Agriculture, Ecosystems and Environment xxx (2011) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

An analysis of trade-offs between multiple ecosystem services and stakeholders linked to land use and water quality management in the Great Barrier Reef, Australia

James R.A. Butler[a,*], Grace Y. Wong[b], Daniel J. Metcalfe[c], Miroslav Honzák[b], Petina L. Pert[c], Nalini Rao[b], Martijn E. van Grieken[d], Tina Lawson[c], Caroline Bruce[c], Frederieke J. Kroon[c], Jon E. Brodie[e]

[a] CSIRO Ecosystem Sciences and Climate Adaptation Flagship, EcoSciences Precinct, GPO Box 2583, Brisbane, Qld 4001, Australia
[b] Conservation International, 2011 Crystal Drive, Suite 500, Arlington, VA 22202, USA
[c] CSIRO Ecosystem Sciences and Water for a Healthy Country Flagship, PO Box 780, Atherton, Qld 4883, Australia
[d] CSIRO Ecosystem Sciences and Water for a Healthy Country Flagship, EcoSciences Precinct, GPO Box 2583, Brisbane, Qld 4001, Australia
[e] Australian Centre for Tropical Freshwater Research, James Cook University, Townsville, Qld 4814, Australia

ARTICLE INFO

Article history:
Received 10 April 2011
Received in revised form 17 August 2011
Accepted 29 August 2011
Available online xxx

Keywords:
Biodiversity
Coral reef
Ecosystem services
Governance
Resilience
Scale mis-matches
Riparian vegetation
Social–ecological systems
Thresholds
Wetlands

ABSTRACT

The Great Barrier Reef (GBR), Australia, is threatened by declining water quality largely derived from agricultural run-off. Water quality planning aims to mitigate pollutant run-off through land management, including riparian and wetland restoration, but no tools exist to assess trade-offs in land use change across the catchment-to-reef continuum. We adapted the Millennium Ecosystem Assessment framework in the GBR's Tully–Murray catchment to identify trade-offs between linked ecosystem services and stakeholders. Applying four land use scenarios we assessed outcomes for the ecosystem service of water quality regulation, and trade-offs with six floodplain services and four GBR services. Based on statistical correlations between ecosystem services' status under the scenarios, we identified trade-offs and thresholds between services and associated stakeholders. The most direct trade-off in floodplain services (and primary stakeholders) was food and fibre production (farmers) versus water quality regulation (community, GBR tourists, tour operators and fishermen). There were synergies between water quality regulation (community, GBR tourists, tour operators and fishermen) and floodplain recreational and commercial fisheries (fishermen). Scale mis-matches between water quality management structures and ecosystem service flows were also evident. We discuss the strengths and weaknesses of this ecosystem services approach, and its potential application in the GBR and other catchment-to-reef social–ecological systems.

1. Introduction

Ecosystem services are the benefits that people obtain from functioning ecosystems (Millennium Ecosystem Assessment, 2005). The identification of ecosystem services, their values and beneficiaries to inform trade-offs in natural resource management is an evolving field of research (Costanza et al., 1997; Daily et al., 2000; De Groot et al., 2002, 2010; Goldman et al., 2008; TEEB, 2009; Maes et al., 2011), and plays a central role in the design of sustainable agro-ecosystems (IAASTD, 2009; Brussard et al., 2010; Sachs et al., 2010). The Millennium Ecosystem Assessment (MA) aimed to provide policy-makers with scientific information on the consequences of ecosystem modification for ecosystem services and human well-being (MA, 2005). However, many research needs have since been highlighted, including techniques to measure the status of linked ecosystem services, and trade-offs in benefit flows to stakeholders across spatial and temporal scales (Carpenter et al., 2006, 2009; Hein et al., 2006; Rodriguez et al., 2006; Tallis et al., 2008; De Groot et al., 2010; Ring et al., 2010; Silvestri and Kershaw, 2010).

'Regulating' ecosystem services are defined by the MA (2005) as benefits obtained from the regulation of ecosystem processes. Of these, hydrological services provide particular challenges for trade-off analysis (Brauman et al., 2007). For example, water quality regulation is provided by vegetation type and extent in a catchment, but the effects of land use change on vegetation are largely evident downstream from the point of impact. Similarly, there is likely to be a time lag between changes in land use and subsequent downstream costs and benefits (Pattanayak, 2004). The supply of water quality regulation services by vegetation may also result in the coincidental delivery of other services, such as habitat

* Corresponding author. Tel.: +61 7 3833 5734; fax: +61 2 6776 1333.
E-mail address: james.butler@csiro.au (J.R.A. Butler).

0167-8809/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.agee.2011.08.017

supporting biodiversity or fisheries (Brauman et al., 2007), requiring the assessment of trade-offs between multiple services (Turner et al., 2003; Pattanayak and Wendland, 2007), and thresholds where the provision of services may radically alter due to changes in ecosystem function (Walker et al., 2009). Furthermore, stakeholders benefitting from these services will include private and public interests, potentially creating 'asymmetrical' trade-offs at various spatial scales (Turner et al., 2003; Carpenter et al., 2006, 2009).

In spite of imperfect scientific data and understanding, it is important to tackle these methodological challenges by conducting integrated assessments in real-world contexts at scales relevant for managers and policy-makers (Carpenter et al., 2006, 2009; Chan et al., 2006; Smajgl et al., 2011). Coral reefs provide an opportunity for this, since they are increasingly impacted by anthropogenic activities on land which degrade water quality in catchments, and subsequently in coastal receiving waters (Bellwood et al., 2004; Silvestri and Kershaw, 2010). Such interfaces between terrestrial and marine ecosystems create considerable complexity due to the wide range of associated stakeholders and their values, necessitating innovative cross-scale governance and policy structures (Armitage et al., 2009; Silvestri and Kershaw, 2010).

The ecological health of the Great Barrier Reef (GBR) World Heritage Area in Queensland, Australia, is threatened by diffuse pollution from agriculture, delivered by catchments that discharge into the GBR lagoon (Brodie et al., 2008). Since European settlement in the 1860s loads of suspended sediments, nitrogen and phosphorus have increased by factors of 5, 2–5 and 2–10, respectively (Furnas, 2003; Brodie et al., 2008). Impacts of nutrient and sediment on GBR biodiversity include changes in coral and fish species composition (Fabricius et al., 2005), dominance of macro-algal cover (Jupiter et al., 2008) and crown-of-thorns starfish (*Acanthaster planci*) population outbreaks caused by nutrient enrichment (Brodie et al., 2005; Fabricius et al., 2010). In-shore reefs are worst affected, and poor reef condition is correlated with poor water quality (Fabricius, 2005; Fabricius et al., 2005; Devantier et al., 2006; Wooldridge et al., 2006; De'ath and Fabricius, 2010; Brodie et al., 2011). In addition, stress from water quality decline may reduce the resilience of GBR coral ecosystems to climate change pressures such as rising sea temperatures and acidification (Wooldridge, 2009; Wooldridge and Done, 2009). However, there remain large gaps in the understanding of causal relationships between catchment water quality and GBR ecosystem health, complicated by lag times in hydrological processes (Brodie et al., 2008, 2009, 2011).

To address these threats the Australian and Queensland governments jointly implemented a Reef Water Quality Protection Plan in 2003, which promoted the development and implementation of Water Quality Improvement Plans (WQIPs) for coastal catchments (Anonymous, 2003). Through a participatory process involving catchment stakeholders, WQIPs identified critical water quality issues, estimated current and sustainable target loads for pollutants, and described the land management actions needed to achieve those targets (Brodie et al., 2009; Kroon et al., 2009). One action is re-vegetation of riparian habitat and wetlands to restore floodplain functions and mitigate nutrient and sediment run-off from agriculture (Kroon, 2008). To support WQIPs various approaches to analysing trade-offs between land management and water quality within catchments have been developed, including cost-benefits of agricultural best management practices (Roebeling et al., 2007, 2009), community-visioned alternative landscapes (Bohnet et al., 2008) and participatory analysis of community values of water (Bohnet and Kinjun, 2009; Gooch et al., in press).

However, while it is recognised that GBR catchments and reefs are linked social–ecological systems (Gordon, 2007; Gordon and Nelson, 2007), WQIPs have not assessed multiple trade-offs across the catchment-to-reef continuum resulting from land and water quality management. In this paper we present a study of the Tully–Murray catchment in the Wet Tropics of the GBR, where we adapted the MA ecosystem services framework to assess trade-offs in the floodplain and GBR resulting from land use and water quality change, cross-scale flows in ecosystem service benefits and implications for water quality management. Through this illustrative case study we explore the potential strengths and weaknesses of the ecosystem services approach, and research required to further develop this as a land use and water quality planning tool in the GBR and similar catchment-to-reef systems.

2. Study area and methods

2.1. GBR and Tully–Murray catchment

The GBR World Heritage Area covers 348,000 km^2 along Australia's tropical north-east coast (Fig. 1), and generates ecosystem services for local, national and international beneficiaries (Stoeckl et al., 2011). Most services have not been valued (Stoeckl et al., 2011), but Access Economics (2007) has estimated that the GBR generates AU$6 billion per year from tourism, $623 million per year from recreational fisheries, and $251 million per year from commercial fisheries, and supports 66,000 full-time equivalent jobs.

The greatest threat of diffuse pollution to the GBR exists in the Wet Tropics bioregion (Fig. 1), where dissolved inorganic nitrogen (DIN) in surface and groundwater is derived from fertilisers applied in sugarcane and banana production (Brodie, 2007). Pesticide pollution is a growing threat to reef health (Schaffelke et al., 2005; Brodie et al., 2008; Lewis et al., 2009), and sediment run-off is also of concern (Bainbridge et al., 2009; Mitchell et al., 2009). Reefs in the Wet Tropics have greatly reduced coral biodiversity associated with these water quality impacts (Devantier et al., 2006).

The Tully–Murray catchment is located in the Wet Tropics (Fig. 1) and has an area of 2787 km^2, and average annual rainfall of 2000–4000 mm, mostly falling in the December–April wet season. The primary land cover in the catchment is native tropical rainforest, covering 57%. Most of this occurs on the escarpment slopes, and is protected by the Wet Tropics World Heritage Area (Figs. 1 and 2). Since European settlement 80% of native vegetation, 60% of riparian habitat and 69% of wetlands have been cleared from the floodplain for agricultural production (Furnas, 2003), which is dominated today by sugarcane and bananas (McDonald and Weston, 2004). In the 1990s crop production doubled, resulting in a 118% increase in nitrogen fertiliser use (Mitchell et al., 2001; Brodie et al., 2001). Consequently, the Tully–Murray catchment was identified as a priority for the development of a WQIP, which was completed in 2008.

The Tully WQIP focussed on reducing DIN run-off by applying agricultural best management practices (e.g. zero tillage, split fertiliser applications) and the restoration of riparian vegetation and wetlands (Kroon, 2008; Kroon et al., 2009). Riparian vegetation removes nitrate from groundwater (McKergow et al., 2004a,b; Hunter et al., 2006; Hunter and Walton, 2008; Rassam et al., 2008), and in the Tully–Murray catchment Rassam and Pagendam (2007, 2009) identified 286 km of floodplain riverbank where re-vegetation was likely to have the greatest de-nitrification impact. Armour et al. (2007) identified a further 124 km of degraded stream banks requiring re-vegetation to control erosion. Wetlands are also important for maintaining floodplain filter functions (Wallace et al., 2008), and in the Tully–Murray they may regulate dissolved organic nitrogen (DON) run-off, which is largely flushed by overbank flows during floods (Wallace et al., 2009).

Floodplain clearing has also resulted in significant losses of terrestrial biodiversity. Many lowland floral and faunal communities occur in tiny percentages of their former extent, and some are extinct, reducing ecosystem connectivity (QPWS, 2001;

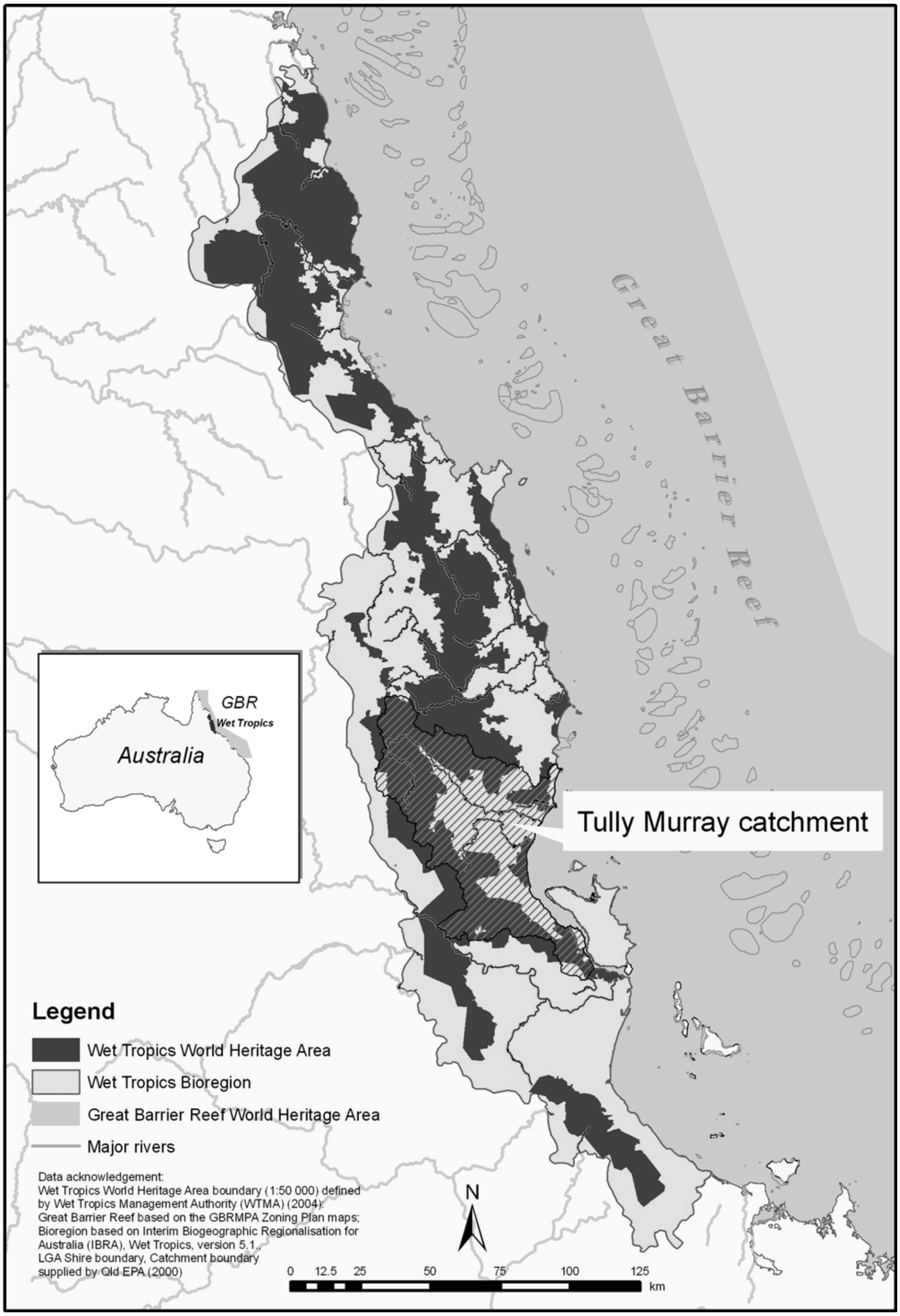

Fig. 1. The Wet Tropics bioregion, Tully–Murray catchment and Great Barrier Reef (GBR) in north-east Australia.

Metcalfe and Ford, 2008; DEWHA, 2009). Floodplain wetlands in the Wet Tropics also provide habitat for important aquatic biodiversity (Pearson and Stork, 2008). Seventy-nine fish species in the Tully–Murray floodplain use both freshwater and marine habitats (Hogan, 2000). Amongst these the barramundi (*Lates calcarifer*), a highly valued commercial and recreational fishery species, is particularly dependent on freshwater wetlands as nursery habitat (Veitch and Sawynok, 2004; Bayliss and Bartolo, 2008). Declining riparian vegetation extent and condition, prolonged periods of high sediment loads and low levels of dissolved oxygen resulting from nutrient enrichment can disrupt freshwater aquatic biodiversity assemblages (Pearson and Connolly, 2000). Clearance of riparian vegetation also allows sunlight to promote the growth of invasive aquatic weeds which restrict flows, promoting anoxic conditions (Bunn et al., 1998). These processes are likely to have depleted aquatic biodiversity throughout the Wet Tropics, including the Tully–Murray catchment (Pearson and Stork, 2008).

The impact of pollutants from the Tully–Murray catchment on the adjacent GBR is dependent on the extent of wet season flood plumes (Devlin and Schaffelke, 2009). These are influenced by wind direction, and frequently mix with plumes from neighbouring rivers (Devlin and Brodie, 2005; Maughan and Brodie, 2009). Analysis of Tully–Murray floods has identified primary, secondary and tertiary plume types, with declining dissolved organic matter

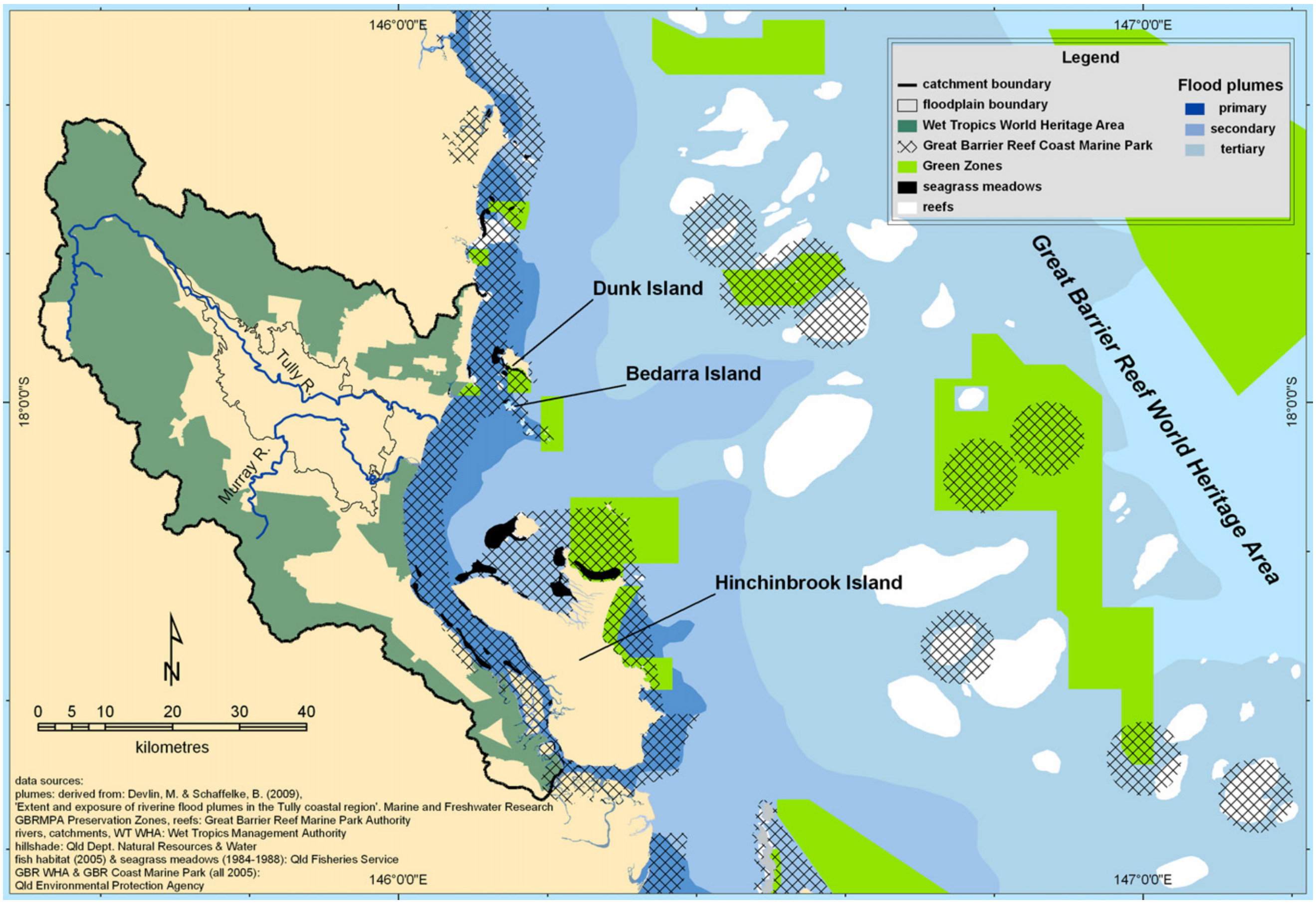

Fig. 2. The primary, secondary and tertiary flood plume extents recorded from the Tully–Murray catchment in 2008 (re-drawn from Devlin and Schaffelke, 2009), relative to coastal and marine ecosystems and Australian and Queensland government designations. Also shown is the floodplain study area.

and sediment concentration for each (Devlin and Schaffelke, 2009; Fig. 2). Within the primary and secondary plumes there are 37 coral reefs and 14 seagrass meadows (Devlin and Schaffelke, 2009). Dunk, Bedarra and Hinchinbrook Islands and their surrounding reefs are popular tourist destinations. The area generated an annual tourist expenditure of $10.6 million in 2006, and coastal commercial fisheries earnings of $3 million in 2005 (OESR, 2007). There are no data available on recreational angler effort or catches. Australian and Queensland government designations protecting these ecosystems include the GBR Marine Park, the GBR Coast Marine Park and within it Green Zones, areas of high biodiversity value where resource exploitation is prohibited (Fig. 2).

Cause–effect relationships between flood plume hydrochemistry, reef health, fisheries production and the economic utility of tourists and fishermen have not been fully quantified. In the GBR's Port Douglas region, Kragt et al. (2006) estimated a 59% decline in tourists given a hypothetical 80% decline in coral cover, 30% decline in coral diversity and 70% decline in fish species, but it is not known what pollutant levels would result in this level of reef degradation. Prayaga et al. (2010) estimated in the GBR's Capricorn Coast region that hypothetical increases and decreases in recreational anglers' catches of 25% resulted in minor changes in their visit rates and the value of the fishery, but the condition of the reef that would yield such changes in catches is not known.

2.2. Millennium Ecosystem Assessment framework

The MA (2005) provides a framework for the global and regional identification of ecosystem services, their status and trends, and potential future scenarios and resulting trade-offs in ecosystem services and human well-being. We adapted this framework for the analysis of potential trade-offs in water quality regulation and related ecosystem services in the Tully–Murray floodplain and the adjacent GBR. We categorised ecosystem services using the MA definitions of 'regulating', 'provisioning' (products obtained from ecosystems), and 'cultural' (non-material benefits obtained from ecosystems).

2.3. Ecosystem functions and services

We focussed our study on the Tully–Murray floodplain (as delineated by the Queensland Government (EPA, 2005a)), and Devlin and Schaffelke's (2009) primary, secondary and tertiary flood plumes in the adjacent GBR (Fig. 2). Based on the current scientific understanding of the linkages between terrestrial and hydrological ecosystem functions in this area, we constructed a simplified framework to assess related ecosystem services (Table 1). The fundamental linkages were as follows. Anthropogenic intervention in land use modifies primary production on the floodplain, providing the service of food and fibre production. Land use also alters floodplain vegetation and ecological function, and governs agricultural inputs such as fertiliser, determining the service of water quality regulation. This service then influences flood plume hydrochemistry, which in turn influences GBR ecology, which provides the recognised ecosystem services of tourism, commercial and recreational fisheries (Table 1).

We also assessed five other services related to floodplain function which would be affected by these linkages (Table 1). The

Table 1
Ecosystem functions and services identified in the Tully–Murray floodplain and adjacent GBR which are linked by water quality regulation. Indicators of ecosystem service status and their units are also shown.

Human intervention	Ecosystem function	Ecosystem services	Ecosystem service category	Ecosystem service status indicator	Indicator units
FLOODPLAIN					
Land use	*Primary production*	Food and fibre production	Provisioning	Agricultural revenue	AUS $ million per year
	Floodplain function	Water quality regulation	Regulating	Total N	tonnes per year
		Recreational fisheries	Cultural	Wetland area	ha
		Commercial fisheries	Provisioning	Wetland area	ha
		Biodiversity	Cultural	Terrestrial/aquatic biodiversity index	1-5
		Agricultural pest regulation	Regulating	Riparian habitat area	ha
		Pollination	Regulating	Terrestrial biodiversity index	1-5
GBR	*Flood plume hydro-chemistry*				
	GBR ecology	Reef tourism	Cultural		Increase/decrease
		Recreational fisheries	Cultural		Increase/decrease
		Commercial fisheries	Provisioning		Increase/decrease
		GBR cultural benefits	Cultural		Increase/decrease

cultural benefits of biodiversity, commercial and recreational freshwater fisheries were identified by Bohnet and Kinjun's (2009) survey of the Tully–Murray community's environmental values of waterways. Drinking water for people and livestock from surface and groundwater was also highlighted to be of importance by Bohnet and Kinjun. However, the relationship between land use and drinking water quality, and the number of household water supplies dependent on waterways is not known (Kroon, 2008), and hence we omitted this service. Swimming and white water rafting were also identified by Bohnet and Kinjun, but occur outside the floodplain study area. Abstraction for agricultural irrigation and processing also occur, but do not depend on water quality and so were also omitted.

Brauman et al. (2007) identified pollination as an important ecosystem service provided by terrestrial biodiversity in riparian habitat, and there is evidence from the Wet Tropics that proximity to rainforest enhances the pollination of fruit crops (Blanche and Cunningham, 2005; Blanche et al., 2006). Given the importance of horticulture in the catchment we added this. We also included the service of agricultural pest regulation, since 80–100% reductions in rodent damage have been recorded in sugar cane adjacent to restored riparian zones, which provide refuge for predators of rodents (N. Tucker, *pers. comm.*). Similar results were found by Ward et al. (2003) for Australian fruit crops. In addition to the three GBR services we added the cultural benefits of the GBR adjacent to the Tully–Murray catchment, which were also identified as being of value to the local community by Bohnet and Kinjun (2009) (Table 1).

2.4. *Trade-off analysis*

To assess future trade-offs between ecosystem services, potential development scenarios are used to estimate relative changes in ecosystem services (e.g. Rodriguez et al., 2006; Tallis et al., 2008; Bohensky et al., 2011; Costanza et al., in press). We applied the same approach with a three-stage analysis, outlined below. Stage 1 developed plausible land use scenarios for the Tully–Murray floodplain. Stage 2 measured the status of floodplain ecosystem services for each scenario, and Stage 3 estimated the resulting trend in GBR ecosystem services.

2.4.1. *Stage 1: Land use scenario development*

Using a Geographical Information System (ESRI ArcGIS9.2) we constructed four land use scenarios along a continuum of agricultural production ranging from intensive with minimal native vegetation (Scenario 1) to extensive with native habitat restoration (Scenario 4) (Figs. 3–6). For each we measured areas (ha) of production systems and wetlands. Following Pert et al.'s (2010a) methodology, riparian vegetation was mapped by applying sugar industry guidelines (Lovett and Price, 2001) for buffer widths according to stream order: 1 and 2 were assigned 50 m, 3 and 4 were assigned 100 m, and 5 and 6 were assigned 200 m.

Scenario 1: No Vegetation Management Act: In 1999 the Queensland Government introduced the Vegetation Management Act which controls the clearance of native vegetation outside protected areas. To represent land use that could have eventuated in the floodplain without the introduction of the Act we:

- removed all 2007 native riparian vegetation and forest fragments;
- reversed all 2007 riparian re-vegetation that had occurred since 1999;
- converted all 2007 plantation forestry to grazing;
- applied protected area boundaries from 2000.

Scenario 2: Present Day: This was based on the following 2007 data layers

- the extent of all native riparian, remnant vegetation, re-vegetation and wetlands;
- existing agricultural land use;
- existing protected area boundaries.

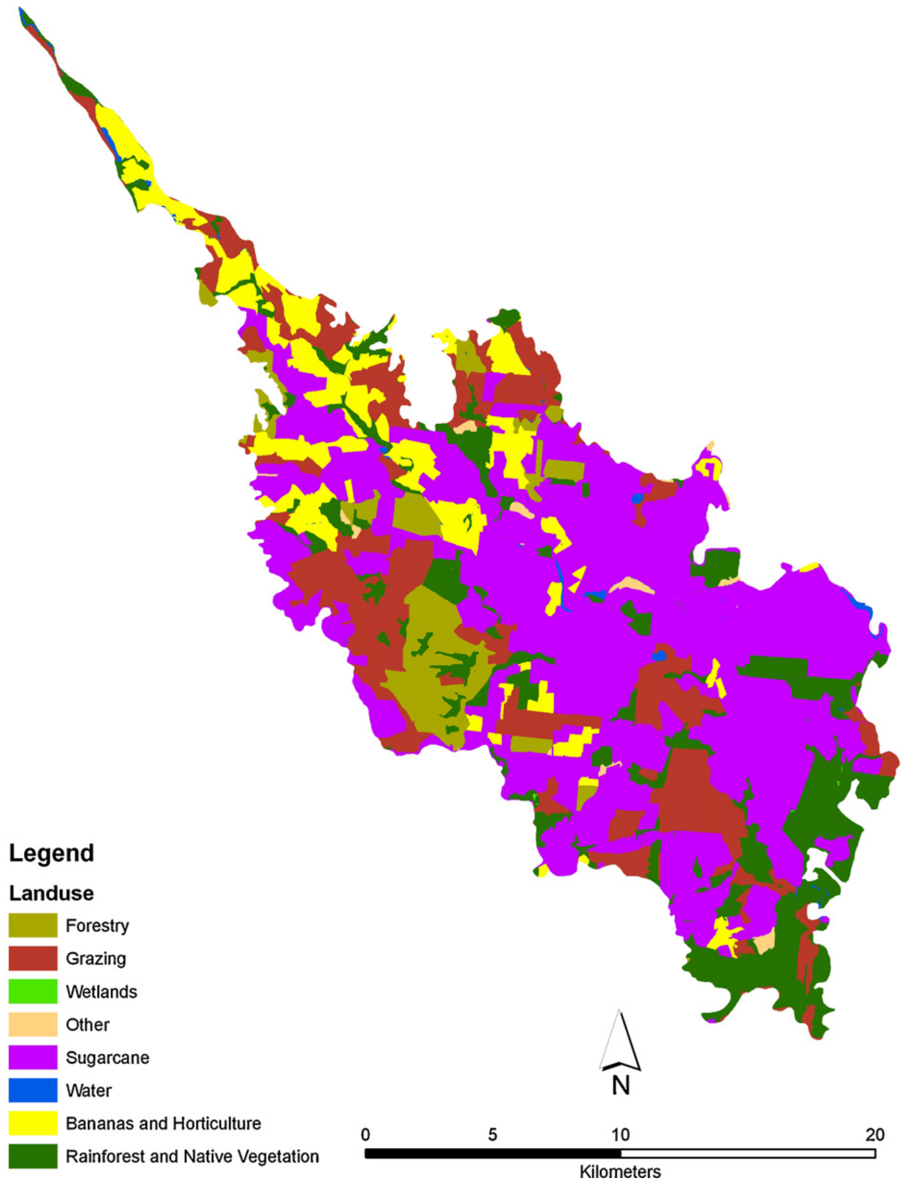

Fig. 3. Land use in the Tully–Murray catchment for Scenario 1: No Vegetation Management Act.

Scenario 3: De-nitrification and Sediment Priorities: Using the areas of riparian re-vegetation identified by Rassam and Pagendam (2007, 2009) and Armour et al. (2007) in the Tully WQIP as priorities for de-nitrification and erosion control, we:

- maintained 2007 protected areas, re-vegetation and agricultural land use;
- substituted crops or grazing with riparian vegetation in the Tully WQIP's priority areas;
- restored wetlands according to the Queensland Wetland Data Version 1.2 (EPA, 2005b)

Scenario 4: Native Forestry: Since 2000 areas of sugarcane in the Tully–Murray catchment have been converted into plantation forestry using native timber species. This scenario assumed that all current agricultural production was replaced with forestry using native timber, in conjunction with reinstatement of wetland and riparian vegetation. We:

- substituted 2007 sugarcane, banana and grazing with forestry;
- converted all forestry within protected areas and all re-growth to native vegetation;
- restored wetland habitat to pre-European extents;
- maintained riparian vegetation as for the De-nitrification and Sediment Priorities scenario;
- maintained protected areas with 2007 boundaries.

2.4.2. Stage 2: status of floodplain ecosystem services

Based on available scientific knowledge we developed status indicators for each floodplain ecosystem service to measure changes in services resulting from the scenarios (Table 1). Where data allowed we developed indicators of ecosystem service flows (the benefits people receive from services, as defined by Layke (2009); e.g. tonnes per year), but where it was impossible we used indicators of ecosystem service stocks (the capacity of an ecosystem to provide a service; e.g. area of habitat). Indicator development methodology and assumptions were as follows:

- Food and fibre production: Because it was not feasible to combine quantities of different agricultural commodities into one

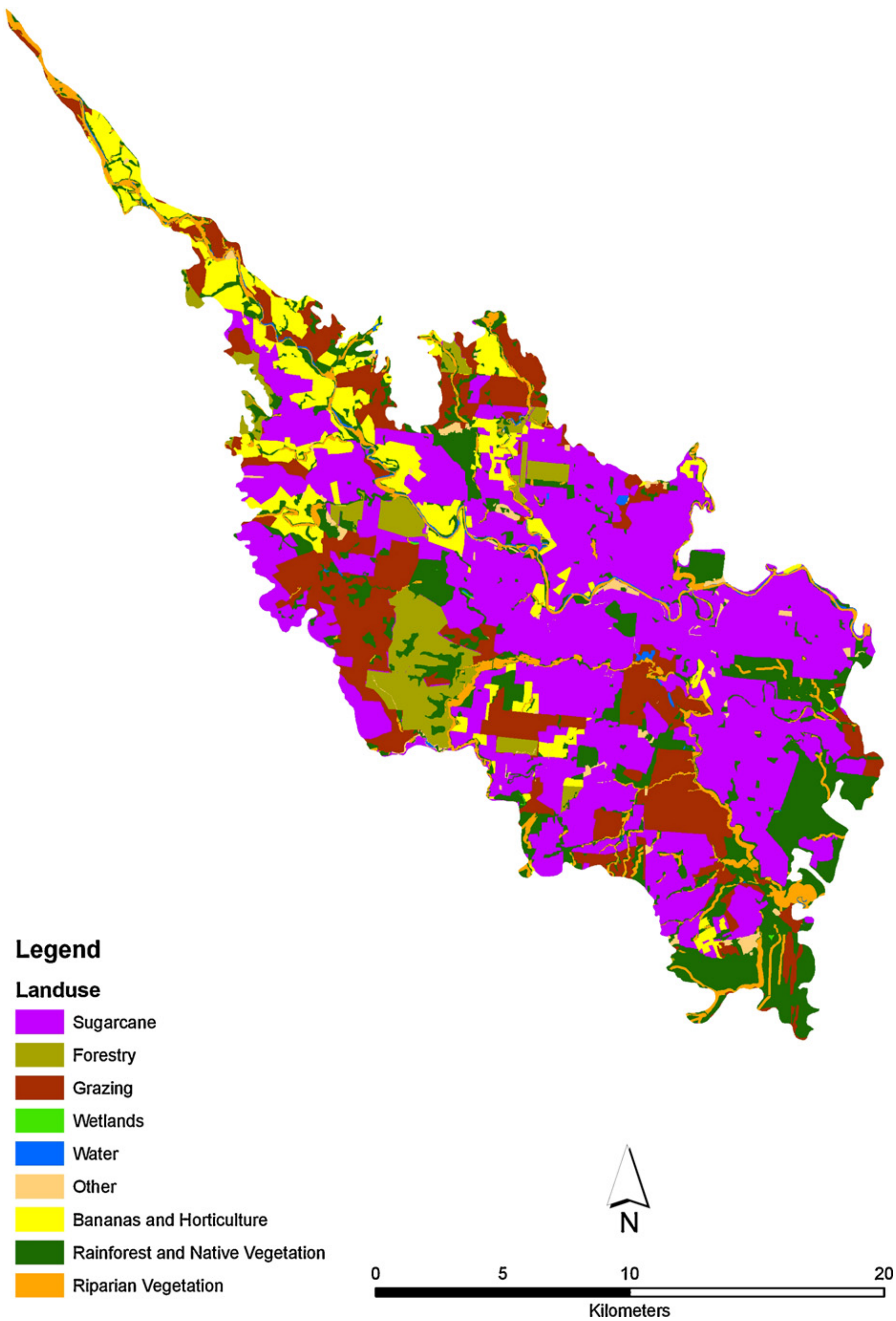

Fig. 4. Land use in the Tully–Murray catchment for Scenario 2: Present Day.

indicator of food and fibre production, we selected total agricultural revenues ($ million per year) from all production systems as a standardised measure. Following Roebeling et al.'s (2007) methodology, revenues for each primary production system in the catchment (sugarcane, banana, forestry and cattle grazing) were estimated by calculating gross margins at the 1 ha scale to account for differences in soil type. These were multiplied by the area (ha) of each production system to give total revenue, and these totals were then summed. Gross margins were defined as the total production value (based on final products) less corresponding production, transport and processing costs, assuming constant 2005 input prices and average 2003–2005 product prices. We assumed that the standard management practices (i.e. soil tillage, fertiliser application and stocking rates) recorded by Roebeling et al. (2007) for each production system were applied in all scenarios.

- Water quality regulation: Total nitrogen (N, combining DIN and DON), was the primary pollutant identified by the Tully WQIP. Hence we used total N (tonnes per year) as an inverse indicator of water quality regulation. To calculate changes in annual delivery of total N for each scenario, we applied the Nonpoint-Source Pollution and Erosion Comparison Tool (N-SPECT), version 1.5.0 (Eslinger et al., 2005). The model was run separately for each scenario using Armour et al.'s (2007, 2009) hydrological input data for the catchment, including modified K and C factors. Following Jeffrey et al. (2001) and Brodie et al. (2003), model runs used average annual rainfall data derived from daily rainfall data in 1980–1999.

Run-off in N-SPECT is estimated with a methodology that applies empirically derived curve numbers (USDA-NRCS, 1986) that are related to the NOAA Coastal Change Analysis Program (C-CAP) land cover classification scheme (NOAA, 2009). N-SPECT

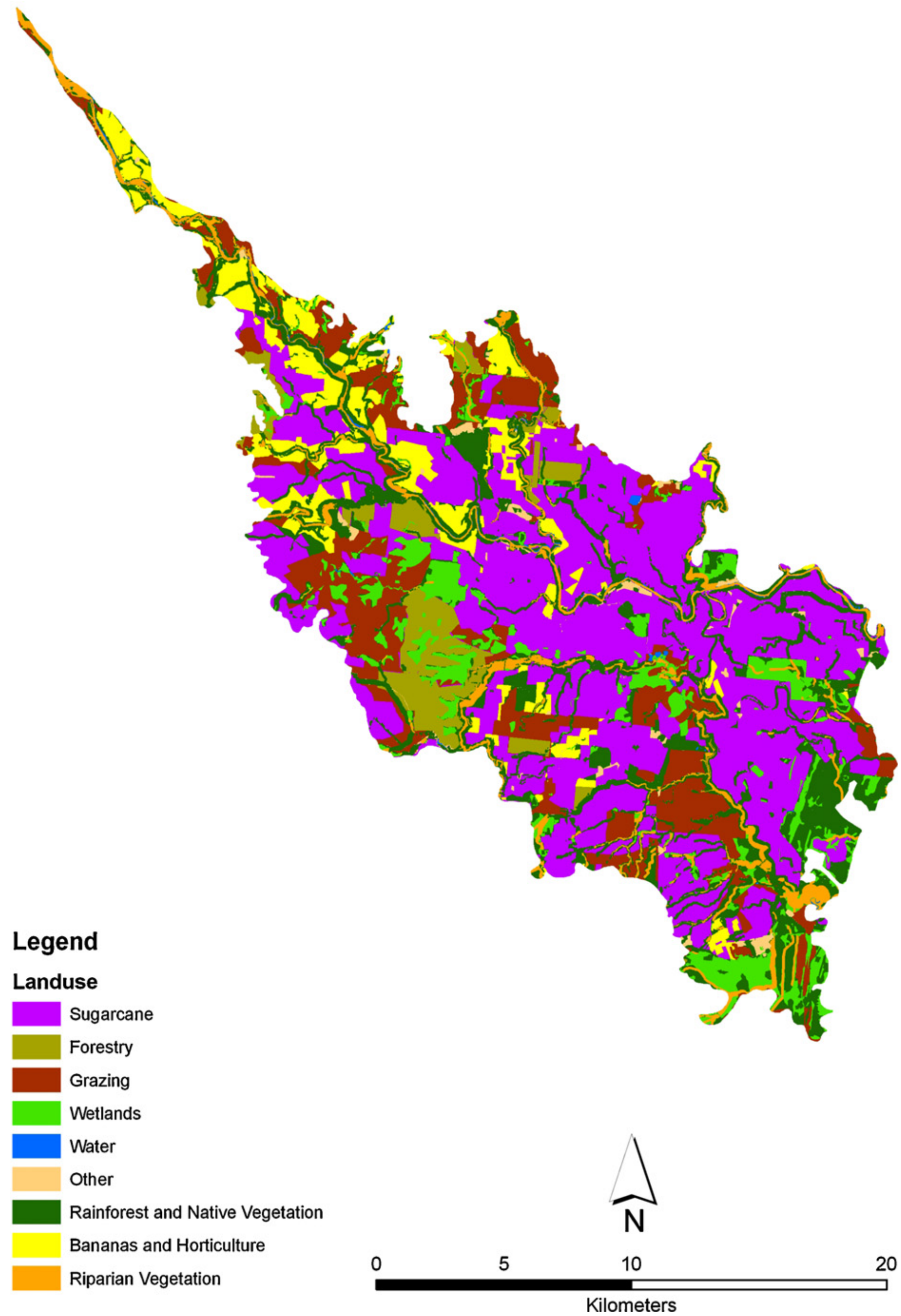

Fig. 5. Land use in the Tully–Murray catchment for Scenario 3: De-nitrification and Sediment Priorities.

estimates pollutant export coefficients from each land use class in a catchment, developed using water quality sampling data for the Wai'anae region in Hawaii (Eslinger et al., 2005). To derive run-off and pollutant loads we matched land cover classes occurring in the Tully–Murray catchment with the C-CAP classification scheme. Potential de-nitrification of DIN and DON in surface and groundwater by riparian vegetation and wetlands was not included in the model, since there is currently insufficient scientific understanding of the hydro-chemical relationships concerned (P. Nelson, *pers. comm.*).

- Recreational and commercial fisheries: Because wetlands are important for the annual production of barramundi (Bayliss and Bartolo, 2008) and many other fish species (Veitch and Sawynok, 2004) we assumed that wetland area (ha) was a surrogate indicator for floodplain fisheries production, and hence the status of recreational and commercial fisheries.
- Biodiversity: Although data on biodiversity patterns and condition exist for the Wet Tropics (e.g. for vegetation extent and condition (Stanton and Stanton, 2005), fauna (Williams, 2006), rare and threatened species (Metcalfe and Ford, 2008) and ecosystem function (Laliberté et al., 2009)), they are not easily synthesised for catchment-scale analysis. Instead, we developed a qualitative index for biodiversity condition based on expert opinion informed by these data. For terrestrial biodiversity we applied the four indicators developed for state of the environment reporting in the Wet Tropics (Pert et al., 2010b): native vegetation extent, native vegetation condition, rare and threatened species abundance and terrestrial fauna abundance. For aquatic biodiversity we used one indicator, aquatic habitat condition. We presented maps of each scenario (Figs. 3–6) to nine Wet Tropics ecologists (including two authors, DJM and FJK) who ranked each indicator on a scale of 1 (poor) to 5 (good). We averaged the scores

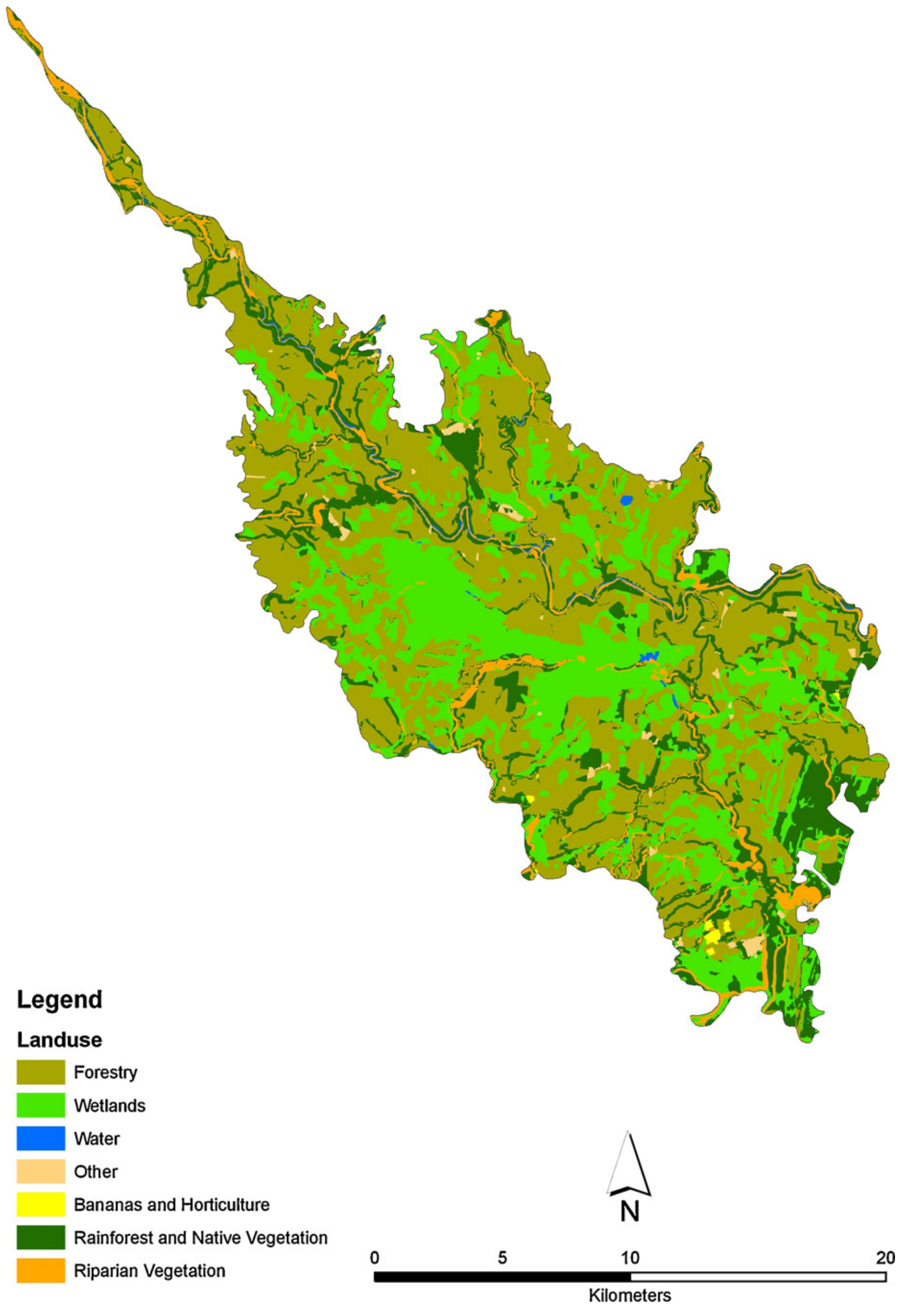

Fig. 6. Land use in the Tully–Murray catchment for Scenario 4: Native Forestry.

for each indicator, and then the five means were averaged again to provide a composite biodiversity condition score.

- Agricultural pest regulation: Following Ward et al. (2003) and Tucker's (*pers. comm.*) studies of the positive correlation between riparian habitat and pest control in crops, we used the area of riparian habitat as the indicator for this service.
- Pollination: We assumed that the status of this service was related to terrestrial biodiversity condition, and therefore used the composite average score of the four terrestrial biodiversity indicators described above.

To assess the relative status of ecosystem services for each scenario we plotted the indicators' values on radial diagrams (after Rodriguez et al., 2006; Tallis et al., 2008; Carpenter et al., 2009). For each indicator we set the maximum recorded value amongst all scenarios at 100%, and plotted other values as a percentage of this value. Because total N was an inverse indicator for water quality regulation, we reversed the scaling so that the maximum total N value became zero, and the minimum value 100%. For each scenario we assumed an equal weighting for all services, and averaged their values to give an overall status (%). To assess relationships between individual ecosystem services' status amongst the four scenarios we calculated paired Pearson's correlation coefficients (r).

2.4.3. Stage 3: Trends of marine GBR ecosystem services

Given the limited understanding of causal and temporal relationships between flood plume hydro-chemistry and GBR health (Brodie et al., 2008, 2009, 2011), and knock-on effects on the services of reef tourism, commercial and recreational fisheries and GBR cultural values, it was impossible to develop indicators of their status. Instead we inferred likely trends in ecosystem services relative to water quality using radial diagrams. The Tully WQIP has

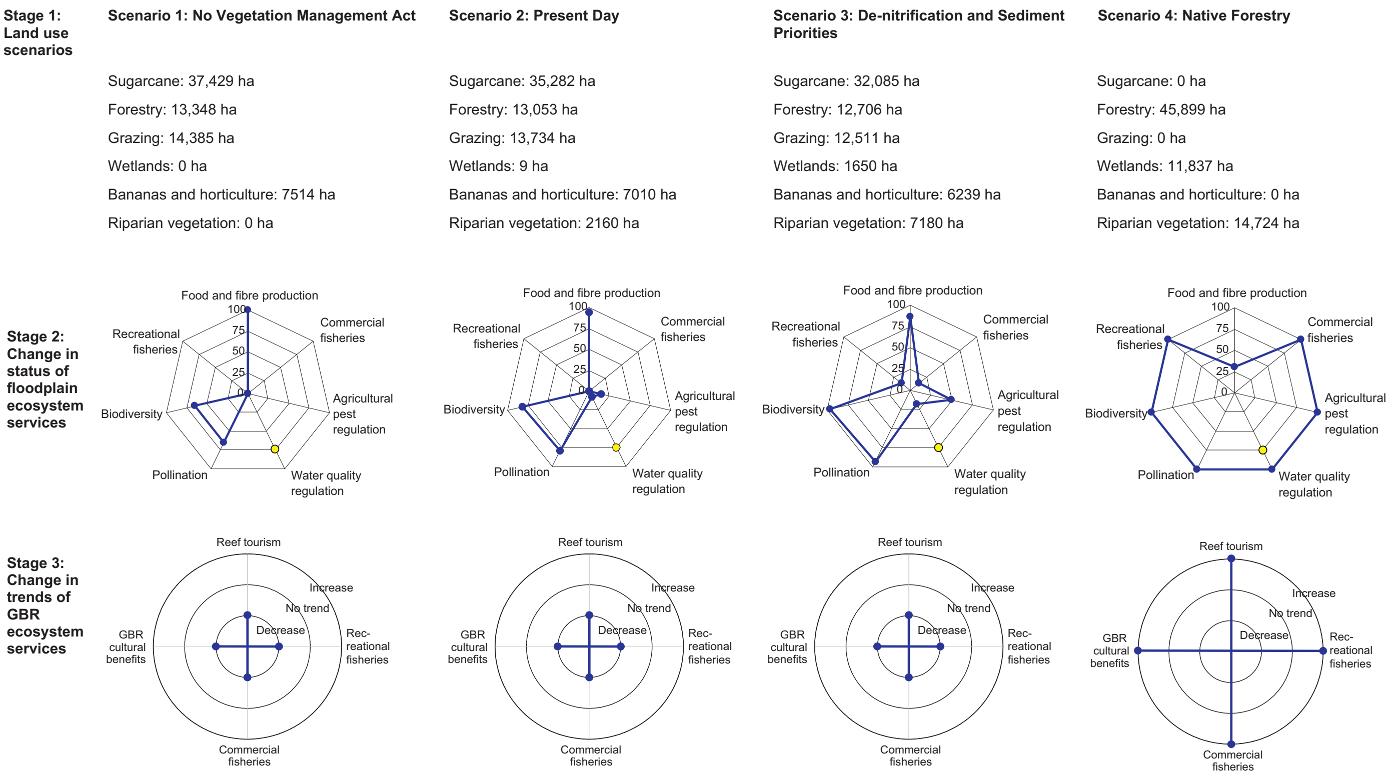

Fig. 7. Results of the three-stage analysis, showing land use scenarios, and resultant changes in floodplain ecosystem service status (%) and trends in GBR ecosystem services. The yellow circle on the water quality regulation axis represents the Tully WQIP pre-European total N threshold of 940 tonnes per year.

identified that pre-European delivery of total N was 940 tonnes per year (Kroon, 2008). Consequently we assumed that total N delivery greater than this threshold would result in a declining trend in the status of these four ecosystem services. Delivery less than this would result in an increasing trend.

2.5. Stakeholder analysis and trade-offs

From the Tully WQIP (Kroon, 2008) and Bohnet and Kinjun (2009) we identified stakeholders linked to ecosystem services in the Tully–Murray catchment and adjacent GBR, and applied Brown et al.'s (2001) framework to categorise them from a local to global scale. We considered the local on-site stakeholders for each service to be the primary stakeholders, defined by De Groot (2006) as those who stand to lose the most from a management decision, and defined them as private or public interests. Based on the correlations between the status of floodplain ecosystem services and trends in GBR services under the scenarios, we identified key trade-offs and synergies between the primary stakeholders.

3. Results

3.1. Land use scenarios, ecosystem services and trade-offs

- Scenario 1: No Vegetation Management Act: This yielded the highest agricultural revenue of $119.99 million per year, and the highest total N output of 1999 tonnes per year, resulting in the maximum status for food and fibre production and lowest for water quality regulation amongst the scenarios. Consequently, the total N threshold was not reached, resulting in decreasing trends of marine GBR services (Fig. 7). Recreational and commercial fisheries production and agricultural pest regulation had zero values, the lowest status amongst the scenarios. Biodiversity and pollination had moderate status. The average status of services was 33%.
- Scenario 2: Present Day: Agricultural revenue decreased to $113.04 million per year, and total N output to 1887 tonnes per year, resulting in a slight decline in food and fibre production and slight increase in water quality regulation. The total N threshold was not reached, resulting in decreasing trends of marine GBR services. Recreational and commercial fisheries production and pest regulation increased, but their status remained low. Biodiversity and pollination increased slightly (Fig. 7). The average status of services was 38%.
- Scenario 3: De-nitrification and Sediment Priorities: Agricultural revenue decreased to $103.6 million per year, and total N output to 1748 tonnes per year, resulting in a further slight decline in food and fibre production and slight increase in water quality regulation. The total N threshold was not reached, resulting in decreasing trends of marine GBR services. Recreational and commercial fisheries production and pest regulation increased but their status was moderate. Biodiversity and pollination increased to near maximum status (Fig. 7). The average status of services was 53%.
- Scenario 4: Native Forestry: Agricultural revenues decreased to $36.77 million per year, resulting in the lowest status of food and fibre production. Total N declined markedly to 596 tonnes per year, giving the highest status of water quality regulation. The total N threshold was reached, resulting in increasing trends of marine GBR services. Recreational and commercial fisheries production, pest regulation, biodiversity and pollination increased to their maximum status (Fig. 7). The average status of services was 91%.

Amongst floodplain ecosystem services, the strongest negative correlation was between food and fibre production and water quality regulation. Other strong negative correlations occurred between food and fibre production and recreational and commercial fisheries, and food and fibre production and agricultural pest regulation. There were strong positive correlations between water quality regulation and recreational and commercial fisheries, biodiversity and pollination (Table 2).

3.2. Stakeholder analysis and trade-offs

The primary stakeholders for floodplain ecosystem services were farmers and fishermen (private) and the community (public). For GBR services they were tourists, tour operators and fishermen (private) and the community (public; Table 3).

There were multiple stakeholders at the local off-site, regional, national and global scale. These included service providers, consumers and the general public, plus organisations such as industry bodies, local council, non-government organisations (NGOs), Terrain Natural Resource Management (NRM), Wet Tropics Management Authority (WTMA), the Great Barrier Reef Marine Park Authority (GBRMPA) and the Australian and Queensland governments (Table 3).

Amongst the primary stakeholders the strongest negative trade-off ($r = -1.00$, $P < 0.001$) was between farmers for food and fibre production and community, GBR tourists, tour operators, commercial and recreational fishermen for water quality regulation and linked GBR services. There were also strong trade-offs between farmers for food and fibre production and recreational and commercial fishermen for

Table 2
Pearson correlation coefficients (r) for paired relationships between the status of floodplain ecosystem services (in bold) for the four scenarios shown in Fig. 7, and linked primary floodplain and GBR stakeholders (in italics).

	Commercial fisheries *Fishermen*	**Agricultural pest regulation** *Farmers*	**Water quality regulation** *Community* *GBR tourists* *GBR tour operators* *GBR fishermen*	**Pollination** *Farmers*	**Biodiversity** *Community*	**Recreational fisheries** *Fishermen*
Food and fibre production *Farmers*	−0.99**	−0.95*	−1.00***	−0.79	−0.73	−0.99**
Commercial fisheries *Fishermen*		0.94	0.99**	0.75	0.69	1.00***
Agricultural pest regulation *Farmers*			0.95*	0.92	0.89	0.94
Water quality regulation *Community* *GBR tourists* *GBR tour operators* *GBR fishermen*				0.77*	0.72	0.99**
Pollination *Farmers*					0.99**	0.74
Biodiversity *Community*						0.69

*** $P < 0.001$.
** $P < 0.01$.
* $P < 0.05$.

fisheries within the floodplain ($r = -0.99$, $P < 0.01$). The strongest synergies were between community, GBR tourists, tour operators and fishermen for water quality regulation and fishermen for floodplain recreational and commercial fisheries ($r = 0.99$, $P < 0.01$; Table 2).

4. Discussion

This study is the first attempt in the GBR region to apply an ecosystem services framework to assess complex social–ecological dynamics between floodplain land use, diffuse agricultural pollution and reef health. Recently, whole-of-system assessments of the GBR region have analysed potential change in ecosystem services and human well-being under alternative future development and climate change scenarios (Bohensky et al., 2011; Costanza et al., in press). Our approach compliments this by enabling a more holistic assessment of potential future trade-offs at the individual catchment and flood plume scale.

The scenarios used to reveal these relationships were plausible past, present and future land use in the Tully–Murray catchment, which were designed to represent potential options for agricultural production, run-off and riparian and wetland area. The No Vegetation Management Act scenario represented an agriculturally intensive situation which may have eventuated without the protection of native vegetation in 1999. This was reflected in the skewed status of floodplain ecosystem services, with maximum food and fibre production and minimal water quality regulation, and the lowest scores for other floodplain services, and lowest average service status (33%). The Present Day scenario reflected land

Table 3
Stakeholders for ecosystem services in the Tully–Murray catchment and adjacent GBR, categorised according to scale. See text for acronyms.

Ecosystem services	Stakeholders			
	Local on-site	Local off-site	Regional and national	Global
Floodplain				
Food and fibre production	Farmers	Processors, service providers	Hauliers, processors, input suppliers, industry bodies, consumers	Consumers
Water quality regulation	Community	Local council, local NGOs	Queensland and Australian governments, Terrain NRM	
Recreational fisheries	Fishermen	Tourist accommodation, service providers	Queensland Government, input suppliers, industry bodies	
Commercial fisheries	Fishermen	Service providers	Queensland Government, industry bodies, input suppliers, processors, hauliers, consumers	Consumers
Biodiversity	Community	Local council, local NGOs	Queensland/Australian governments, WTMA, NGOs, Terrain NRM, public	Public
Agricultural pest regulation	Farmers	Processors, service providers	Hauliers, processors, input suppliers, industry bodies, consumers	Consumers
Pollination	Farmers	Processors, service providers	Hauliers, processors, input suppliers, industry bodies, consumers	Consumers
GBR				
Reef tourism	Tourists, tour operators	Tourist accommodation, service providers	GBRMPA, input suppliers, industry bodies, transport	
Recreational fisheries	Fishermen	Tourist accommodation, service providers	GBRMPA, input suppliers, industry bodies	
Commercial fisheries	Fishermen	Service providers	GBRMPA, Queensland Government, industry bodies, input suppliers, processors, hauliers, consumers	Consumers
GBR cultural benefits	Community		GBRMPA, Queensland Government, NGOs, public	Public

use in 2007, and was again skewed towards food and fibre production, with an average status of 38%. Consequently, the pre-European threshold for water quality was not reached, resulting in declining trends in GBR services.

The De-nitrification and Sediment Priorities represented full implementation of riparian re-vegetation and wetlands as recommended by the Tully WQIP, resulting in a more balanced outcome between food and fibre production and other services, with an average status of 58%. However, while biodiversity and pollination increased to near maximum status, commercial and recreational fisheries' status remained minimal. Importantly, in spite of improved water quality regulation, the pre-European threshold was not reached suggesting that future implementation of these WQIP actions alone will not improve GBR services. The most optimal scenario was Native Forestry, which had the highest average status (91%), and achieved the pre-European threshold, resulting in increases in the trends of GBR services. Hence, although agricultural revenues fell to $36.77 million per year, tourism and commercial fisheries revenues values of $10.6 and $3 million per year recorded in the GBR adjacent to the catchment (OESR, 2007) would be maintained or increased, compensating at least partially for agricultural economic losses.

The most marked negative trade-off amongst primary stakeholders was between farmers (for food and fibre production) and community, GBR tourists, tour operators, recreational and commercial fishermen (for water quality regulation and linked GBR services). Farmers, recreational and commercial fishermen in the floodplain also had strong negative trade-offs. In identifying 'winners' and 'losers' this analysis highlights the stakeholders relevant to potential water quality management and policy, plus the scales at which they occur. Amongst the primary stakeholders the analysis also identifies private (farmers, fishermen, tourists and tour operators) and public (community) beneficiaries. Water quality regulation is largely regarded as a public good (Pattanayak and Wendland, 2007), but our study revealed numerous private interests and private–private trade-offs amongst primary stakeholders (i.e. farmers versus tourists, tour operators and fishermen). Such symmetry is notable, since benefits derived from regulating services often only involve asymmetrical trade-offs between private and public interests (Turner et al., 2003; Carpenter et al., 2006, 2009).

The identification of linked ecological functions and stakeholders also allows an assessment of the design of existing water quality management. 'Scale mis-matches' occur when the spatial scale of management is not aligned with the ecosystem processes it aims to manage, resulting in social–ecological system disruption and loss of resilience (Cumming et al., 2006). Through the GBRMPA, the Australian Government has statutory powers to manage the GBR Marine Park, while the adjoining GBR Coast Marine Park is managed by the Queensland Government. National and state co-ordination has been established through intergovernmental co-management agreements (Olsson et al., 2008). Responsibility for water quality regulation lies with the Queensland Department of the Environment and Resource Management (DERM), which has recently acquired powers to enforce improved land management practice, but their jurisdiction only covers catchments and the inshore GBR Coast Marine Park. GBRMPA has statutory powers to manage threatening processes originating outside the GBR Marine Park, including catchments, but does not currently implement them. WQIPs are voluntary catchment-based plans negotiated amongst water quality stakeholders and facilitated by regional non-statutory NRM Boards such as Terrain NRM for the Tully WQIP (Kroon et al., 2009; Robinson et al., 2009). Consequently, although the Tully WQIP engaged the primary stakeholders for floodplain ecosystem services, it did not directly involve stakeholders for GBR services (Kroon, 2008). Hence our analysis suggests that at the catchment-to-reef scale there is a mis-match between statutory and non-statutory governance structures, hydrological ecosystem functions, services and linked primary stakeholders (Table 4).

The protection of ecosystem services can have reciprocal benefits for biodiversity conservation because their delivery usually depends upon the maintenance of natural habitats (Chan et al., 2006; Naidoo and Ricketts, 2006; Egoh et al., 2007; Goldman et al., 2008; TEEB, 2009). This is also evident for water quality regulation, which is partly determined by the extent and condition of native vegetation (Pattanayak, 2004; Pattanayak and Wendland, 2007; Turpie et al., 2008). The application of an ecosystem services approach in our study enabled an assessment of the effects of enhanced water quality regulation through land use and riparian and wetland regeneration on floodplain biodiversity, which is not currently considered in GBR water quality planning.

Terrestrial and aquatic biodiversity condition was integrated into indicators which measured the status of the biodiversity and pollination ecosystem services. Interestingly, although the status of water quality regulation was positively correlated with both services, only the correlation with pollination was statistically significant, and this was not strong ($r = 0.77$, $P < 0.05$; Table 2). Hence relationships between underlying biodiversity condition and water quality regulation were not clear-cut, suggesting that some elements of biodiversity are maintained in the floodplain under all the scenarios considered. This corroborates previous studies which show that relationships between ecosystem service provision and biodiversity condition are not necessarily linear (Swift et al., 2004; Kremen, 2005; Mertz et al., 2007; Tallis et al., 2008). However, one partial explanation for our equivocal result is that the estimates of biodiversity condition were based on expert opinion rather than empirically based models. Also, we utilised four indicators for terrestrial biodiversity and only one for aquatic biodiversity, biasing the measure of biodiversity condition towards terrestrial habitat.

Several important caveats should also be noted in our approach and results. First, the scenarios are static and do not include full cost-accounting of land use change. For example, we did not consider riparian re-vegetation costs. In the case of the Native Forestry scenario 14,724 ha of riparian vegetation was created. The local council estimates that current re-vegetation methods cost $20,000 per ha (D. Sydes, *pers. comm.*); hence this scenario could potentially have an establishment cost of $29.45 million, though large-scale re-vegetation could be carried out more cheaply. Also unaccounted for were the significant economic losses which would occur if the area of sugarcane production fell below the minimum required to maintain viable processing infrastructure such as the Tully Sugar Mill, which would have major impacts on local employment (Van Grieken et al., 2011). Identifying such economic thresholds is also important in the planning of agricultural social–ecological systems (Walker et al., 2009). Likewise, our scenarios did not incorporate other pressures and thresholds which will potentially distort future ecosystem service delivery in the GBR region, such as climate change impacts on reef ecology or urbanisation impacts on water quality (Bohensky et al., 2011; Costanza et al., in press).

Second, it is not feasible to analyse all potential services without incurring high levels of complexity and overlap. To focus on the principal linkages and trade-offs related to water quality regulation, and due to limited data, we only considered seven floodplain services and four GBR services. Hence we omitted other regulating services influenced by land use and water quality regulation in the floodplain (e.g. carbon sequestration, nutrient cycling, water quantity regulation), plus the provisioning service of drinking water supply. The potential development of markets for bio-sequestered carbon and linked biodiversity outcomes in the Wet Tropics (Hunt, 2008) justifies the inclusion of carbon sequestration in future integrated assessments. Also, agricultural run-off may have impacts on other coastal and marine ecosystems which are ecologically linked

Table 4
Statutory (solid line) and non-statutory (dashed line) bodies responsible for water quality management in the Tully–Murray catchment and adjacent GBR relative to ecosystem functions, services and primary (local on-site) stakeholders. See text for acronyms.

Ecosystem function	Ecosystem services	Primary stakeholders	Management bodies: Catchment	Wet Tropics	Queensland Government	Australian Government
FLOODPLAIN			*WQIP*	*Terrain NRM*	*DERM*	
Primary production	Food and fibre production	Farmers				
Floodplain function	Water quality regulation	Community				
	Recreational fisheries	Fishermen				
	Commercial fisheries	Fishermen				
	Biodiversity	Community				
	Agricultural pest regulation	Farmers				
	Pollination	Farmers				
GBR						*GBRMPA*
Flood plume hydro chemistry						
GBR ecology	Reef tourism	Tourists, tour operators				
	Recreational fisheries	Fishermen				
	Commercial fisheries	Fishermen				
	GBR cultural benefits	Community				

to reefs (e.g. seagrass meadows, mangroves) and also deliver services including tourism and fisheries (Stoeckl et al., 2011), but for this illustration of the approach we restricted our focus to reefs.

Third, our analysis of relationships between ecosystem services did not account for several potential sources of complexity. For example, we did not consider the application of potential best management practices in the land use scenarios, which may reduce DIN run-off in the catchment by 25–29% when fully employed (Armour et al., 2009; Roebeling et al., 2009). Hence the highly significant inverse relationship between food and fibre production and water quality regulation, plus trade-offs amongst linked stakeholders, may be less clear-cut when these practices are fully implemented. Also, due to data constraints the N-SPECT modelling of land use and total N run-off did not account for the potential mitigation of run-off by riparian vegetation and wetlands, which may further obscure this relationship. Our assumption of linked improvements in water quality regulation and GBR fisheries may also be more complex. Gehrke (2007) showed that coastal fisheries production in the Wet Tropics may be enhanced by nutrient run-off, but losses in productivity through water quality improvement would be compensated for by associated restoration of floodplain wetlands and other fish habitat. Similarly, there may be costs associated with riparian rainforest habitat for agricultural pest regulation, because proximity to native vegetation can induce crop damage from other fauna benefitting from additional habitat (Cunningham and Blanche, 2008).

Fourth, we assumed that all services were of equal weight, and did not consider their relative market and non-market values, a further component of integrated assessments (MA, 2005; De Groot, 2006; TEEB, 2009; Maes et al., 2011). We estimated the market value of food and fibre production as a surrogate indicator for the flow of this service. However, valuation of regulating and cultural services for comparison is inherently problematic (De Groot et al., 2002, 2010; MA, 2005; Carpenter et al., 2006, 2009; Hein et al., 2006; Ring et al., 2010), perpetuating the question as to how ecosystem services should be valued (Sagoff, 2011). Although Bohnet and Kinjun (2009) recorded high consumptive and non-consumptive demand for water in the catchment, they did not attempt to quantify values. Hence there remains a research challenge to value regulation services such as water quality, agricultural pest regulation and pollination, and the cultural services of biodiversity and recreational fisheries in the floodplain. The latter are inherently complex because fishermens' utility is not directly related to their catches or the status of fish stocks (Rolfe and Prayaga, 2006; Butler et al., 2009; Prayaga et al., 2010).

Similarly, we did not consider the potential trade-offs between ecosystem services and human well-being, a key component of the MA. Larson (2009) developed indicators of well-being for communities in the Tully–Murray catchment, and water quality was identified as the most important determinant. Other important factors were air quality, landscape and beaches' condition, access to natural areas, soil quality, swimming and bushwalking, hunting, fishing and the collection of produce. Many of these are particularly important determinants for the well-being of Indigenous Australians in the region (Bohnet and Kinjun, 2009; Sangha et al., 2011). In terms of floodplain ecosystem services, Larson's water quality indicator may be analogous to water quality regulation, landscape and beaches' condition equivalent to biodiversity cultural values, and hunting, fishing and the collection of produce equivalent to recreational fisheries. Hence it is possible that relative human well-being was highest in the Native Forestry scenario, where the status of these services was maximised.

5. Conclusion

Our study was considerably limited by data availability and scientific understanding, which necessitated numerous assumptions about the relationships between land use, water quality, biodiversity and related ecosystem services. This is notable considering that the Tully–Murray catchment is perhaps the most intensively researched catchment in the GBR region (Kroon et al., 2009). In spite of these limitations, our framework provides a novel and progressive step towards identifying generalised catchment-to-reef trade-offs in land use, water quality regulation, and linked services in adjacent marine areas which to date have not been considered in the GBR. Its strengths are the inclusion of linkages in ecosystem functions across terrestrial and marine ecosystems, thresholds in ecosystem service delivery, and their beneficiaries. This allows the analysis of 'winners' and 'losers' in land use change, which is important for designing and evaluating environmental and economic policy aiming to balance food and fibre production with other ecosystem services (Brussard et al., 2010; Ring et al., 2010; Silvestri and Kershaw, 2010). Related to this, the approach enables an assessment of potential mis-matches between governance structures, ecosystem functions and ecosystem service flows, which appear to exist in the GBR.

A major research priority is to better understand the cause–effect relationships between flood plume hydro-chemistry, reef health and the utility of beneficiaries, which would allow the prediction of trade-offs between floodplain and GBR ecosystem services. Similarly, measures of human well-being which can be integrated with our ecosystem services framework do not exist. The valuation of regulating and cultural services for comparison with provisioning services such as food and fibre production is a further challenge. However, such data may not be required if our approach is applied as a participatory planning tool, and values can be revealed through deliberative valuation techniques (e.g. De Groot, 2006; De Groot et al., 2008). Finally, it should be noted that while the approach can be applied generically in other catchment-to-reef contexts, the results of our study are specific to the Tully–Murray floodplain and flood plume, since other catchments and adjacent reef areas will have different ecological and social characteristics. Hence we propose that the framework should now be applied and refined through participatory water quality planning, either in the GBR or in similar social–ecological systems in other tropical regions.

Acknowledgements

The research was funded by Conservation International and the Australian Government's Marine and Tropical Sciences Research Facility. We are grateful to Matt Bradford, David Westcott, Andrew Ford, Graham Harrington, Adam McKeown, Keith MacDonald and Alistair Freeman for their expert opinions of biodiversity condition. Nigel Tucker (Biotropica Australia Pty. Ltd.), Paul Nelson (James Cook University) and Damon Sydes (Cassowary Coast Regional Council) provided advice and data.

References

Anonymous, 2003. The State of Queensland and Commonwealth of Australia Reef Water Quality Protection Plan for Catchments Adjacent to the Great Barrier Reef World Heritage Area. Queensland Department of Premier and Cabinet, Brisbane, Australia.
Access Economics, 2007. Economic and Financial Value of the Great Barrier Reef Marine Park 2005-06. Report for Great Barrier Reef Marine Park Authority, Townsville, Australia.
Armitage, D., Plummer, R., Berkes, F., Arthur, R., Charles, A.T., Davidson-Hunt, I., Diduck, A.P., Doubleday, N.C., Johnson, D.S., Marschke, M., McConney, P., Pinkerton, E.W., Wollenberg, E.K., 2009. Adaptive co-management for social-ecological complexity. Front. Ecol. Environ. 7, 95–102.
Armour, J.D., Hateley, L.R., Pitt, G.L., 2007. Improved SedNet and Annex Modelling of the Tully-Murray Catchment. A Report Prepared for the Tully Water Quality Improvement Plan. Queensland Department of Natural Resources and Water, Mareeba, Australia.
Armour, J.D., Hateley, L.R., Pitt, G.L., 2009. Catchment modelling of sediment, nitrogen and phosphorus nutrient loads with SedNet/ANNEX in theTully–Murray basin. Mar. Fresh. Res. 60, 1091–1096.
Bainbridge, Z., Faithful, J., Lewis, S., Brodie, J., 2009. Identifying the land-based sources of suspended sediments, nutrients and pesticides discharged to the Great Barrier Reef from the Tully basin, Queensland, Australia. Mar. Fresh. Res. 60, 1081–1090.
Bayliss, P., Bartolo, R., 2008. Quantitative ecological risk assessments for the Daly River. In: Bartolo, R., Bayliss, P., van Dam, R. (Eds.), Ecological Risk Assessment for Australia's Northern Tropical Rivers. Environmental Research Institute of the Supervising Scientist. National Centre for Tropical Wetland Research, Darwin, Australia, pp. 271–415.
Bellwood, D.R., Hughes, T.P., Folke, C., Nystrom, M., 2004. Confronting the coral reef crisis. Nature 429, 827–833.
Blanche, K.R., Cunningham, S.A., 2005. Rainforest provides pollinating beetles for atemoya crops. J. Econ. Entom. 98, 1193–1201.
Blanche, K.R., Ludwig, J.A., Cunningham, S.A., 2006. Proximity to rainforest enhances pollination and fruit set. J. Appl. Ecol. 43, 1182–1187.
Bohensky, E., Butler, J.R.A., Costanza, R., Bohnet, I., Delisle, A., Fabricius, K., Gooch, M., Kubiszewski, I., Lukacs, G., Pert, P., Wolanski, E., 2011. Future takers or future makers? A scenario analysis of climate change and the Great Barrier Reef. Glob. Environ. Change 21, 876–893.
Bohnet, I., Brodie, J., Bartley, R., 2008. Assessing water quality impacts of community defined land use change scenarios for the Douglas Shire Far North Queensland. In: Pettit, C., Carwright, W., Bishop, I., Lowell, K., Pullar, D., Duncan, D. (Eds.), Landscape Analysis and Visualisation. Springer, Berlin, pp. 383–406.
Bohnet, I., Kinjun, C., 2009. Community uses and values of water informing water quality improvement planning: a study from the Great Barrier Reef region, Australia. Mar. Fresh. Res. 60, 1176–1182.
Brauman, K.A., Daily, G.C., Duarte, T.K., Mooney, H.A., 2007. The nature and value of ecosystem services: an overview highlighting hydrological services. Annu. Rev. Environ. Resour. 32, 67–98.
Brodie, J.E., 2007. Nutrient Management Zones in the Great Barrier Reef Catchment: A Decision System for Zone Selection. Nutrient Management Zones (NMZ) Technical Report. Australian Centre for Tropical Freshwater Research Technical Report No. 06/07. Townsville, Australia.
Brodie, J.E., Furnas, M., Ghonim, S., Haynes, D., Mitchell, A., Morris, S., Waterhouse, J., Yorkston, H., Audas, D., Lowe, D., Ryan, M., 2001. Great Barrier Reef Catchment Water Action Plan. Great Barrier Reef Marine Park Authority, Townsville, Australia.
Brodie, J.E., McKergow, L.W., Prosser, I.P., Furnas, M., Hughes, A.O., Hunter, H., 2003. Sources of Sediment and Nutrient Exports to the Great Barrier Reef World Heritage Area. Australian Centre for Tropical Freshwater Research Technical Report No. 03/11. Townsville, Australia.
Brodie, J.E., Fabricius, K.E., De'ath, G., Okaji, K., 2005. Are increased nutrient inputs responsible for more outbreaks of crown-of-thorns starfish? An appraisal of the evidence. Mar. Poll. Bull. 51, 266–278.
Brodie, J.E., Binney, J., Fabricius, K.E., Gordon, I., Hoegh-Guldberg, O., Hunter, H., O'Reagain, P., Pearson, R., Quirk, M., Thorburn, P., Waterhouse, J., Webster, I., Wilkinson, S., 2008. Synthesis of Evidence to Support the Scientific Consensus Statement on Water Quality in the Great Barrier Reef. Queensland Department of Premier and Cabinet, Brisbane, Australia.
Brodie, J.E., Lewis, S., Bainbridge, Z., Mitchell, A., Waterhouse, J., Kroon, F.J., 2009. Target setting for pollutant discharge management of rivers in the Great Barrier Reef catchment area. Mar. Fresh. Res. 60, 1141–1149.
Brodie, J.E., Devlin, M.J., Haynes, D., Waterhouse, J., 2011. Assessment of the eutrophication status of the Great Barrier Reef lagoon (Australia). Biogeochemistry, doi:10.1007/s10533-010-9542-2.
Brown, K., Tompkins, E., Adger, W.N., 2001. Trade-off Analysis for Participatory Coastal Zone Decision-making. Overseas Development Group, University of East Anglia, Norwich, UK.
Brussard, L., Caron, P., Campbell, B., Lipper, L., Mainka, S., Rabbinge, R., Babin, D., Pullerman, M., 2010. Reconciling biodiversity conservation and food security: scientific challenges for a new agriculture. Curr. Opin. Environ. Sustain. 2, 34–42.
Bunn, S.E., Davies, P.M., Kellaway, D.M., Prosser, I.P., 1998. Influence of invasive macrophytes on channel morphology and hydrology in an open tropical lowland stream, and potential control by riparian shading. Fresh. Biol. 39, 171–178.
Butler, J.R.A., Radford, A., Riddington, G., Laughton, R.L., 2009. Evaluating an ecosystem service provided by Atlantic salmon, sea trout and other fish species in the River Spey, Scotland: the economic impact of recreational rod fisheries. Fish. Res. 96, 259–266.
Carpenter, S.R., DeFries, R., Dietz, T., Mooney, H.A., Polasky, S., Reid, W.V., Scholes, R.J., 2006. Millennium Ecosystem Assessment: research needs. Science 314, 257–258.
Carpenter, S.R., Mooney, H.A., Agard, J., Capistrano, D., DeFriese, R.S., Díaz, S., Dietz, T., Duraiappah, A.K., Oteng-Yeboah, A., Pereira, H.M., Perrings, C., Reid, W.V., Sarukhan, J., Scholes, R.J., Whyte, A., 2009. Science for managing ecosystem services: beyond the millennium ecosystem assessment. Proc. Natl. Acad. Sci. U.S.A. 106, 1305–1312.
Chan, K.M.A., Shaw, M.R., Cameron, D.R., Underwood, E.C., Daily, G.C., 2006. Conservation planning for ecosystem services. PLoS Biol. 4, 2138–2152.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neil, R.V., Paruelo, J., Raskins, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.
Costanza, R., Bohensky, E., Butler, J.R.A., Bohnet, I., Delisle, A., Fabricius, K., Gooch, M., Kubiszewski, I., Lukacs, G., Pert, P. Wolanski, E. A scenario analysis of climate change and ecosystem services for the Great Barrier Reef. In: van den Belt, M., Costanza, R. (Eds.), Ecological Economics of Estuaries and Coasts. In: Wolanski, E., McLusky, D. (Eds.), The Treatise on Estuarine and Coastal Science. Elsevier, London, UK, in press.
Cumming, G.S., Cumming, D.H.M., Redman, C.L., 2006. Scale mismatches in social-ecological systems: causes, consequences and solutions. Ecol. Soc. 11, 14.
Cunningham, S.A., Blanche, K.R., 2008. Services and disservices from insects in agricultural landscapes of the Atherton Tableland. In: Stork, N.E., Turton, S. (Eds.), Living in a Dynamic Tropical Forest Landscape. Blackwell Publishing Ltd., pp. 240–250.
Daily, G.C., Soderqvist, T., Aniyar, S., Arrow, K., Dasgupta, P., Ehrlich, P.R., Folke, C., Jansson, A., 2000. The value of nature and the nature of value. Science 289, 395–396.
De Groot, R.S., Wilson, M.A., Boumans, R.M.J., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol. Econ. 41, 393–408.
De Groot, R.S., 2006. Function-analysis and valuation as a tool to assess land use conflicts in planning for sustainable, multi-functional landscapes. Land. Urban Plan. 75, 175–186.
De Groot, R.S., Finlayson, C.M., Verschuuren, B., Ypma, O., Zylstra, M., 2008. Integrated Assessment of Wetland Services and Values as a Tool to Analyse Policy Trade-offs and Management Options: A Case Study in the Daly and Mary River Catchments, Northern Australia. Supervising Scientist Report 198. Supervising Scientist, Darwin, Australia.
De Groot, R.S., Alkemade, R., Braat, L., Hein, L., Willemen, L., 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecol. Complex. 7, 260–272.
DEWHA, 2009. Littoral Rainforest and Coastal Vine Thickets of Eastern Australia. Policy Statement 3.9. Department of the Environment, Water, Heritage and the Arts, Canberra, Australia.
De'ath, G., Fabricius, K.E., 2010. Water quality as regional driver of coral biodiversity and macroalgal cover on the Great Barrier Reef. Ecol. Appl. 20, 840–850.
Devantier, L.M., De'ath, G., Turak, E., Done, T.J., Fabricius, K.E., 2006. Species richness and community structure of reef-building corals on the nearshore Great Barrier Reef. Coral Reefs 25, 329–340.
Devlin, M., Brodie, J., 2005. Terrestrial discharge into the Great Barrier Reef Lagoon: nutrient behaviour in coastal waters. Mar. Poll. Bull. 51, 9–22.
Devlin, M., Schaffelke, B., 2009. Extent and exposure of riverine flood plumes in the Tully coastal region. Mar. Fresh. Res. 60, 1109–1122.
Egoh, B., Rouget, M., Reyers, B., Knight, A.T., Cowling, R.M., van Jaarsveld, A.S., Welz, A., 2007. Integrating ecosystem services into conservation assessments: a review. Ecol. Econ. 63, 714–721.
EPA, 2005. Directory of Important Wetlands, 3rd ed. Queensland Environmental Protection Agency, Brisbane, Australia. http://epa.qld.gov.au/wetlandinfo/site/SupportTools/AssessmentMethods/Toolbox/20.html (Accessed 20 November 2009).
EPA, 2005. Wetland Mapping and Classification Methodology Overall Framework: A Method to Provide Baseline Mapping and Classification for Wetlands in Queensland Version 1.2. Queensland Environmental Protection Agency, Brisbane, Australia. http://www.epa.qld.gov.au/register/p01769aa.pdf (Accessed 25 May 2009).
Eslinger, D.L., Jamieson Carter, H., Dempsey, E., van der Wilt, M., Wilson, B., Meredith, A., 2005. The Nonpoint-Source Pollution and Erosion Comparison Tool. NOAA Coastal Services Center, Charleston, SC, http://csc.noaa.gov/nspect/ (Accessed 5 May 2009).
Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Mar. Poll. Bull. 50, 125–146.
Fabricius, K.E., De'ath, G., McCook, L.J., Turak, E., Williams, D., 2005. Coral, algae and fish communities on inshore reefs of the Great Barrier Reef: ecological gradients along water quality gradients. Mar. Poll. Bull. 51, 384–398.
Fabricius, K.E., Okaji, K., De'ath, G., 2010. Three lines of evidence to link outbreaks of the crown-of-thorns seastar *Acanthaster planci* to the release of larval food limitation. Coral Reefs 29, 593–605.
Furnas, M., 2003. Catchments and Corals: Terrestrial Run-off to the Great Barrier Reef. Australian Institute of Marine Science, Townsville, Australia.
Gehrke, P.C., 2007. A Comparative Analysis of Coastal Fishery Food Webs in the Great Barrier Reef Region. CSIRO Water for a Healthy Country National Research Flagship.
Goldman, R.L., Tallis, H., Kareiva, P., Daily, G.C., 2008. Field evidence that ecosystem service projects support biodiversity and diversify options. Proc. Natl. Acad. Sci. U.S.A. 105, 9445–9448.
Gooch, M., Butler, J.R.A., Cullen-Unsworth, L.C., Rigano, D., Manning, C. Community-derived indicator domains for social resilience to water quality decline in a Great Barrier Reef catchment, Australia. Soc. Nat. Res., in press.
Gordon, I.J., 2007. Linking land to ocean: feedbacks in the management of socio-ecological systems in the Great Barrier Reef catchments. Hydrobiologia 591, 25–33.
Gordon, I.J., Nelson, B., 2007. Reef safe beef: environmentally sensitive livestock management for the grazing lands of the Great Barrier Reef catchments. In: Swain, D., Charmley, E., Steel, J., Coffey, S. (Eds.), Redesigning Animal Agriculture. CAB International, pp. 171–184.
Hein, L., van Koppen, K., de Groot, R.S., van Lerland, E.C., 2006. Spatial scales, stakeholders and the valuation of ecosystem services. Ecol. Econ. 57, 209–228.
Hogan, A., 2000. Use of Lagoons on the Tully-Murray Floodplain by Native Fish. Freshwater Fisheries and Aquaculture Centre, Queensland Department of Primary Industries, Walkamin, Australia.
Hunt, C., 2008. Economy and ecology of emerging markets and credits for bio-sequestered carbon on private land in tropical Australia. Ecol. Econ. 66, 309–318.
Hunter, H., Fellows, C., Rassam, D., DeHayr, R., Pagendam, D., Conway, C., Bloesch, P., Beard, N., 2006. Managing riparian lands to improve water quality: optimising nitrate removal via denitrification. In: Technical Report No. 57. Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Indooroopilly, Australia.
Hunter, H.M., Walton, R.S., 2008. Land-use effects on fluxes of suspended sediment, nitrogen and phosphorus from a river catchment of the Great Barrier Reef, Australia. J. Hydrol. 356, 131–146.
IAASTD, 2009. International Assessment of Agricultural Knowledge, Science and Technology for Development: Summary for Decision Makers of the Global Report. Island Press, Washington DC.
Jeffrey, S.J., Carter, J.O., Moodie, K.B., Beswick, A.R., 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environ. Modell. Softw. 16, 309–330.
Jupiter, S., Roff, G., Marion, G., Henderson, M., Schrameyer, V., McCulloch, M., Hoegh-Guldberg, O., 2008. Linkages between coral assemblages and coral proxies of terrestrial exposure along a cross-shelf gradient on the southern Great Barrier Reef. Coral Reefs 27, 887–903.
Kragt, M.E., Roebeling, P.C., Ruijs, A., 2006. Effects of Great Barrier Reef degradation on recreational demand: a contingent behaviour approach. Fondazione Eni Enrico Mattei Social Science Research Network Electronic Paper Collection: http://www.feem.it/Feem/Pub/Publications/WPapers/default.htm.
Kremen, C., 2005. Managing ecosystem services: what do we need to know about their ecology? Ecol. Lett. 8, 468–479.
Kroon, F.J., 2008. Draft Tully Water Quality Improvement Plan. Report to Terrain Natural Resource Management Ltd. CSIRO Sustainable Ecosystems, Atherton, Australia.
Kroon, F.J., Robinson, C., Dale, A.P., 2009. Integrating knowledge to inform water quality planning in the Tully–Murray basin, Australia. Mar. Fresh. Res. 60, 1183–1188.
Laliberté, E., Wells, J., DeClerck, F., Metcalfe, D.J., Catterall, C., Queiroz, C., Aubin, I., Bonser, S., Yi, D., Fraterrigo, J.M., McNamara, S., Morgan, J., Sánchez Merlos, D., Vesk, P., Mayfield, M., 2009. Land use intensification reduces functional redundancy and response diversity in plant communities. Ecol. Lett. 13, 76–86.
Larson, S., 2009. Communicating stakeholder priorities in the Great Barrier Reef Region. Soc. Nat. Resour. 22, 650–664.
Layke, C., 2009. Measuring Nature's Benefits: A Preliminary Roadmap for Improving Ecosystem Service Indicators. WRI Working Paper. World Resources Institute, Washington DC.
Lewis, S., Brodie, J., Bainbridge, Z., Rohde, K., Davis, A., Masters, B., Maughan, M., Devlin, M., Müller, J., Schaffelke, B., 2009. Pesticides: a potential threat to the Great Barrier Reef. Environ. Poll. 157, 2470–2484.
Lovett, S., Price, P., 2001. Managing Riparian Lands in the Sugar Industry: A Guide to Principles and Practices. Sugar Research and Development Corporation/Land and Water Australia, Brisbane, Australia.
Maes, J., Paracchini, M.L., Zulian, G., 2011. A European Assessment of the Provision of Ecosystem Services: Towards an Atlas of Ecosystem Services. Institute for Environment and Sustainability, European Commission Joint Research Centre, Publications Office of the European Union, Luxembourg.
Maughan, M., Brodie, J., 2009. Reef exposure to river-borne contaminants: a spatial model. Mar. Fresh. Res. 60, 1132–1140.
McDonald, G., Weston, N., 2004. Sustaining the Wet Tropics: A Regional Plan for Natural Resource Management Volume 1, Background to the Plan, Rainforest CRC and FNQ NRM Ltd, Cairns, Australia.
McKergow, L.A., Prosser, I.P., Grayson, R.B., Heiner, D., 2004a. Performance of grass and rainforest riparian buffers in the Wet Tropics, far North Queensland. 1. Riparian hydrology. Aust. J. Soil Res. 42, 473–484.
McKergow, L.A., Prosser, I.P., Grayson, R.B., Heiner, D., 2004b. Performance of grass and rainforest riparian buffers on banana plantations, far north Queensland. 2. Water quality. Aus. J. Soil Res. 42, 485–498.
Mertz, O., Ravnborg, H.M., Lövei, G.L., Nielsen, I., Konijnendijk, C.C., 2007. Ecosystem services and biodiversity in developing countries. Biodivers. Conserv. 16, 2729–2737.
Metcalfe, D.J., Ford, A.J., 2008. Floristic biodiversity in the Wet Tropics. In: Stork, N.E., Turton, S. (Eds.), Living in a Dynamic Tropical Forest Landscape. Blackwell Publishing Ltd, pp. 123–132.
Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: A Framework for Assessment. Island Press, Washington DC.
Mitchell, A., Reghenzani, J., Furnas, M., 2001. Nitrogen levels in the Tully River – a long-term view. Water Sci. Technol. 43, 99–105.
Mitchell, A., Reghenzani, J., Faithful, J., Furnas, M., Brodie, J., 2009. Relationships between land use and nutrient concentrations in streams draining a 'wet-tropics' catchment: the Tully River, north Queensland, Australia. Mar. Fresh. Res. 60, 1097–1108.
Naidoo, R., Ricketts, T.H., 2006. Mapping the economic costs and benefits of conservation. PLoS Biol. 4, 1895–1896.

NOAA, 2009. http://www.csc.noaa.gov/crs/lca/tech_cls.html (accessed 22 November 2009).

OESR, 2007. Queensland Regional Profiles, far North Queensland Statistical Division. Office of Economic and Statistical Research, Queensland Treasury, Brisbane, Australia.

Olsson, P., Folke, C., Hughes, T.P., 2008. Navigating the transition to ecosystem-based management of the Great Barrier Reef, Australia. Proc. Natl. Acad. Sci. U.S.A. 105, 9489–9494.

Pattanayak, S.K., 2004. Valuing watershed services: concepts and empirics from southeast Asia. Agric. Ecosyst. Environ. 104, 171–184.

Pattanayak, S.K., Wendland, K.J., 2007. Nature's care: diarrhea, watershed protection, and biodiversity conservation in Flores, Indonesia. Biodivers. Conserv. 16, 2801–2819.

Pearson, R.G., Connolly, N., 2000. Nutrient enhancement, food quality and community dynamics in a tropical rainforest stream. Fresh. Biol. 43, 31–42.

Pearson, R.G., Stork, N.E., 2008. Catchment to reef: water quality and ecosystem health in tropical streams. In: Stork, N.E., Turton, S. (Eds.), Living in a Dynamic Tropical Forest Landscape. Blackwell Publishing Ltd, pp. 557–576.

Pert, P.L., Butler, J.R.A., Brodie, J.E., Bruce, C., Honzák, M., Kroon, F.J., Metcalfe, D.J., Mitchell, D., Wong, G.Y., 2010a. A catchment-based approach to mapping hydrological ecosystem services using riparian habitat: a case study from the Wet Tropics. Ecol. Complex. 7, 378–388.

Pert, P.L., Bruce, C., Butler, J.R.A., Metcalfe, D.J., Webster, T., Goosem, S., 2010. A Prototype Report Card for the Status and Trends of Biodiversity, Soils and Landscapes in the Wet Tropics. Final Report to the Australian Government's Marine and Tropical Sciences Research Facility. Cairns, Queensland, Australia.

Prayaga, P., Rolfe, J., Stoeckl, N., 2010. The value of recreational fishing in the Great Barrier Reef, Australia: a pooled revealed preference and contingent behaviour model. Mar. Pol. 34, 244–251.

QPWS, 2001. Mahogany Glider Recovery Plan 2000–2004. Report to Environment Australia, Canberra. Queensland Parks and Wildlife Service, Brisbane, Australia.

Rassam, D.W., Pagendam, D., 2007. Identifying Riparian Re-vegetation Location Priorities in the Tully Catchment with Regards to Nitrogen Removal Ability of these Systems. Final Report to FNQ NRM Ltd. CSIRO Land and Water, Brisbane, Australia.

Rassam, D.W., Pagendam, D., 2009. Development and application of the Riparian Mapping Tool to identify priority rehabilitation areas for nitrogen removal in the Tully–Murray basin, Queensland, Australia. Mar. Fresh. Res. 60, 1165–1175.

Rassam, D.W., Pagendam, D., Hunter, H., 2008. Conceptualisation and application of models for groundwater–surface water interactions and nitrate attenuation potential in riparian zones. Environ. Mod. Soft. 23, 859–875.

Ring, I., Hansjurgens, B., Elmqvist, T., Wittmer, H., Sukhdev, P., 2010. Challenges in framing the economics of ecosystems and biodiversity: the TEEB initiative. Curr. Opin. Environ. Sustain. 2, 15–26.

Robinson, C.J., Taylor, B.M., Pearson, L., O-Donohue, M., Harman, B., 2009. A SMART assessment of water quality partnerships needs in the Great Barrier Reef catchments. Aust. J. Environ. Manage. 16, 84–93.

Rodriguez, J.P., Beard, T.D., Bennett, E.M., Cumming, G.S., Cork, S.J., Agard, J., Dobson, A.P., Peterson, G.D., 2006. Trade-offs across space, time and ecosystem services. Ecol. Soc. 11, 28.

Roebeling, P.C., Webster, A.J., Biggs, J., Thorburn, P., 2007. Financial-economic Analysis of Current Best Management Practices for Sugarcane, Horticulture, Grazing and Forestry Industries in the Tully-Murray Catchment. Report to the Australian Government's Marine and Tropical Sciences Research Facility, Cairns, Queensland, Australia.

Roebeling, P.C., van Grieken, M.E., Webster, A.J., Biggs, J., Thorburn, P.J., 2009. Cost-effective water quality improvement in linked terrestrial and marine ecosystems: a spatial environmental-economic modelling approach. Mar. Fresh. Res. 60, 1150–1158.

Rolfe, J., Prayaga, P., 2006. Estimating values for recreational fishing at freshwater dams in Queensland. Aust. J. Agric. Res. Econ. 51, 157–174.

Sachs, J., Remens, R., Smukler, S., Winowiecki, L., Andelman, S.J., Cassman, K.G., Castle, D., DeFries, R., Denning, G., Fanzo, J., Jackson, L.E., Leemands, R., Lehmann, J., Milder, J.C., Naeem, S., Nziguheba, G., Palm, C.A., Pingali, P.L., Reganold, J.P., Richter, D.D., Scherr, S.J., Sircely, J., Sullivan, C., Tomich, T.P., Sanchez, P.A., 2010. Monitoring the world's agriculture. Nature 466, 558–560.

Sagoff, M., 2011. The quantification and valuation of ecosystem services. Ecol. Econ. 70, 497–502.

Sangha, K.K., Butler, J.R.A., Delisle, A., Stanley, O., 2011. Identifying links between ecosystem services and human well-being for Aboriginal people in north Australia: applying the Millennium Ecosystem Assessment framework. J. Environ. Sci. Eng. 5, 931–946.

Schaffelke, B., Mellors, J., Duke, N.C., 2005. Water quality in the Great Barrier Reef region: responses of mangrove, seagrass and macroalgal communities. Mar. Poll. Bull. 51, 279–296.

Silvestri, S., Kershaw, F. (Eds.), 2010. Framing the Flow: Innovative Approaches to Understand, Protect and Value Ecosystem Services across Linked Habitats. United Nations Environment Program World Conservation Monitoring Centre, Cambridge, UK.

Smajgl, A., House, A., Butler, J.R.A., 2011. Implications of ecological data constraints for integrated policy and livelihoods modelling: an example from East Kalimantan, Indonesia. Ecol. Model. 222, 888–896.

Stanton, J.P., Stanton, D.J., 2005. Vegetation of the Wet Tropics of Queensland Bioregion. Wet Tropics Management Authority, Cairns, Australia.

Stoeckl, N., Hicks, C.C., Mills, M., Fabricius, K., Esparon, M., Kroon, F., Kaur, K., Costanza, R., 2011. The economic value of ecosystem services in the Great Barrier Reef: our state of knowledge. In: Costanza, R., Limburg, K., Kubiszewski, I. (Eds.), Ecological Economics Reviews. Ann. N. Y. Acad. Sci. 1219, 113–133.

Swift, M.J., Izac, A.-M.N., van Noordwijk, M., 2004. Biodiversity and ecosystem services in agricultural landscapes – are we asking the right questions? Agric. Ecosyst. Environ. 104, 113–134.

Tallis, H., Kareiva, P., Marvier, M., Chang, A., 2008. An ecosystem services framework to support both practical conservation and economic development. Proc. Natl. Acad. Sci. U.S.A. 105, 9457–9464.

TEEB, 2009. The Economics of Ecosystems and Biodiversity for National and International Policy Makers. http://www.teebweb.org/ (accessed 21 November 2009).

Turner, R.K., Paavola, J., Cooper, P., Farber, S., Jessamy, V., Georgiou, S., 2003. Valuing nature: lessons learned and future research directions. Ecol. Econ. 46, 493–510.

Turpie, J.K., Marais, C., Blignaut, J.N., 2008. The working for water programme: evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. Ecol. Econ. 65, 788–798.

USDA-NRCS, 1986. Urban Hydrology for Small Watersheds. Technical Release 55 (TR-55), second ed. Washington, D.C. ftp://ftp.wcc.nrcs.usda.gov/downloads/hydrology hydraulics/tr55/tr55.pdf.

Van Grieken, M.E., Thomas, C.R., Roebeling, P.C., Thorburn, P.J., 2011. Integrating economic drivers of social change in agricultural water quality improvement strategies. Agric. Ecosyst. Environ., doi:10.1016/j.agee.2011.06.013.

Veitch, W., Sawynok, B., 2004. Freshwater Wetlands and Fish: Importance of Freshwater Wetlands to Marine Fisheries Resources in the Great Barrier Reef. Sunfish Queensland Report to the Great Barrier Reef Marine Park Authority, Townsville, Australia.

Walker, B.H., Abel, N., Anderies, J.M., Ryan, P., 2009. Resilience, adaptability and transformability in the Goulburn-Broken catchment, Australia. Ecol. Soc. 14, 12.

Wallace, J., Stewart, L., Hawdon, A., Keen, R., 2008. The role of coastal floodplains in generating sediment and nutrient fluxes to the Great Barrier Reef Lagoon in Australia. Int. J. Ecohydrol. Hydrobiol. 8, 183–194.

Wallace, J., Stewart, L., Hawdon, A., Keen, R., Karim, F., Kemei, J., 2009. Flood water quality and marine sediment and nutrient loads from the Tully and Murray catchments in north Queensland, Australia. Mar. Fresh. Res. 60, 1123–1131.

Ward, D., Tucker, N., Wilson, J., 2003. Cost-effectiveness of revegetating degraded riparian habitats adjacent to macadamia orchards in reducing rodent damage. Crop Protect. 22, 935–940.

Williams, S.E., 2006. Vertebrates of the Wet Tropics Rainforests of Australia: Species Distributions and Biodiversity. Rainforest CRC, Cairns, Australia.

Wooldridge, S.A., 2009. Water quality and coral bleaching thresholds: formalising the linkage for the inshore reefs of the Great Barrier Reef, Australia. Mar. Poll. Bull. 58, 745–751.

Wooldridge, S., Brodie, J., Furnas, M., 2006. Exposure of inner-shelf reefs to nutrient enriched runoff entering the Great Barrier Reef Lagoon: post-European changes and the design of water quality targets. Mar. Poll. Bull. 52, 1467–1479.

Wooldridge, S.A., Done, T.J., 2009. Improved water quality can ameliorate effects of climate change on corals. Ecol. Appl. 19, 1492–1499.