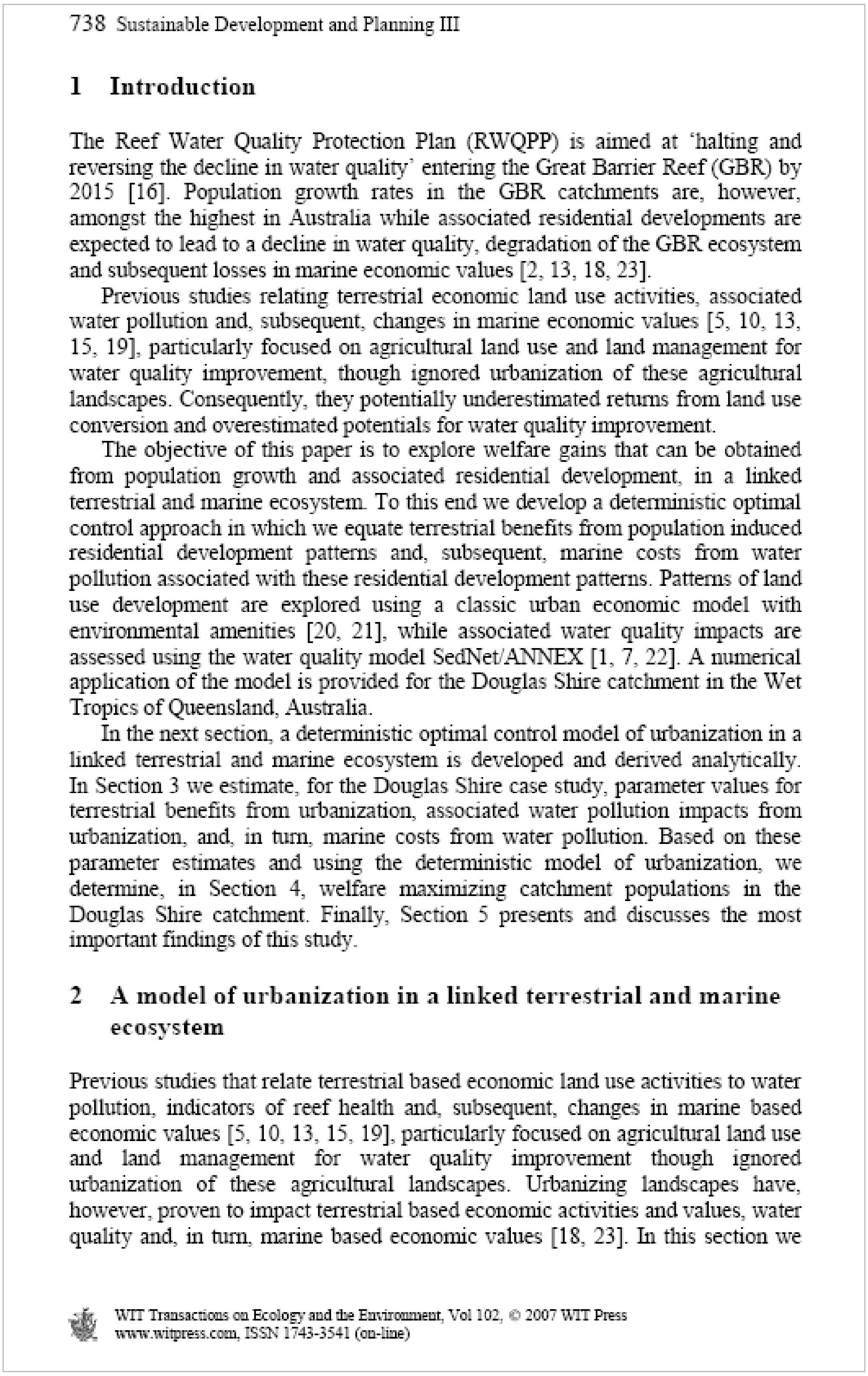


1 Introduction

The Reef Water Quality Protection Plan (RWQPP) is aimed at 'halting and reversing the decline in water quality' entering the Great Barrier Reef (GBR) by 2015 [16]. Population growth rates in the GBR catchments are, however, amongst the highest in Australia while associated residential developments are expected to lead to a decline in water quality, degradation of the GBR ecosystem and subsequent losses in marine economic values [2, 13, 18, 23].

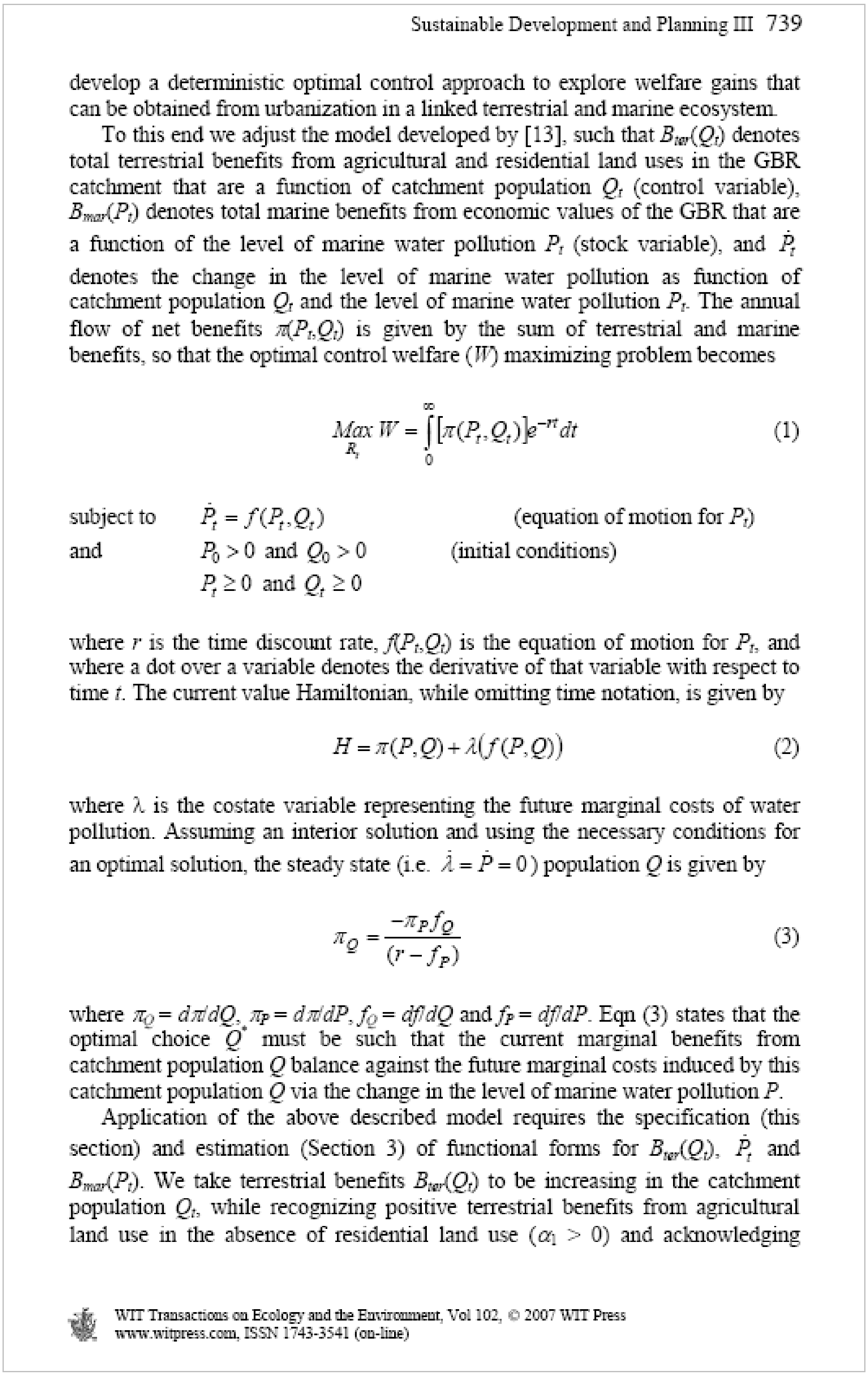
Previous studies relating terrestrial economic land use activities, associated water pollution and, subsequent, changes in marine economic values [5, 10, 13, 15, 19], particularly focused on agricultural land use and land management for water quality improvement, though ignored urbanization of these agricultural landscapes. Consequently, they potentially underestimated returns from land use conversion and overestimated potentials for water quality improvement.

The objective of this paper is to explore welfare gains that can be obtained from population growth and associated residential development, in a linked terrestrial and marine ecosystem. To this end we develop a deterministic optimal control approach in which we equate terrestrial benefits from population induced residential development patterns and, subsequent, marine costs from water pollution associated with these residential development patterns. Patterns of land use development are explored using a classic urban economic model with environmental amenities [20, 21], while associated water quality impacts are assessed using the water quality model SedNet/ANNEX [1, 7, 22]. A numerical application of the model is provided for the Douglas Shire catchment in the Wet Tropics of Queensland, Australia.

In the next section, a deterministic optimal control model of urbanization in a linked terrestrial and marine ecosystem is developed and derived analytically. In Section 3 we estimate, for the Douglas Shire case study, parameter values for terrestrial benefits from urbanization, associated water pollution impacts from urbanization, and, in turn, marine costs from water pollution. Based on these parameter estimates and using the deterministic model of urbanization, we determine, in Section 4, welfare maximizing catchment populations in the Douglas Shire catchment. Finally, Section 5 presents and discusses the most important findings of this study.

2 A model of urbanization in a linked terrestrial and marine ecosystem

Previous studies that relate terrestrial based economic land use activities to water pollution, indicators of reef health and, subsequent, changes in marine based economic values [5, 10, 13, 15, 19], particularly focused on agricultural land use and land management for water quality improvement though ignored urbanization of these agricultural landscapes. Urbanizing landscapes have, however, proven to impact terrestrial based economic activities and values, water quality and, in turn, marine based economic values [18, 23]. In this section we



develop a deterministic optimal control approach to explore welfare gains that can be obtained from urbanization in a linked terrestrial and marine ecosystem.

To this end we adjust the model developed by [13], such that $B_{ter}(Q_t)$ denotes total terrestrial benefits from agricultural and residential land uses in the GBR catchment that are a function of catchment population Q_t (control variable), $B_{mar}(P_t)$ denotes total marine benefits from economic values of the GBR that are a function of the level of marine water pollution P_t (stock variable), and $\dot{P}_t$ denotes the change in the level of marine water pollution as function of catchment population Q_t and the level of marine water pollution P_t. The annual flow of net benefits $\pi(P_t,Q_t)$ is given by the sum of terrestrial and marine benefits, so that the optimal control welfare (W) maximizing problem becomes

$$\underset{R_t}{Max}\, W = \int_0^{\infty} \left[\pi(P_t,Q_t)\right] e^{-rt}\, dt \tag{1}$$

subject to $\dot{P}_t = f(P_t,Q_t)$ (equation of motion for P_t)

and $P_0 > 0$ and $Q_0 > 0$ (initial conditions)

$P_t \geq 0$ and $Q_t \geq 0$

where r is the time discount rate, $f(P_t,Q_t)$ 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 current value Hamiltonian, while omitting time notation, is given by

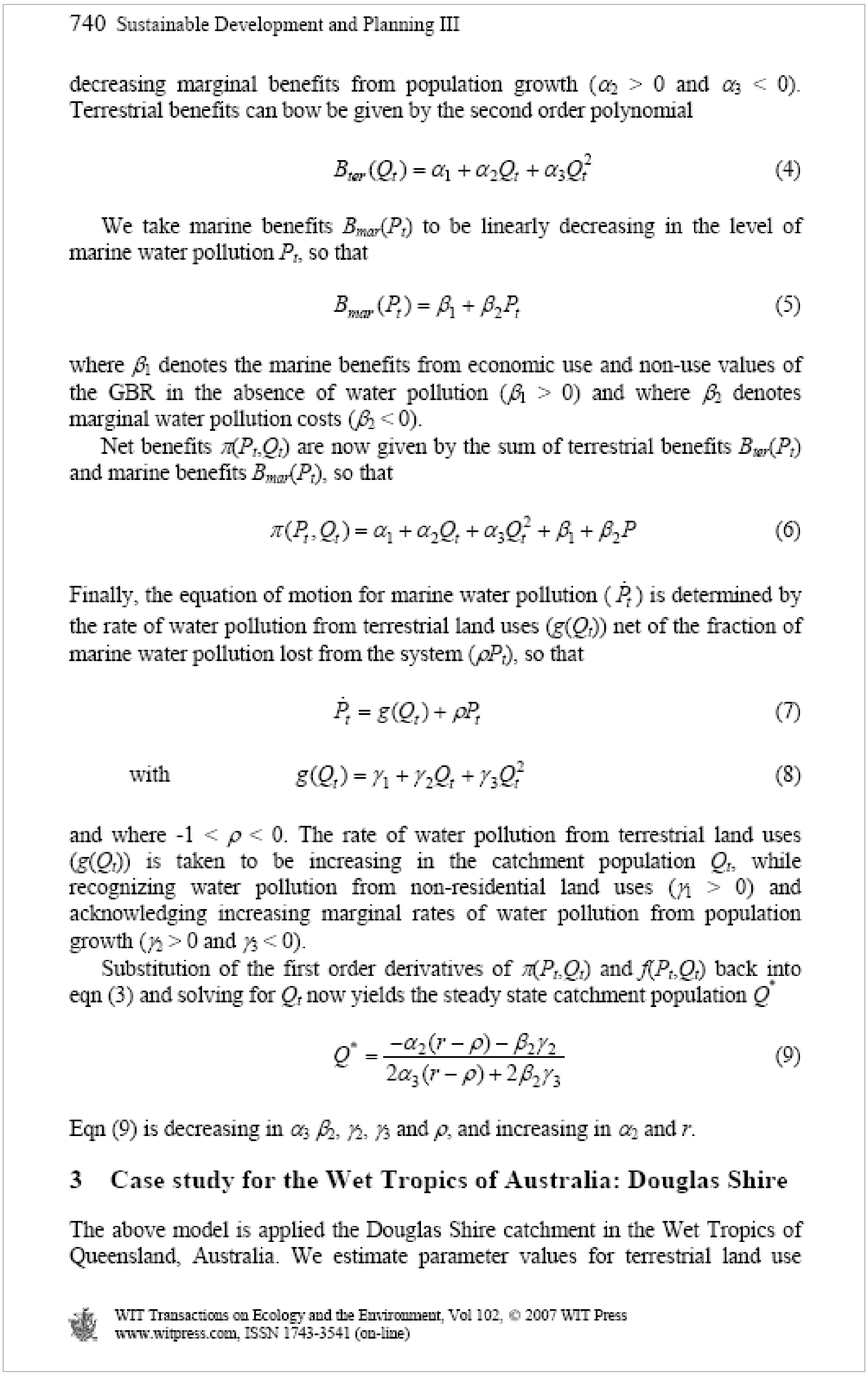
$$H = \pi(P,Q) + \lambda\big(f(P,Q)\big) \tag{2}$$

where λ is the costate variable representing the future marginal costs of water pollution. Assuming an interior solution and using the necessary conditions for an optimal solution, the steady state (i.e. $\dot{\lambda} = \dot{P} = 0$) population Q is given by

$$\pi_Q = \frac{-\pi_P f_Q}{(r - f_P)} \tag{3}$$

where $\pi_Q = d\pi/dQ$, $\pi_P = d\pi/dP$, $f_Q = df/dQ$ and $f_P = df/dP$. Eqn (3) states that the optimal choice Q^* must be such that the current marginal benefits from catchment population Q balance against the future marginal costs induced by this catchment population Q via the change in the level of marine water pollution P.

Application of the above described model requires the specification (this section) and estimation (Section 3) of functional forms for $B_{ter}(Q_t)$, $\dot{P}_t$ and $B_{mar}(P_t)$. We take terrestrial benefits $B_{ter}(Q_t)$ to be increasing in the catchment population Q_t, while recognizing positive terrestrial benefits from agricultural land use in the absence of residential land use ($\alpha_1 > 0$) and acknowledging



decreasing marginal benefits from population growth ($\alpha_2 > 0$ and $\alpha_3 < 0$). Terrestrial benefits can bow be given by the second order polynomial

$$B_{ter}(Q_t) = \alpha_1 + \alpha_2 Q_t + \alpha_3 Q_t^2 \tag{4}$$

We take marine benefits $B_{mar}(P_t)$ to be linearly decreasing in the level of marine water pollution P_t, so that

$$B_{mar}(P_t) = \beta_1 + \beta_2 P_t \tag{5}$$

where β_1 denotes the marine benefits from economic use and non-use values of the GBR in the absence of water pollution ($\beta_1 > 0$) and where β_2 denotes marginal water pollution costs ($\beta_2 < 0$).

Net benefits $\pi(P_t,Q_t)$ are now given by the sum of terrestrial benefits $B_{ter}(P_t)$ and marine benefits $B_{mar}(P_t)$, so that

$$\pi(P_t, Q_t) = \alpha_1 + \alpha_2 Q_t + \alpha_3 Q_t^2 + \beta_1 + \beta_2 P \tag{6}$$

Finally, the equation of motion for marine water pollution ($\dot{P}_t$) is determined by the rate of water pollution from terrestrial land uses ($g(Q_t)$) net of the fraction of marine water pollution lost from the system (ρP_t), so that

$$\dot{P}_t = g(Q_t) + \rho P_t \tag{7}$$

with $$g(Q_t) = \gamma_1 + \gamma_2 Q_t + \gamma_3 Q_t^2 \tag{8}$$

and where $-1 < \rho < 0$. The rate of water pollution from terrestrial land uses ($g(Q_t)$) is taken to be increasing in the catchment population Q_t, while recognizing water pollution from non-residential land uses ($\gamma_1 > 0$) and acknowledging increasing marginal rates of water pollution from population growth ($\gamma_2 > 0$ and $\gamma_3 < 0$).

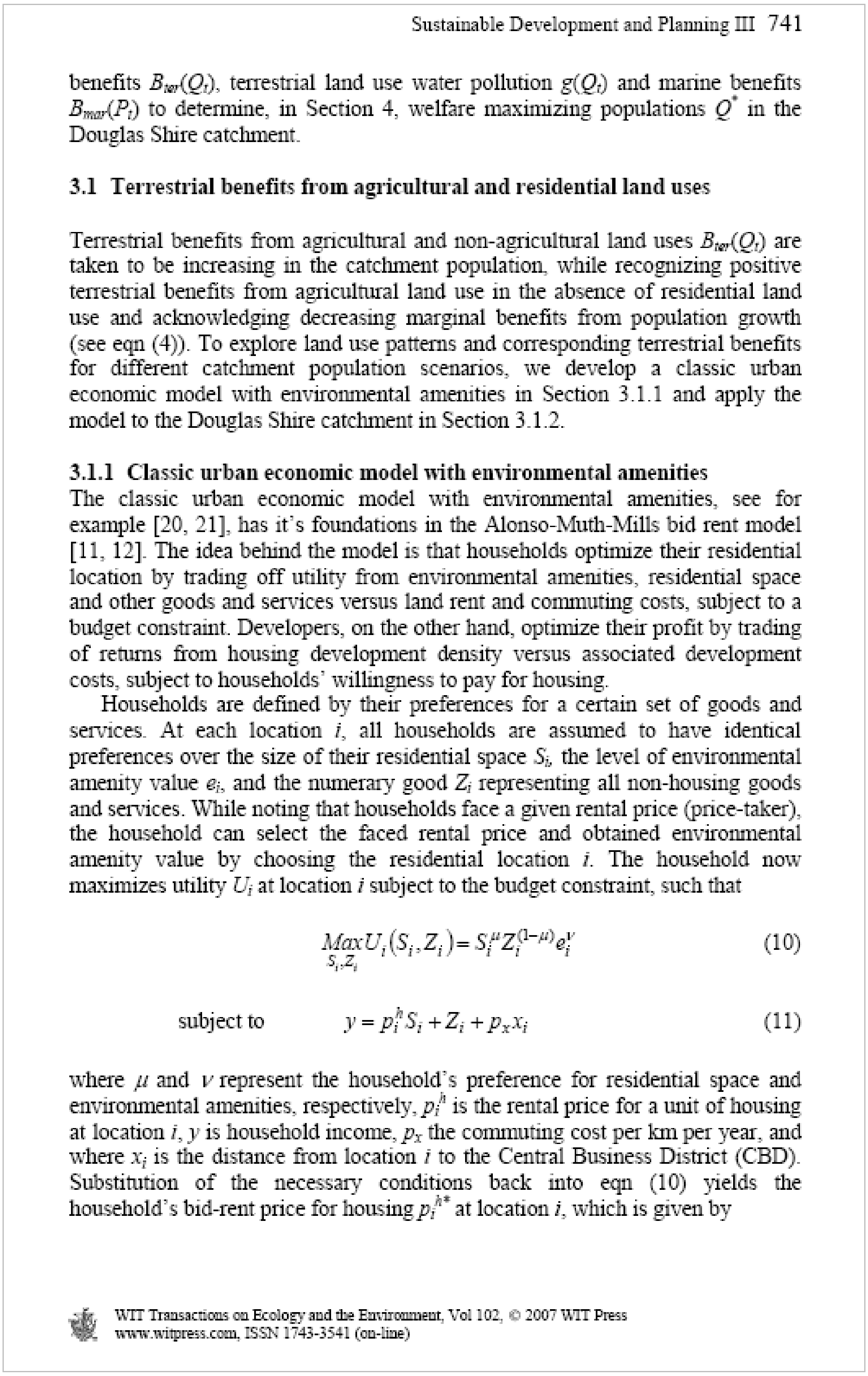
Substitution of the first order derivatives of $\pi(P_t,Q_t)$ and $f(P_t,Q_t)$ back into eqn (3) and solving for Q_t now yields the steady state catchment population Q^*

$$Q^* = \frac{-\alpha_2(r-\rho) - \beta_2\gamma_2}{2\alpha_3(r-\rho) + 2\beta_2\gamma_3} \tag{9}$$

Eqn (9) is decreasing in α_3 β_2, γ_2, γ_3 and ρ, and increasing in α_2 and r.

3 Case study for the Wet Tropics of Australia: Douglas Shire

The above model is applied the Douglas Shire catchment in the Wet Tropics of Queensland, Australia. We estimate parameter values for terrestrial land use



benefits $B_{ter}(Q_t)$, terrestrial land use water pollution $g(Q_t)$ and marine benefits $B_{mar}(P_t)$ to determine, in Section 4, welfare maximizing populations Q^* in the Douglas Shire catchment.

3.1 Terrestrial benefits from agricultural and residential land uses

Terrestrial benefits from agricultural and non-agricultural land uses $B_{ter}(Q_t)$ are taken to be increasing in the catchment population, while recognizing positive terrestrial benefits from agricultural land use in the absence of residential land use and acknowledging decreasing marginal benefits from population growth (see eqn (4)). To explore land use patterns and corresponding terrestrial benefits for different catchment population scenarios, we develop a classic urban economic model with environmental amenities in Section 3.1.1 and apply the model to the Douglas Shire catchment in Section 3.1.2.

3.1.1 Classic urban economic model with environmental amenities

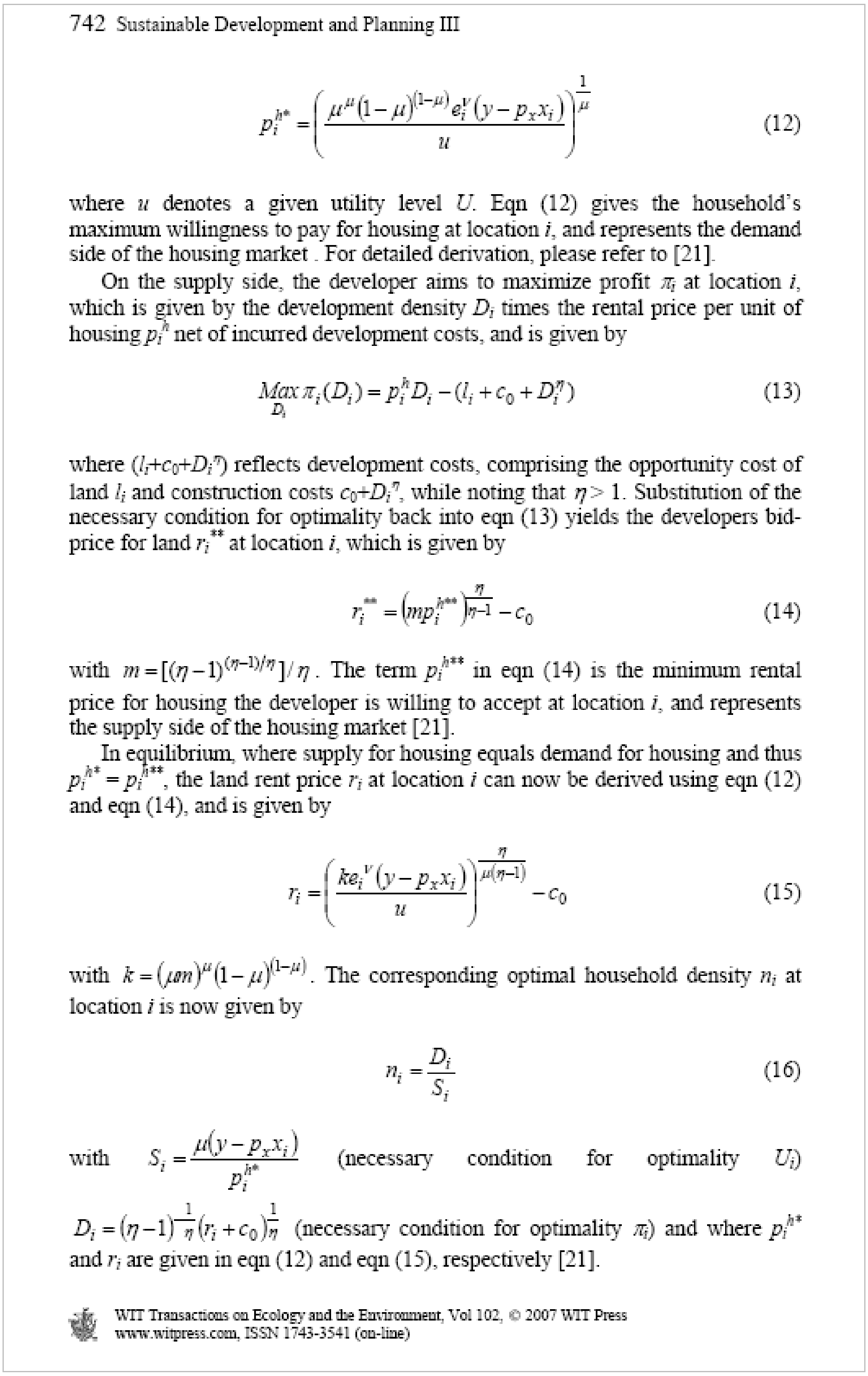
The classic urban economic model with environmental amenities, see for example [20, 21], has it's foundations in the Alonso-Muth-Mills bid rent model [11, 12]. The idea behind the model is that households optimize their residential location by trading off utility from environmental amenities, residential space and other goods and services versus land rent and commuting costs, subject to a budget constraint. Developers, on the other hand, optimize their profit by trading of returns from housing development density versus associated development costs, subject to households' willingness to pay for housing.

Households are defined by their preferences for a certain set of goods and services. At each location i, all households are assumed to have identical preferences over the size of their residential space S_i, the level of environmental amenity value e_i, and the numerary good Z_i representing all non-housing goods and services. While noting that households face a given rental price (price-taker), the household can select the faced rental price and obtained environmental amenity value by choosing the residential location i. The household now maximizes utility U_i at location i subject to the budget constraint, such that

$$\underset{S_i,Z_i}{Max}\,U_i(S_i,Z_i)=S_i^{\mu}Z_i^{(1-\mu)}e_i^{\nu} \tag{10}$$

subject to $$y = p_i^h S_i + Z_i + p_x x_i \tag{11}$$

where μ and ν represent the household's preference for residential space and environmental amenities, respectively, p_i^h is the rental price for a unit of housing at location i, y is household income, p_x the commuting cost per km per year, and where x_i is the distance from location i to the Central Business District (CBD). Substitution of the necessary conditions back into eqn (10) yields the household's bid-rent price for housing p_i^{h*} at location i, which is given by



$$p_i^{h*} = \left(\frac{\mu^{\mu} (1-\mu)^{(1-\mu)} e_i^{V} (y - p_x x_i)}{u} \right)^{\frac{1}{\mu}} \tag{12}$$

where u denotes a given utility level U. Eqn (12) gives the household's maximum willingness to pay for housing at location i, and represents the demand side of the housing market . For detailed derivation, please refer to [21].

On the supply side, the developer aims to maximize profit π_i at location i, which is given by the development density D_i times the rental price per unit of housing p_i^h net of incurred development costs, and is given by

$$\underset{D_i}{Max}\, \pi_i(D_i) = p_i^h D_i - (l_i + c_0 + D_i^{\eta}) \tag{13}$$

where $(l_i+c_0+D_i^{\eta})$ reflects development costs, comprising the opportunity cost of land l_i and construction costs $c_0+D_i^{\eta}$, while noting that $\eta > 1$. Substitution of the necessary condition for optimality back into eqn (13) yields the developers bid-price for land r_i^{**} at location i, which is given by

$$r_i^{**} = \left(m p_i^{h**} \right)^{\frac{\eta}{\eta - 1}} - c_0 \tag{14}$$

with $m = [(\eta - 1)^{(\eta-1)/\eta}]/\eta$. The term p_i^{h**} in eqn (14) is the minimum rental price for housing the developer is willing to accept at location i, and represents the supply side of the housing market [21].

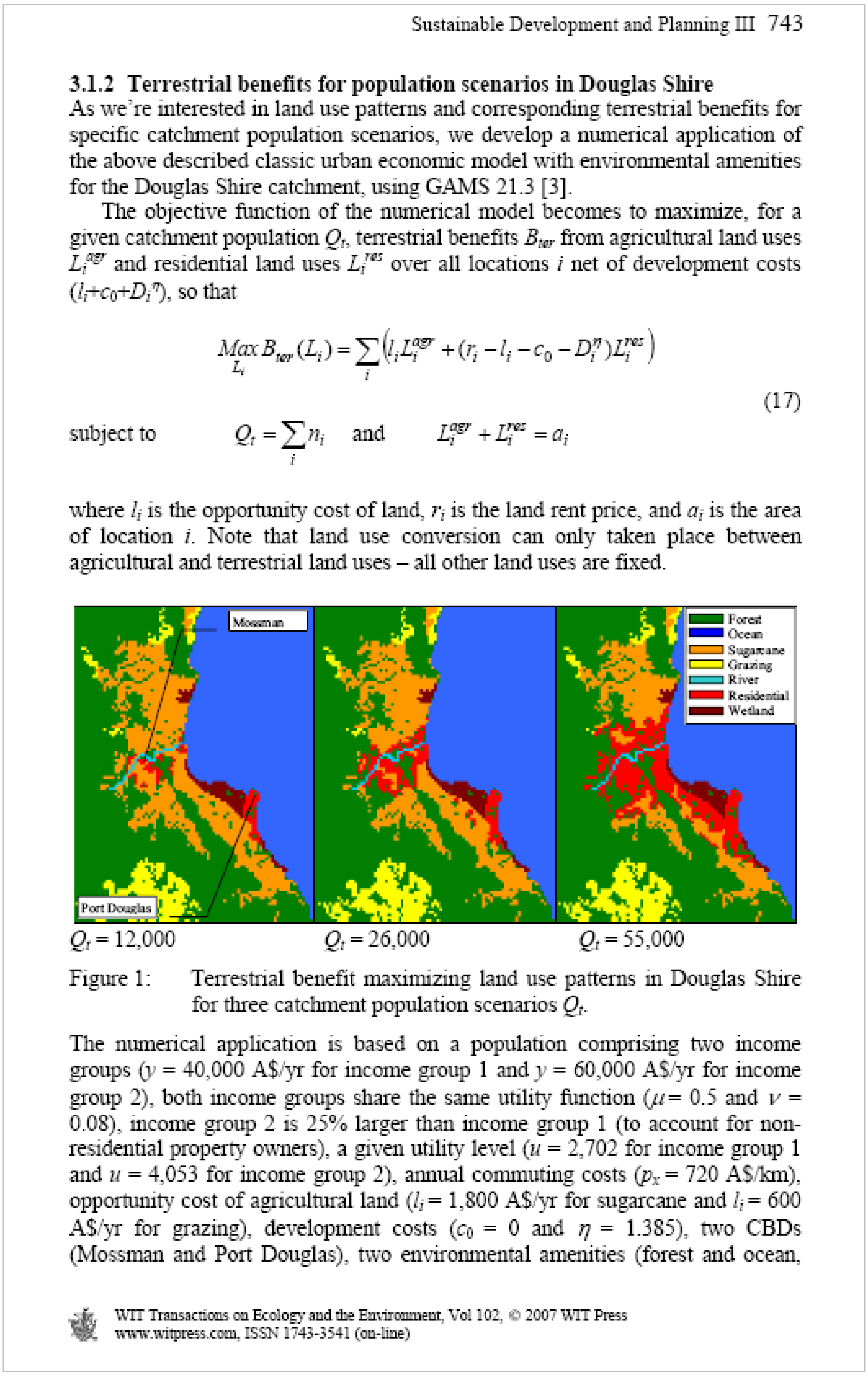
In equilibrium, where supply for housing equals demand for housing and thus $p_i^{h*} = p_i^{h**}$, the land rent price r_i at location i can now be derived using eqn (12) and eqn (14), and is given by

$$r_i = \left(\frac{k e_i^{V} (y - p_x x_i)}{u} \right)^{\frac{\eta}{\mu(\eta - 1)}} - c_0 \tag{15}$$

with $k = (\mu m)^{\mu} (1-\mu)^{(1-\mu)}$. The corresponding optimal household density n_i at location i is now given by

$$n_i = \frac{D_i}{S_i} \tag{16}$$

with $S_i = \frac{\mu (y - p_x x_i)}{p_i^{h*}}$ (necessary condition for optimality U_i) $D_i = (\eta - 1)^{-\frac{1}{\eta}} (r_i + c_0)^{\frac{1}{\eta}}$ (necessary condition for optimality π_i) and where p_i^{h*} and r_i are given in eqn (12) and eqn (15), respectively [21].



3.1.2 Terrestrial benefits for population scenarios in Douglas Shire

As we're interested in land use patterns and corresponding terrestrial benefits for specific catchment population scenarios, we develop a numerical application of the above described classic urban economic model with environmental amenities for the Douglas Shire catchment, using GAMS 21.3 [3].

The objective function of the numerical model becomes to maximize, for a given catchment population Q_t, terrestrial benefits B_{ter} from agricultural land uses L_i^{agr} and residential land uses L_i^{res} over all locations i net of development costs $(l_i+c_0+D_i^{\eta})$, so that

$$\underset{L_i}{Max}\, B_{ter}(L_i) = \sum_i \left(l_i L_i^{agr} + (r_i - l_i - c_0 - D_i^{\eta}) L_i^{res} \right)$$

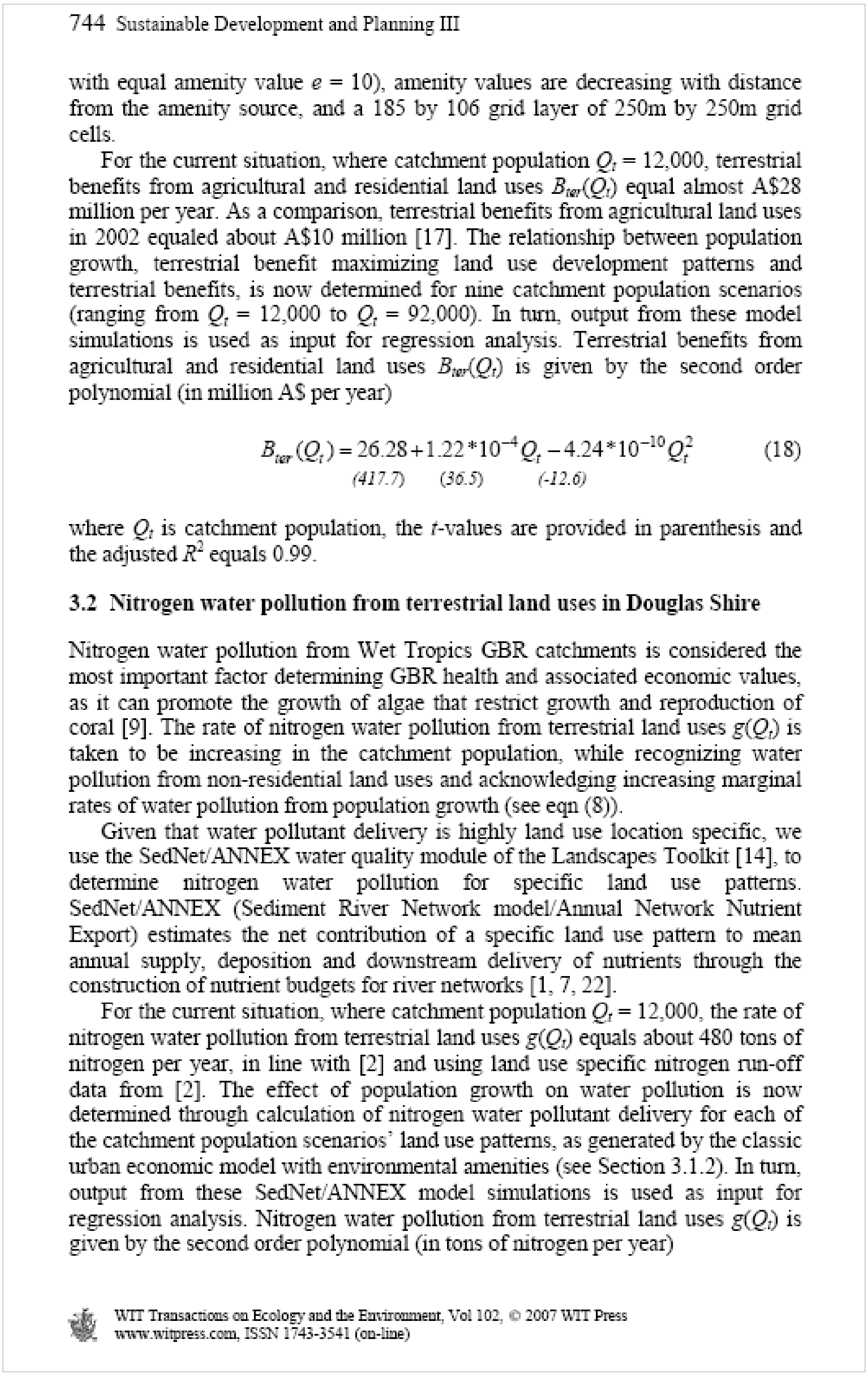
$$\text{subject to} \qquad Q_t = \sum_i n_i \quad \text{and} \quad L_i^{agr} + L_i^{res} = a_i \tag{17}$$

where l_i is the opportunity cost of land, r_i is the land rent price, and a_i is the area of location i. Note that land use conversion can only taken place between agricultural and terrestrial land uses – all other land uses are fixed.

$Q_t = 12{,}000$ $Q_t = 26{,}000$ $Q_t = 55{,}000$

Figure 1: Terrestrial benefit maximizing land use patterns in Douglas Shire for three catchment population scenarios Q_t.

The numerical application is based on a population comprising two income groups (y = 40,000 A\$/yr for income group 1 and y = 60,000 A\$/yr for income group 2), both income groups share the same utility function (μ = 0.5 and ν = 0.08), income group 2 is 25% larger than income group 1 (to account for non-residential property owners), a given utility level (u = 2,702 for income group 1 and u = 4,053 for income group 2), annual commuting costs (p_x = 720 A\$/km), opportunity cost of agricultural land (l_i = 1,800 A\$/yr for sugarcane and l_i = 600 A\$/yr for grazing), development costs (c_0 = 0 and η = 1.385), two CBDs (Mossman and Port Douglas), two environmental amenities (forest and ocean,



with equal amenity value $e = 10$), amenity values are decreasing with distance from the amenity source, and a 185 by 106 grid layer of 250m by 250m grid cells.

For the current situation, where catchment population $Q_t = 12{,}000$, terrestrial benefits from agricultural and residential land uses $B_{ter}(Q_t)$ equal almost A\$28 million per year. As a comparison, terrestrial benefits from agricultural land uses in 2002 equaled about A\$10 million [17]. The relationship between population growth, terrestrial benefit maximizing land use development patterns and terrestrial benefits, is now determined for nine catchment population scenarios (ranging from $Q_t = 12{,}000$ to $Q_t = 92{,}000$). In turn, output from these model simulations is used as input for regression analysis. Terrestrial benefits from agricultural and residential land uses $B_{ter}(Q_t)$ is given by the second order polynomial (in million A\$ per year)

$$B_{ter}(Q_t) = \underset{(417.7)}{26.28} + \underset{(36.5)}{1.22 * 10^{-4}} Q_t - \underset{(-12.6)}{4.24 * 10^{-10}} Q_t^2 \qquad (18)$$

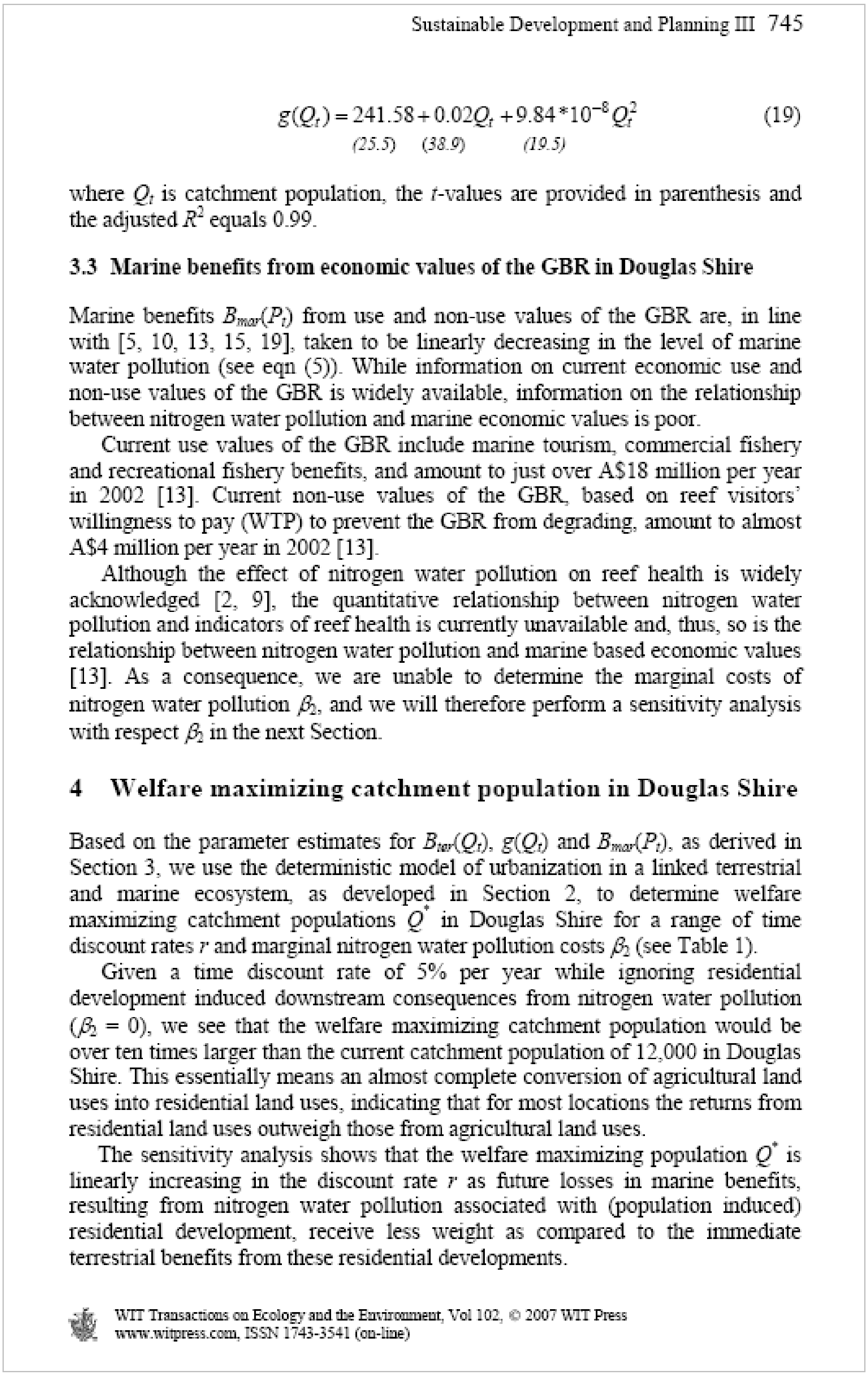
where Q_t is catchment population, the t-values are provided in parenthesis and the adjusted R^2 equals 0.99.

3.2 Nitrogen water pollution from terrestrial land uses in Douglas Shire

Nitrogen water pollution from Wet Tropics GBR catchments is considered the most important factor determining GBR health and associated economic values, as it can promote the growth of algae that restrict growth and reproduction of coral [9]. The rate of nitrogen water pollution from terrestrial land uses $g(Q_t)$ is taken to be increasing in the catchment population, while recognizing water pollution from non-residential land uses and acknowledging increasing marginal rates of water pollution from population growth (see eqn (8)).

Given that water pollutant delivery is highly land use location specific, we use the SedNet/ANNEX water quality module of the Landscapes Toolkit [14], to determine nitrogen water pollution for specific land use patterns. SedNet/ANNEX (Sediment River Network model/Annual Network Nutrient Export) estimates the net contribution of a specific land use pattern to mean annual supply, deposition and downstream delivery of nutrients through the construction of nutrient budgets for river networks [1, 7, 22].

For the current situation, where catchment population $Q_t = 12{,}000$, the rate of nitrogen water pollution from terrestrial land uses $g(Q_t)$ equals about 480 tons of nitrogen per year, in line with [2] and using land use specific nitrogen run-off data from [2]. The effect of population growth on water pollution is now determined through calculation of nitrogen water pollutant delivery for each of the catchment population scenarios' land use patterns, as generated by the classic urban economic model with environmental amenities (see Section 3.1.2). In turn, output from these SedNet/ANNEX model simulations is used as input for regression analysis. Nitrogen water pollution from terrestrial land uses $g(Q_t)$ is given by the second order polynomial (in tons of nitrogen per year)



$$g(Q_t) = \underset{(25.5)}{241.58} + \underset{(38.9)}{0.02Q_t} + \underset{(19.5)}{9.84 * 10^{-8}Q_t^2} \qquad (19)$$

where Q_t is catchment population, the t-values are provided in parenthesis and the adjusted R^2 equals 0.99.

3.3 Marine benefits from economic values of the GBR in Douglas Shire

Marine benefits $B_{mar}(P_t)$ from use and non-use values of the GBR are, in line with [5, 10, 13, 15, 19], taken to be linearly decreasing in the level of marine water pollution (see eqn (5)). While information on current economic use and non-use values of the GBR is widely available, information on the relationship between nitrogen water pollution and marine economic values is poor.

Current use values of the GBR include marine tourism, commercial fishery and recreational fishery benefits, and amount to just over A$18 million per year in 2002 [13]. Current non-use values of the GBR, based on reef visitors' willingness to pay (WTP) to prevent the GBR from degrading, amount to almost A$4 million per year in 2002 [13].

Although the effect of nitrogen water pollution on reef health is widely acknowledged [2, 9], the quantitative relationship between nitrogen water pollution and indicators of reef health is currently unavailable and, thus, so is the relationship between nitrogen water pollution and marine based economic values [13]. As a consequence, we are unable to determine the marginal costs of nitrogen water pollution β_2, and we will therefore perform a sensitivity analysis with respect β_2 in the next Section.

4 Welfare maximizing catchment population in Douglas Shire

Based on the parameter estimates for $B_{ter}(Q_t)$, $g(Q_t)$ and $B_{mar}(P_t)$, as derived in Section 3, we use the deterministic model of urbanization in a linked terrestrial and marine ecosystem, as developed in Section 2, to determine welfare maximizing catchment populations Q^* in Douglas Shire for a range of time discount rates r and marginal nitrogen water pollution costs β_2 (see Table 1).

Given a time discount rate of 5% per year while ignoring residential development induced downstream consequences from nitrogen water pollution ($\beta_2 = 0$), we see that the welfare maximizing catchment population would be over ten times larger than the current catchment population of 12,000 in Douglas Shire. This essentially means an almost complete conversion of agricultural land uses into residential land uses, indicating that for most locations the returns from residential land uses outweigh those from agricultural land uses.

The sensitivity analysis shows that the welfare maximizing population Q^* is linearly increasing in the discount rate r as future losses in marine benefits, resulting from nitrogen water pollution associated with (population induced) residential development, receive less weight as compared to the immediate terrestrial benefits from these residential developments.

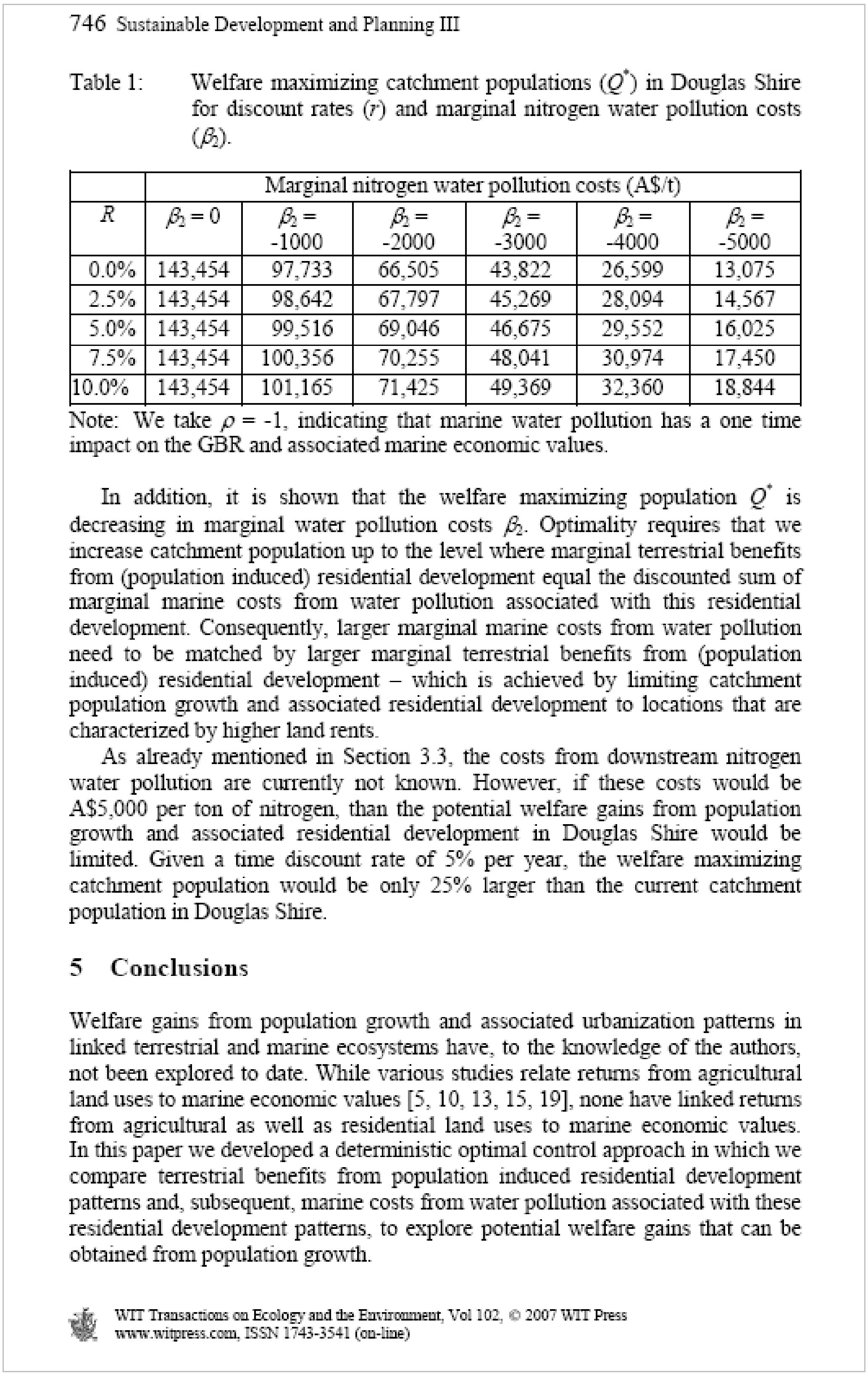


Table 1: Welfare maximizing catchment populations (Q^*) in Douglas Shire for discount rates (r) and marginal nitrogen water pollution costs (β_2).

	Marginal nitrogen water pollution costs (A$/t)					
R	$\beta_2 = 0$	$\beta_2 =$ -1000	$\beta_2 =$ -2000	$\beta_2 =$ -3000	$\beta_2 =$ -4000	$\beta_2 =$ -5000
0.0%	143,454	97,733	66,505	43,822	26,599	13,075
2.5%	143,454	98,642	67,797	45,269	28,094	14,567
5.0%	143,454	99,516	69,046	46,675	29,552	16,025
7.5%	143,454	100,356	70,255	48,041	30,974	17,450
10.0%	143,454	101,165	71,425	49,369	32,360	18,844

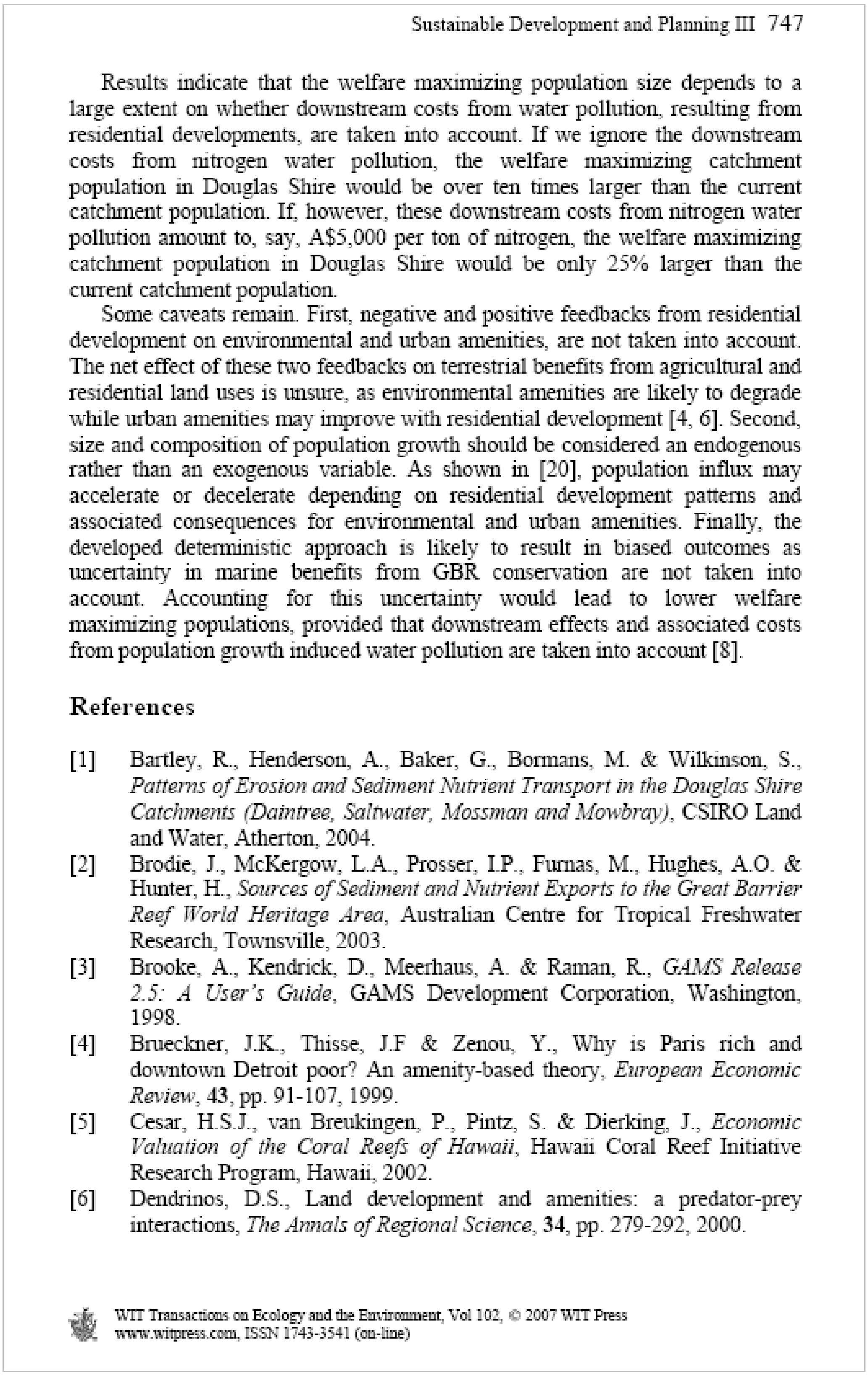
Note: We take ρ = -1, indicating that marine water pollution has a one time impact on the GBR and associated marine economic values.

In addition, it is shown that the welfare maximizing population Q^* is decreasing in marginal water pollution costs β_2. Optimality requires that we increase catchment population up to the level where marginal terrestrial benefits from (population induced) residential development equal the discounted sum of marginal marine costs from water pollution associated with this residential development. Consequently, larger marginal marine costs from water pollution need to be matched by larger marginal terrestrial benefits from (population induced) residential development – which is achieved by limiting catchment population growth and associated residential development to locations that are characterized by higher land rents.

As already mentioned in Section 3.3, the costs from downstream nitrogen water pollution are currently not known. However, if these costs would be A$5,000 per ton of nitrogen, than the potential welfare gains from population growth and associated residential development in Douglas Shire would be limited. Given a time discount rate of 5% per year, the welfare maximizing catchment population would be only 25% larger than the current catchment population in Douglas Shire.

5 Conclusions

Welfare gains from population growth and associated urbanization patterns in linked terrestrial and marine ecosystems have, to the knowledge of the authors, not been explored to date. While various studies relate returns from agricultural land uses to marine economic values [5, 10, 13, 15, 19], none have linked returns from agricultural as well as residential land uses to marine economic values. In this paper we developed a deterministic optimal control approach in which we compare terrestrial benefits from population induced residential development patterns and, subsequent, marine costs from water pollution associated with these residential development patterns, to explore potential welfare gains that can be obtained from population growth.



Results indicate that the welfare maximizing population size depends to a large extent on whether downstream costs from water pollution, resulting from residential developments, are taken into account. If we ignore the downstream costs from nitrogen water pollution, the welfare maximizing catchment population in Douglas Shire would be over ten times larger than the current catchment population. If, however, these downstream costs from nitrogen water pollution amount to, say, A$5,000 per ton of nitrogen, the welfare maximizing catchment population in Douglas Shire would be only 25% larger than the current catchment population.

Some caveats remain. First, negative and positive feedbacks from residential development on environmental and urban amenities, are not taken into account. The net effect of these two feedbacks on terrestrial benefits from agricultural and residential land uses is unsure, as environmental amenities are likely to degrade while urban amenities may improve with residential development [4, 6]. Second, size and composition of population growth should be considered an endogenous rather than an exogenous variable. As shown in [20], population influx may accelerate or decelerate depending on residential development patterns and associated consequences for environmental and urban amenities. Finally, the developed deterministic approach is likely to result in biased outcomes as uncertainty in marine benefits from GBR conservation are not taken into account. Accounting for this uncertainty would lead to lower welfare maximizing populations, provided that downstream effects and associated costs from population growth induced water pollution are taken into account [8].

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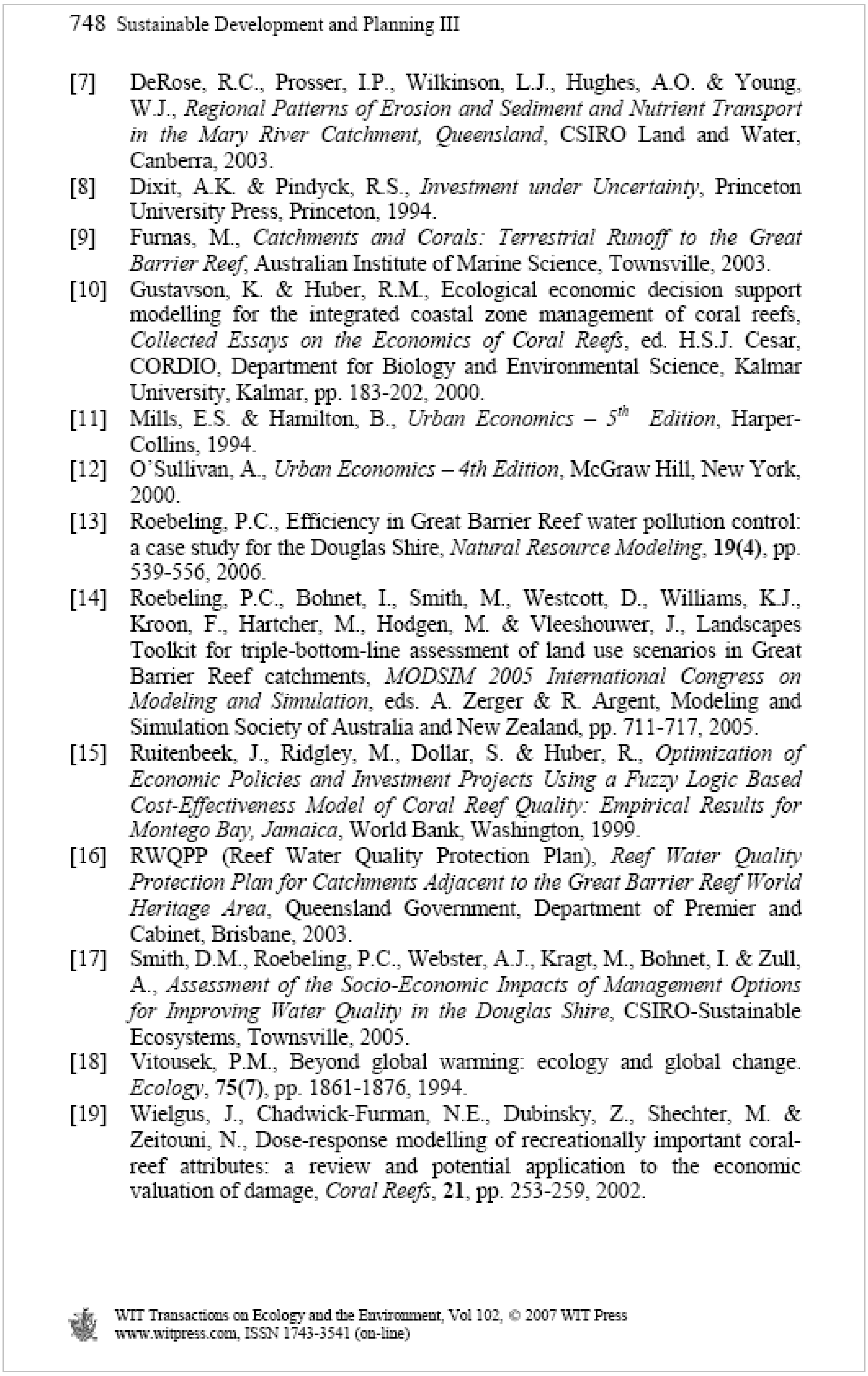

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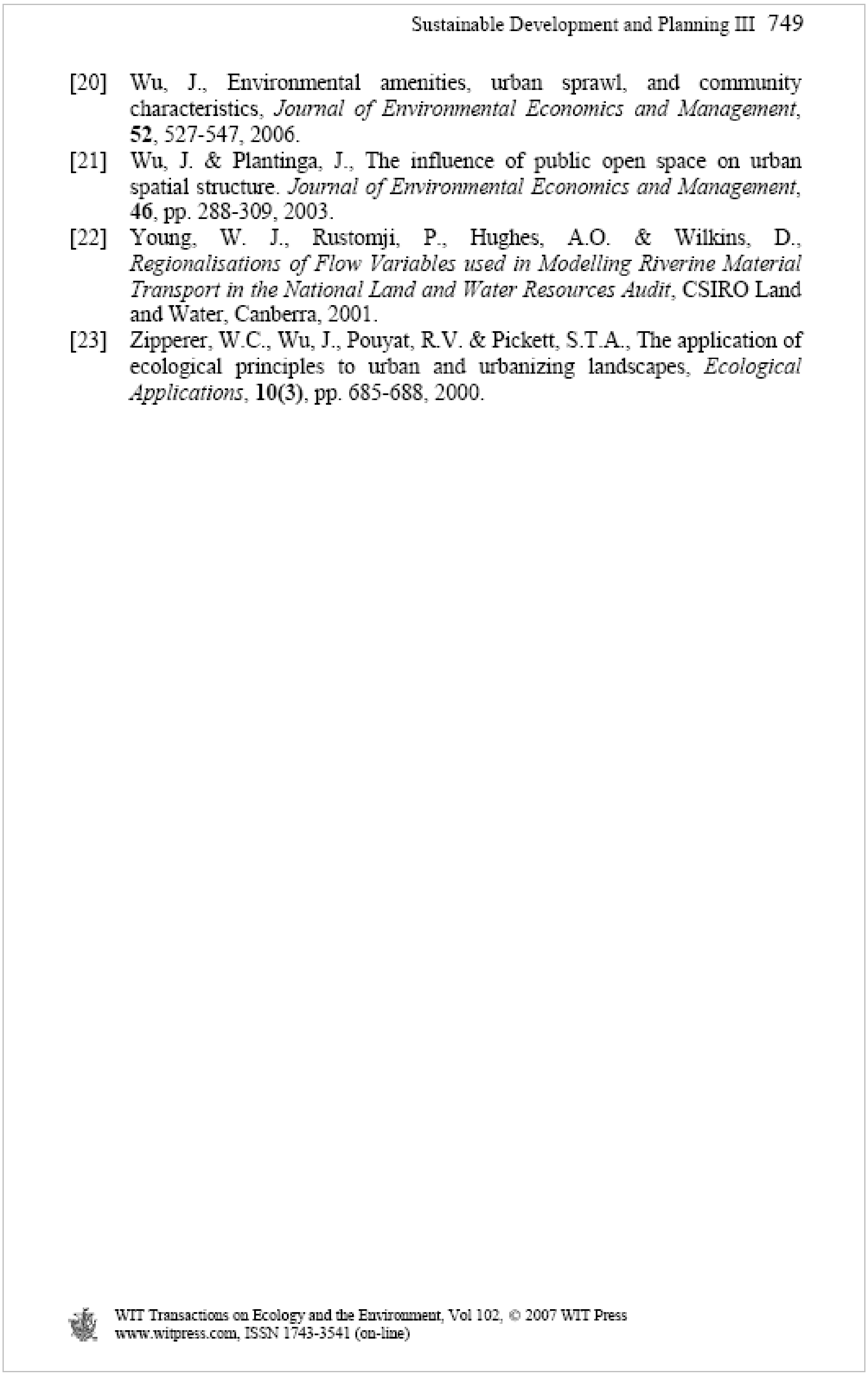

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