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The economic value of ecosystem services in the Great Barrier Reef: our state of knowledge

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This article reviews literature relating to the Great Barrier Reef (GBR) and aims to assess the current state of knowledge about (1) the "value" of ecosystem services (ES) provided by the GBR and (2) the way in which activities that are carried out in regions adjacent to the GBR affect those values. It finds that most GBR valuation studies have concentrated on a narrow range of ES (e.g., tourism and fishing) and that little is known about other ES or about the social, temporal, and spatial distribution of those services. Just as the reef provides ES to humans and to other ecosystems, so too does the reef receive a variety of ES from adjoining systems (e.g., mangroves). Yet, despite the evidence that the reef's ability to provide ES has been eroded because of recent changes to adjoining ecosystems, little is known about the value of the ES provided by adjoining systems or about the value of recent changes. These information gaps may lead to suboptimal allocations of resource use within multiple realms.

Keywords: ecosystem services; economic valuation; Great Barrier Reef (GBR); catchments

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Introduction

In 1981, the Great Barrier Reef (GBR) was inscribed on the World Heritage List. Covering an area of more than 348,000 km^2 and extending for more than 2,300 km along Australia's northeast coast (Fig. 1), the GBR Marine Park includes extensive areas of reefs, seagrass beds, and mangroves. Its selection was based on the criteria that the GBR is an outstanding example of "a major stage of the earth's evolutionary history" and of "significant ongoing geological processes, biological evolution and man's interaction with his natural environment" (p. 16).[1] In addition, it "contains unique, rare and superlative natural phenomena, formations and features and areas of exceptional natural beauty" (p. 16).[1] and provides habitat for rare and endangered species.

Under the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Convention, the listing of the GBR obliges the Federal Government of Australia to ensure the identification, protection, conservation, presentation, and transmission to future generations of the GBR. This is reinforced by Commonwealth Law, including section 3a and 12 of the *Environment Protection and Biodiversity Conservation Act 1999*[2] that specify (1) that "improved valuation, pricing, and incentive mechanisms should be promoted;" (p. 3) and (2) the requirement for approval of activities that have a significant impact on the world heritage values of a declared World Heritage property (p. 10). This has two important—and related—implications for GBR managers.

First, the act seeks to promote improved valuation, pricing, and incentive mechanisms. Whether or not the act should seek to promote improved valuation is not debated here. Rather, this article simply accepts that goal as stated and seeks to review the

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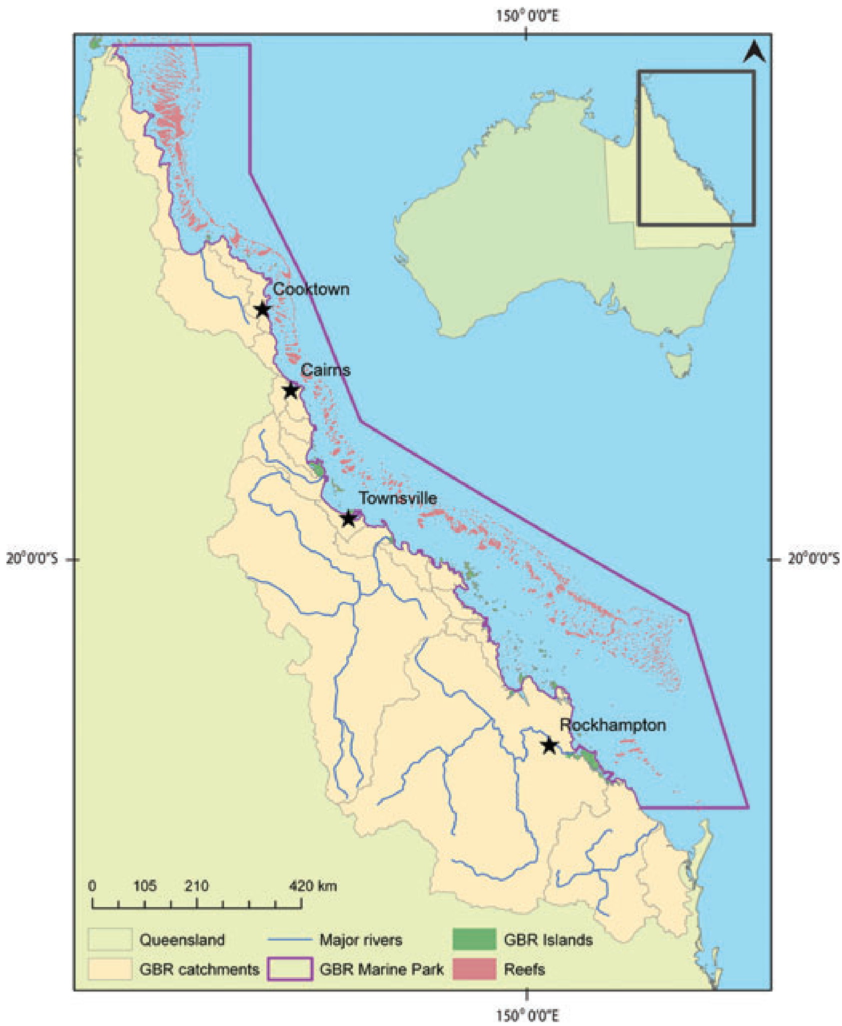

Figure 1. The GBR and environs. (In color in *Annals* online.)

GBR valuation literature, thus providing a baseline from which to assess the stated goal of promoting improvements.

That the GBR is of "value" by and of itself—irrespective of whether it has a market price attached to it or not—has long been accepted, as starkly evidenced by its world heritage listing. And for almost two centuries, economists have known and have sought to highlight the fact that value is not synonymous with price.[a] The Millennium Ecosystem Assessment (MEA) helped bring such issues to the forefront of policy by highlighting the benefits humans derive from nature[3] as recipients of ecosystem services (ES). These benefits include supporting, provisioning, regulating, and cultural services, which sustain and fulfill human life.

In their landmark study, Costanza *et al.*[4] highlighted the importance of 17 ES from 16 biomes all over the world, providing an approximate estimated value of U.S.$16–U.S.$54 trillion per annum. Most relevant here, however, is the fact that although there have been many attempts to value the ES associated with coral reefs, relatively little has been done within the GBR. Conservation International,[5] for example, summarized 57 separate valuation studies. The

[a] To wit the concept of *consumer surplus* introduced by Dupuit in the early 1800s and subsequently developed by Marshall.

Economics of Ecosystems and Biodiversity (TEEB) report[6] analyzed 80 coral reef valuation studies, and Brander *et al.*[7] collected information on 166 different coral reef valuation studies, using a subset of 52 of those studies to conduct a meta-analysis. Yet, the Conservation International[5] compilation includes just three studies of the GBR (one of which is a value derived using a "benefit transfer"[b] from Hawaii),[8] the TEEB report study does not appear to refer to any Australian valuation studies, and Brander *et al.*'s[7] reference list includes just two Australian studies, neither of which contained enough information to be included in the meta-analysis. Clearly, somewhat less is known about the value of the ES provided by the GBR than might be expected given its world heritage status.

Second, the *Environment Protection and Biodiversity Conservation Act 1999* specifies that activities in environments surrounding the GBR World Heritage Area (including the neighboring oceans, coastal zones, and catchments), which may influence the world heritage values need to be considered.[2] This is particularly important because the GBR catchment comprises 35 river basins, covers an area[9] of 424,000 km^2, and has an estimated population of 1,115,000 people that is rapidly increasing.[10] Since European settlement, the development of these river basins has been associated with extensive agricultural and some urban development that has led to the removal of the buffering and filtering function of the landscape. This has generated increased sediment, nutrient, and pesticides loads to the GBR lagoon,[11,c] which has been linked to coastal ecosystem degradation in the GBR.[11–13] Evidently, at least some of the impacts that the *Environment Protection and Biodiversity Conservation Act 1999* seeks to avoid have already occurred.

These two issues, therefore, provide a focus for this review. Specifically, this article sets out to determine the current state of knowledge about (1) the value of ES provided by the GBR and (2) the way in which activities that are carried out in regions adjacent to the GBR affect those values. As suggested by Liu *et al.*,[14] this review adopts a transdisciplinary approach and is structured as follows.

After a brief discussion of valuation methodologies and of the similarities between key terms used by environmental economists and those used in the MEA (see the "*Valuing ES*" subsection), "*ES valuation studies in the GBR*" subsection provides a review of studies that have sought to generate financial estimates of the value of different ES provided by the GBR.

A strong theme that emerges from "The value of the GBR's ecosystem services" section is that many of the GBR's values are influenced by activities that occur outside the GBR management area. Yet, many of the benefits associated with the ES that are provided by the GBR accrue to people, and to ecosystems outside the GBR management area. The "*Conceptual examples of the "flow" of ES*" subsection therefore discusses and presents conceptual models of the "flow" of benefits of four individual ES: capture fisheries, recreation, coastal protection, and water purification). These four case studies provide neither an exhaustive nor a definitive discussion of the flows of ES in this vast region, but they do serve to illustrate the importance of considering such flows when valuing ES in complex regions such as these—as highlighted in the discussion of "*The value of ES provided to the GBR*" subsection. The key contribution of this section is that it clearly identifies the need for terrestrial-based investigations of ES, to explore not only the value of ES that accrue within any specific system being studied, but also the value of the ES that those systems provide to adjoining regions, such as the GBR.

The "Directions for the future" section brings together key observations from the previous discussions, highlighting important gaps in our knowledge, and suggesting topics for future research—topics that are likely to provide essential information to managers and/or policy makers in the face of predicted climate change and population growth.

The value of the GBR's ecosystem services

Valuing ES

Economists have long recognized that there are a multiplicity of values associated with the environment and have coined terms such as: "total

[b] A technique for estimating economic values for ES that transfer available information from studies already completed in another location and/or context.

[c] Suspended sediment loads have been estimated at up to five times pre-European loads in some rivers,[55] some nitrate loads are up six times higher than 150 years ago,[11] and considerable quantities of pesticides are now discharged from rivers that would have been completely absent before the 1950s.

economic value" (TEV); "direct-use value;" "indirect-use value;" and "nonuse value"[d] to help describe those concepts. A vast body of literature on different techniques for attempting to derive monetary estimates of those values now exists, and interested readers are directed to Getzner *et al.*,[15] Bateman *et al.*,[16] Rietbergen-McCracken and Abaza,[17] Garrod & Willis,[18] and Willis *et al.*[19] for detailed reviews. Suffice to say here, none of the valuation methodologies are flawless, and most are surrounded with at least some controversy vis-à-vis the "accuracy" of final estimates. Each requires different types of information as an input, and produces (sometimes subtly) different information as output. However, if used correctly, the valuation exercises allow one to explicitly account for goods and services that might otherwise go unrecognized.

Multiple classification systems exist for assessments of ES, and these different approaches are needed.[20] Yet despite the fact that the terminology used by economists in their TEV framework differs from that of the classification system used in the MEA, it is important to note that the values identified by these frameworks are quite similar. This is illustrated in Figure 2, which lists a variety of different "values" that economists have associated with coral reefs, categorized as direct-use, indirect-use, and nonuse values in accordance with the TEV framework. Each of those values have also been categorized using the MEA framework using color arrows. Other researchers might well choose to classify the ES identified in the MEA into different categories. But renaming would not change the main message conveyed by each framework, namely that there are a multiplicity of values that humans derive from the environment. Moreover, renaming would not alter the fact that both frameworks identify similar types of values. For example, many of the "provisioning services" highlighted in the MEA are also clearly identified within the TEV framework, although in this latter framework they are classified as types of "use-value" (e.g., fishing and coral mining). Similarly, "regulating services" also appear within the TEV, although most are referred to as indirect-use values. So too, are the "cultural services" to which the MEA refers included in the TEV—although in the latter framework, they are most often referred to as recreational, existence, or bequest values.

The key point to be made here, therefore, is that those interested in valuing the "environment" or the ES that an environment provides must consider a range of different factors. It is not sufficient to consider just one or two particular aspects (e.g., recreation and fishing).

ES valuation studies in the GBR

The Australian Bureau of Agricultural and Resource Economics (ABARE) has been collecting information on the value of the region's fisheries for more than a quarter of a century (see, e.g., ABARE[21]). Yet, valuation studies of the GBR arguably began with Driml's[22] study. Using input–output (IO) analysis, Driml[22] estimated the "financial" impact that a range of different reef-based activities had in the GBR region. This impact was substantial: the total direct output was estimated at AUS $159 million per annum[e] with the combined direct and indirect impact closer to AUS$273 million.

There then followed a series of studies, each of which largely followed Driml's[22] approach, focusing on the financial contribution of reef-based activities. Specifically, KPMG[23] updated Driml's[22] estimates to 1997/1998 values (tourism: AUS$454 million; commercial fishing: AUS$136 million; recreational fishing and boating: AUS$108 million); Driml[24]

[d] "Use values" are often subdivided into "direct" and "indirect" use values. Specific examples of direct use values that are relevant to coral reefs include fish, tourism, and recreation; while examples of indirect use values include such things as physical protection that coral reefs provide from storms. In the 1960s, Weisbrod also pointed out that there are other important values associated with the environment: specifically, the "option value." The idea here is that we may not be "using" an environmental area—say parts of the reef, or areas within a forest. But that doesn't mean we should simply get rid of it—we may want to keep it, *in case* we want to use it in the future. In 1967 Krutilla expanded the TEV framework still further, noting that environmental areas/regions/services that are never used, and that one never even intends to use, still have value. The terms coined for these values were *existence* and *bequest* values.

[e] Island resorts: $45.9 million; charter boats: $25.5 million; commercial fishing: $36.3 million; recreational fishing: $42.8 million; island camping: $1.6 million; and research: $6.9 million.

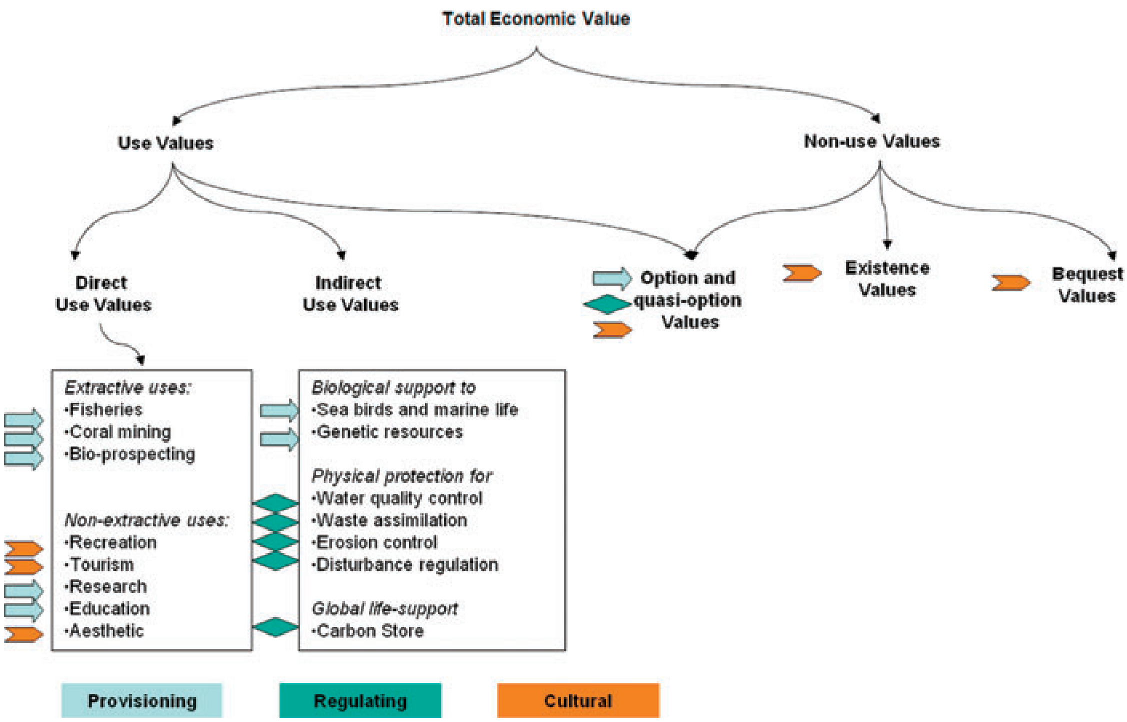

Figure 2. MEA ecosystem services and the TEV framework (coral reef examples adapted from Ahmed *et al.*[109] and Rolfe *et al.*[110]). (In color in *Annals* online.)

estimated the direct (and indirect) output associated with tourism (AUS$647 million), commercial fishing (AUS$143 million), recreational fishing and boating (AUS$122 million); and Access Economics[25,26] used IO analysis to estimate the direct and indirect value of tourism (AUS$3,099 million), recreational fishing, and boating (AUS$406 million) within the GBR catchment area during 2005–2006.[f]

Taking a slightly different approach, Fenton and Marshall[27] provided a social and financial profile of harvesters, charter fishing operators, and commercial fishing operators, estimating the gross value of production (GVP) for these groups in several fishing communities. Although they did not use IO (as did the aforementioned studies), their approach was similar, in that it used income/expenditure data to estimate some of the productive values of the GBR (their combined GVP estimates for towns in the GBR region are: AUS$7 million for Harvesting; AUS$23 million for charter fishing; and AUS$224 million for commercial fishing). In that same year, Harriott[28] found that the total value of the coral harvest fishery was AUS $500,000 per year in 2001, although only 25% of the total allowable catch of 212 tons were harvested then, amounting to approximately 25 tons of live coral and 25 tons of rubble and "living rock." This figure is likely to be much higher in 2009.

In 2003, Policy Development and Planning (PDP) Australia[29] produced a report that was similar in nature to those of KPMG[23] and Driml.[22,24] There were, however, two interesting twists to the PDP Australia[29] study. First, they looked at the gross value of reef-based activities in comparison to the gross value of other key industries in Queensland, specifically agriculture and mining/minerals.[g] Although

[f] They also estimated the GVP of those same subsets of activities for Queensland and for Australia as a whole—clearly generating larger estimates (since these regions are larger).

[g] Mineral production: $7.4 billion, or 49% of GVP; tourism: $4.3 billion, or 28% of GVP; agricultural production: $3.2 billion, or 21% of GVP; fisheries: $130.1 million, or 1% of GVP; and recreational activities: 80.7 million, less than 1% of GVP. They also estimate the research value of the GBR as being close to $25 million.

the focus of their study was NOT on these other industries, or on the tradeoffs that might occur between and within them, the fact that non—reef-based industries were at least acknowledged in the introductory section of their report was important: their activities clearly have an impact upon the GBR, and hence affect the values of the GBR.

Second, the study did not simply attempt to estimate the value of the reef. Instead, it sought to quantify the way in which values might change—in this case, in response to the rezoning of the reef. Specifically, they estimated the value of fishing foregone because of the rezoning as being between AUS$0.52 million and AUS$2.59 million per annum (between 4 and 10 cents per Australian). This heralded the beginning of a new era of research in the GBR—one in which a wider range of values were investigated for a wider variety of scenarios (e.g., exploring the way in which values might change in response to other factors), using a wider range of techniques.

With regard to the methods used: few pre-2003 studies investigated more than just the expenditure (or GVP) of the tourism and/or fishing industries, although there are three examples using different methodological approaches. First, Hundloe *et al.*[30] set out to estimate the likely economic impact of the crown of thorns star-fish. In doing so, they used the travel cost model (TCM) to estimate the consumer surplus (CS) associated with recreation, and they also conducted a contingent valuation study of the (nonuse) values associated with "vicarious users." They found that the CS associated with recreation/tourism on GBR was close to AUS$144 million per annum and that the value of coral sites to vicarious users was AUS$45 million per annum.[30] Second, Knapman and Stoeckl[31] used the TCM to estimate the CS associated with recreation on Hinchinbrook Island (within the GBR); they also looked at the price elasticity of recreation demand, concluding that recreation user fees may be both an efficient and an equitable way to raise money. Finally, Watson *et al.*[32] used simulations to try and estimate the annual yield and landed value of prawns that could be harvested from healthy seagrass beds (AUS$41,000 per hectare).

These three studies were, however, isolated examples; it was not until the turn of the century that a larger group of researchers began to regularly employ a broader range of methods to investigate a broader range of issues. One of the first of the new "wave" of studies was that of Carr and Mendelsohn[33] who used a TCM to estimate the CS associated with tourism in the GBR, concluding that the total CS was between US$710 million and US$1.6 billion. This research was closely followed by that of Windle and Rolfe[34] who used choice modeling to conduct what is probably only the second study of nonuse values in the GBR region (after Hundloe *et al.*[30]). Focusing on the Fitzroy estuary (a catchment adjacent to the GBR), they found that people who lived outside the region (specifically, Brisbane householders, living approximately 600 km away from the Fitzroy estuary) would be willing to pay up to AUS$3.21 per annum for "improvement" in the environmental health of the estuary.

More recent relevant work includes that of:

- Grafton *et al.*,[35–37] who used bioeconomic models to assess the financial costs and benefits of marine reserves. Although none of their empirical work explicitly relates to the GBR, they concluded that there are situations in which reserves can serve to raise the profitability of fisheries since they can provide buffers that will help the broader ecosystem recover from external shocks and this is likely to be relevant to the GBR;
- Kragt *et al.*,[38] who used contingent behavior modeling to look at the way in which tourism is likely to respond to "reef degradation." They estimated that the CS associated with reef-based recreation in the Port Douglas region could fall by as much as AUS$57 million if the local reef were degraded, resulting in an associated decrease in tourism expenditure of between AUS$136 million and AUS$268 million;
- Daley *et al.*,[39] who provided a historical overview of commercial dugong and marine turtle fisheries in Queensland—a topic hitherto somewhat neglected;
- Delisle,[40] who explored some of the costs and benefits of traditional dugong hunting in the Torres Strait (this research is ongoing);
- Prayaga *et al.*,[41] who used contingent valuation, the TCM, and contingent behavior models to estimate the CSs associated with recreational fishing along the Capricorn Coast[h] and to

[h] In the order of $5.53 million and $267 million per annum, respectively.

Table 1. ES valuation studies in the GBR—by methodology

Expenditure, GVP, and/or IO	Travel cost	Contingent valuation and choice modeling	Contingent behavior	Miscellaneous
Driml[22,24,111]	Hundloe *et al.*[30]	Hundloe *et al.*[30]	Kragt *et al.*[38]	**Benefit transfer**
KPMG[23]	Knapman & Stoeckl[31]	Windle & Rolfe[34]	Prayaga *et al.*[41]	Asafu-Adjaye *et al.*[43]
Fenton & Marshall[27]	Carr & Mendelsohn[33]	Prayaga *et al.*[41]		Oxford Economics[44]
Harriot[28]	Prayaga *et al.*[41]	Stoeckl *et al.*[42]		**Other**
PDP Australia[29]				Alam *et al.*[45]
ABARE[21]				Daley *et al.*[39]
Access Economics[25,26]				Delisle[40]
Stoeckl *et al.*[42]				Watson *et al.*[32]

explore the way in which those values would be likely to change in response to other external impacts (such as crowding, algal blooms, and changed catch rates);[i] and

- Stoeckl *et al.*,[42] who looked at the regional economic impact of specialist dive-boat operations and at the willingness of passengers to pay for an increased chance of sighting key marine species in the Northern section of the GBR.

As regards an overall assessment of all ES values associated with the reef: Asafu-Adjaye *et al.*[43] was, perhaps, the first study that sought to comprehensively value a multiplicity of services provided by the GBR. Yet, although these researchers were able to access regionally relevant data on tourism/recreation values, all other estimates of the value of ES provided by the GBR were created via benefit transfer. Indeed, Asafu-Adjaye *et al.*[43] did not collect any new, primary data. Consequently, their contribution to the research was not so much an addition of new knowledge, but a new assemblage of existing knowledge. Similarly, a more recent study (Oxford Economics[44]) also attempted to comprehensively value a full range of ES associated with the GBR, the present value of which was estimated at $51.4 billion. They too, relied almost exclusively on data collected by other researchers, using benefit-transfer techniques wherever possible (although they did provide some innovation in that they used data collected by Prideaux and Coghlan (2009)[j] within a TC framework to generate an estimate of the recreation use value of tourism in the GBR catchment). Additionally, they attempted to determine the extent to which the full range of values would change if there were to be a "complete, catastrophic, and immediate" bleaching event across the entire GBR, the present value of which was estimated at approximately $38 billion.

State of knowledge

As clearly illustrated above, there is but a short history of valuation studies in the GBR. Not only is the overall quantum of research relatively small, but much of what has been published appears in the "gray" literature (i.e., reports rather than in scientific journals). This is, in some ways, a good thing, since reports are often written in a language that is more accessible to managers than that used in scientific journals. Moreover, these reports have often been commissioned by management authorities (to wit the reports by Driml,[22,24] PDP Australia,[29] and Access Economics[25,26]), and thus feed directly into decision-making institutions. That said, this literature is not always peer reviewed or accessed by other scientists, who often use scientific journals as their primary source of information. As such, it may not be as widely disseminated as one might wish. In addition, information about the value of the Reef's ES is somewhat "patchy;" researchers have used relatively few of the valuation tools available to economists (Table 1) and have concentrated on but

[i] With changes valued at between $4 million and $17 million per annum.

[j] Cited in Oxford Economics.[44]

a few of the ES values provided by the GBR. The following subsections consider that work, asking two, related questions:

- What do we know about the total value of the reef's ES?
- What do we know about the way in which those values are changing?

The total value of ES. In line with Liu *et al.*'s[14] findings, it is clear that most research effort has been devoted to those ES that are directly consumed: notably recreation. The research completed since Driml's 1987[22] work has built a relatively good base of information on the financial benefits of the recreational and tourism services provided by the GBR. Information from ABARE,[21] together with that gleaned from the newer studies of fishing and hunting under way by Grafton *et al.*[35–37] and Delisle,[40] and with information about the value of shipping in the region[k] will also, soon provide us with a more solid base of information about the value of (some of) the reef's provisioning services. Moreover, since many of the recreation and fishing studies have used IO analysis, we also have a relatively good base of information about the distribution of some of the financial benefits of those services within the GBR catchment area.

Yet, despite the fact that there have been at least two investigations of nonuse values associated with the GBR,[30,34] there is a paucity of information on the reef's aesthetic and spiritual values.[l] Furthermore, to the best of our knowledge, there has been only one attempt to estimate the value of the reef's supporting services (i.e., Watsons *et al.*,[32] investigation of the value of seagrass to the prawn fisheries) and only one attempt to generate a financial estimate of the value of the reef's regulating services—the Oxford Economics[44] study that includes an estimate of the value of "storm protection."

That the issue of supporting services has been neglected by economists is, arguably, correct: to add their value to that of regulating, provisioning, and cultural services would be akin to "double counting." And there is, at any rate, a substantial body of biophysical research about this vitally important service, as discussed in Appendix A. Nevertheless, the gap in knowledge about the value of cultural and regulating services is significant.

The Oxford Economics[44] study used data from a study of a small community on the coast in the northern part of the GBR (Mission Beach) on the cost of constructing reventment walls to partially "plug" the gap of information about regulating services. They, in essence, calculated the cost per meter, and scaled upward for the length of the GBR. Such an estimate may be better than no estimate at all, but there are problems associated with the benefit transfer method (see TEEB[6]). There is a clear need for better information on this important service, and there are examples of studies in other parts of the world (e.g., Costanza *et al.*[4]) that provide methodological tools for such assessments.

Changes in the value of ES. When assessing the quality of information regarding the value of ES provided by the GBR, it is important to differentiate between research that provides information about the value of the existing set of ES that are provided by the GBR (like those discussed above), and research that provides information about the way in which those values might change (or have changed) in response to some other, external event. That recent (post-European settlement) changes have impacted upon the reef's ability to provide ecosystem services, is evidenced in Table 2. Most marked, perhaps, is the evidence of decline in "supporting services," which themselves underpin the ability of the reef to provide other services that more directly influence human well-being.

Yet, despite stark biophysical evidence of the fact that changes are occurring, to date, economic researchers have only attempted to explicitly quantify the "value" of a small subset of those changes. Managers have at their disposal, at least some information about the way in which the reef's provisioning and/or recreational values are likely to change in response to a limited range of different external "shocks." Unfortunately, information about the way in which the value of other ES are likely to change is all but nonexistent (with the exception of Alam *et. al.*'s[45] qualitative study and the Oxford

[k] The areas between the mid- and outer-shelf reefs and the mainland provide a safe shipping channel each year; approximately 6,000 ships of more than 50 m in length travel within the GBR and Torres Strait Region (p. 103).[82]

[l] There are currently several projects attempting to refine and improve current nonmarket valuation methodologies using case studies within the GBR catchment.[83,84]

Table 2. Documented evidence of declines in the ability of the GBR to provide ES

Service	Changes that have affected the GBR's ability to provide such services
Supporting services	• Since European settlement, 80% of native vegetation, 60% of riparian habitat, and 69% of wetlands have been cleared from the floodplain for agriculture. Associated with this, loads of suspended sediments, nitrogen, and phosphorus have increased by factors of 5, 2–5, and 2–10, respectively.[11] • Increased sedimentation and inputs of nutrients and pesticides has led to a decrease in water quality in the ocean,[87] a decrease in the survivorship and biodiversity of corals, and an increase in macroalgae.[12,13,88] • The accumulation of pollutants in sediments and marine species reduces light[10] and produces muddy marine snow, that increases sedimentation stress and mortality in coral recruits.[89] • Increasing water turbidity also reduces the lower depth limits where seagrasses are found,[90] and there is evidence of decline in seagrass health with increasing concentrations of herbicides.[91] • Increasing concentrations of CO_2 in the atmosphere lead to a reduction in the pH of seawater ("ocean acidification"), which reduces the ability of corals and other calcifying organisms to grow, and diminishes the capacity of coral reefs to withstand erosion and storms.[91] • These effects have themselves affected the overall resilience of the ecosystem, as evidenced by, for example, the following: ○ Disease in corals and pest outbreaks of crown-of-thorns starfish and cyanobacteria appear to be becoming more frequent and more serious.[10] ○ Coral disease has been linked to warming temperatures.[77,78] The natural bacterial communities of corals are severely altered during stress, which suggests a potential mechanism for the link between diseases and stresses arising from global warming.[79]
Regulating services	• Damages to the reef's underlying supporting services (outlined above) may reduce the ability of the GBR to provide coastal protection as a key regulating service. • The frequency and strength of cyclones in Queensland is predicted to increase as a result of climate change. The energy of cyclonic winds and resulting economic damage increases with the cube of wind speed. Fabricius *et al.*[51] predict that a hypothetical increase in cyclone intensity by half a category would result in 50–60% greater cyclone-related loss in coral cover, both inshore and offshore, compared to present-day rates. These effects could be even more significant if there is significant loss of coral, through losses in the supporting services cited above.
Food provisioning service	• Reductions in supporting services and in the overall health of the GBR may in turn affect the ability of the reef to maintain its provisioning services. • There have been changes in coral and fish species, and the abundance of some fishes is reduced in areas open to fishing compared to adjacent areas closed to fishing.[92] • The populations of some ecologically important species, such as dugongs, marine turtles, seabirds, black teatfish, and some sharks, have declined significantly.[10]
Recreational and cultural	• As is the case for provisioning services, reductions in supporting services and in the overall health of the GBR may in turn affect the quality of the recreational and cultural services provided by the reef.

Economics[44] study, which use, predominantly, benefit transfer techniques).

Arguably, more work has been done on the issue of changing water quality than on any other change. This is from the combined efforts of Alam *et al.*,[45] Prayaga *et al.*,[41] and Hajkowicz.[m,46] In general, most of the studies discussed above have investigated different types of shocks (or changes). Consequently, there is but a narrow range of information about the way in which the value of the ES provided by the reef have been impacted upon by any particular change or "shock."[n]

The flow of ES between adjacent ecosystems

A strong theme emerging from the foregoing discussion is that many of the activities that occur in regions adjacent to the GBR influence the ability of the GBR to provide ES. Clearly, the GBR is not just a "provider" of ES: it is also a recipient. And when the reef receives fewer services from its surrounding ecosystems, it is less able to provide ES in return.

The following subsection discusses and presents conceptual models of the "flow" of benefits of four individual ES (capture fisheries, recreation, coastal protection, and water purification). Importantly, these four case studies provide neither an exhaustive nor a definitive discussion of the flows of ES in this vast region, but they do serve to illustrate the importance of considering such flows when "valuing" ES in complex regions such as these—as highlighted in the discussion of "*The value of ES provided to the GBR*" subsection.

Conceptual examples of the "flow" of ES

Capture fisheries. Depicted in Figure 3, capture fisheries represent a provisioning service. In the GBR and its catchments, coral reefs, openocean, seagrass, mangroves, wetlands, and riverways all support significant commercial, recreational, charter, and indigenous fishing. These fisheries target a range of species from sharks, crabs, prawns, crayfish, barramundi, fin fish, and aquaculture, and, as highlighted in the "*State of knowledge*" subsection, many studies have generated estimates of the value of these fisheries, and have used tools, such as IO analysis, to model the way in which those values are distributed across broad industry sectors within the GBR catchment area and beyond (the most recent example being that of Access Economics[26]).

The key point to be gleaned here is not simply that capture fisheries are "of value" but rather that the benefits associated with these fisheries flow from the GBR to regions adjacent to it, and beyond to the rest of the world—as depicted by the width of arrows in Figure 3. To provide some nonfinancial data that highlights that flow of services, in 2007, just over 4,000 commercial licenses were issued in Queensland (the GBR runs along most of the eastern coast of Queensland, shown in yellow in the top right hand corner of Fig. 1).[10] Furthermore, it is estimated that 15% of the coastal population is involved in open-access recreational fishery.[10] The commercial, recreational, charter, and indigenous fisheries of Queensland caught over 38,000 tons of fish in 2007.[47] However, only 38% of that was retained, the rest being returned to the sea with uncertain survival success rates.[10,47] These figures do not include live fish, whose exports amounted to $38,407,000 in 2007/2008.[48] In addition to fish for consumption, the GBR aquarium trade, in 2007, landed 56,000 individual fish for local and global sale.[10] Adjacent to the GBR, the mangroves, wetlands, rivers, and lakes of Queensland also support substantial recreational and commercial fisheries. For example, in 2007/2008, an additional 901 tons of barramundi were landed.[48] The total fisheries production in 2007/2008 for all of Queensland came to 29,079 tons. Of this, Queensland exported 1,624 tons to a value of $191,157,000.[48] Evidently, the GBR provides a great many provisioning services to those living in and around the GBR, as well as to people throughout the world.

Recreation. Recreation represents a cultural service that is provided by the GBR and, like capture fisheries, there is an extensive body of literature on the financial value of this service (see "The value of the

[m] Not previously mentioned, since his work used a multiattributed environmental index (rather than values) to comment upon the potential change in the welfare of residents of north Queensland that might occur in response to changes in the "services" provided by water.

[n] Windle and Rolfe's[34] study, for example, only tells us about the way in which nonuse values are likely to change in response to an improvement in the environmental health of an estuary, but there has been no other matching research that will tell us how the value of other ES might respond to a similar change.

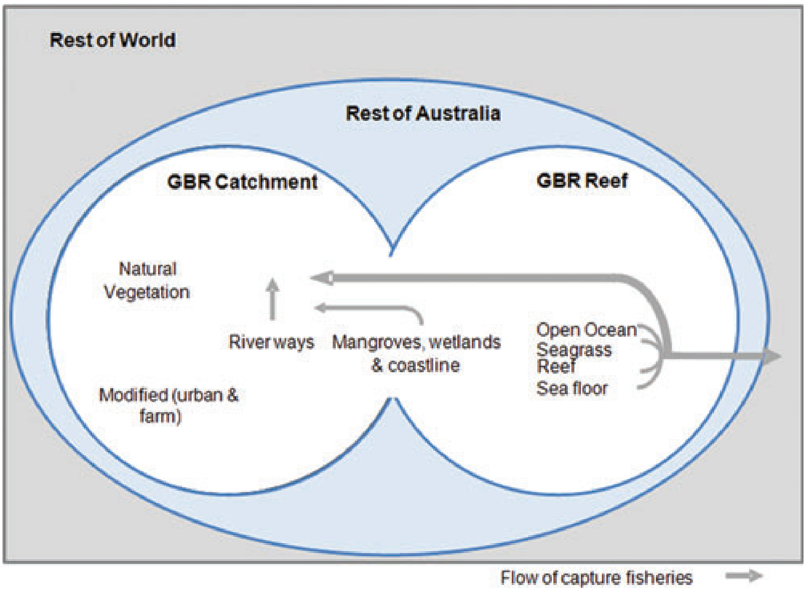

Figure 3. Conceptual flow of benefits from capture fisheries. (In color in *Annals* online.)

GBR's ecosystem services" section). Similar to capture fisheries, the benefits associated with recreation flow from the GBR to regions adjacent to it, and beyond to the rest of the world (Fig. 4).

In 2008/2009, for example, approximately five million visitors came to the GBR region, and there have been close to two million passengers on commercial boat tours to the reef each year since 2005. International visitors comprise 37% of those visiting the GBR catchment and 60% of those visiting the reef.[o,10,49] The visitors themselves reap substantial benefit (or CSs) from their visit[30,31,41] and their expenditures while in the region benefit both land and reef-based businesses.[26,42]

Coastal protection. As illustrated in Figure 5, the benefits associated with coastal protection flow from the GBR to regions adjacent to it—but not (as for fisheries and recreation) outward, to the international community. In contrast to the services already discussed in this section, there is a paucity of information about the value of this service (see the "*State of knowledge*" subsection) in the GBR. Nevertheless, quite a bit is known about the biophysical processes that underlie it.

Hardy and Young,[50] for example, found that healthy, growing coral reef systems on the GBR continental shelf provide significant shore protection to island beaches, with wave heights reduced to approximately 60% of water depth when travelling over a reef flat. Reefs have also been found to attenuate cyclonic wave heights, with the reef matrix north of Princess Charlotte Bay reducing wave heights from more than 15 m offshore to less than 5 m inshore during cyclone Ingrid.[51] Coastal mangroves and wetlands provide further coastal protection: a 200 m strip of mangroves may dissipate wave energy by 75% due to drag exerted by their roots and stems,[52] and this protection is provided not only to material and financial assets but also to seagrass, mangroves, rivers, and natural vegetation of the coastal catchments.[p]

Water purification. Water purification represents a regulating service that adjoining ecosystems provide to the GBR (Fig. 6)—the reverse of services thus far discussed in this section. Both terrestrial and aquatic ecosystems can provide this ES, including forests,

[o] Of the visitors to the catchments, 47% were from the region.

[p] In the past, tsunamis have breached the GBR through passes in the reef,[85] but whether the tsunamis were attenuated or accelerated by being funneled by the coastline morphology and bathymetry remains a subject of debate.[86]

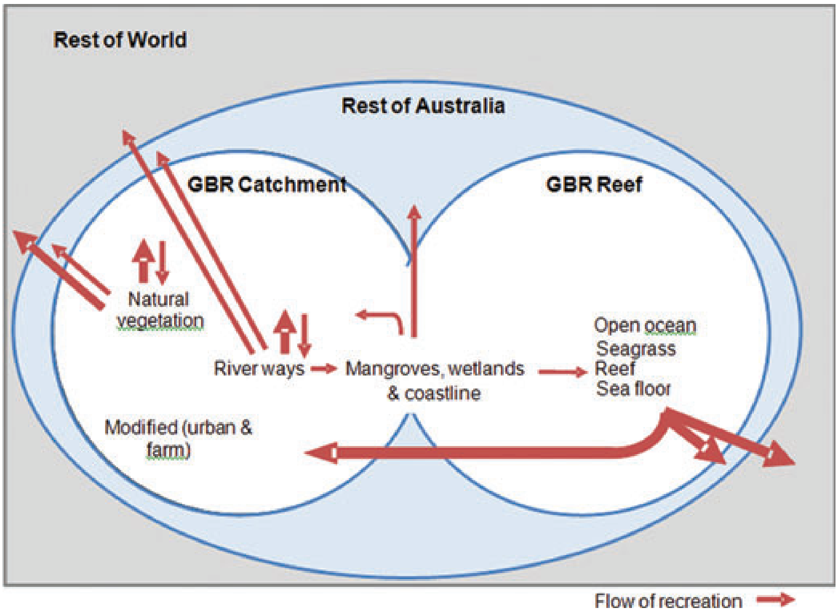

Figure 4. Conceptual flow of benefits from recreation. (In color in *Annals* online.)

floodplains, wetlands, estuaries, and mangroves, as well as the benthic invertebrate species within them, by trapping and/or processing sediments and nutrients.[53,54] Delivery of this service therefore depends on the integrity of the filtering and buffering capacity of the coastal catchment (e.g., Covich *et al.*[53] and Alongi and McKinnon[54]). Like coastal protection, relatively little is known about the financial "value" of this service in the GBR, and although there is only an emerging body of research investigating the way in which changes in water quality are likely to affect the value of ES provided by the GBR (see "The value of the GBR's ecosystem services" section), there has already been quite a bit of biophysical research investigating this important topic.

In the GBR catchment, for example, vegetation cover has been found to be the best predictor of soil erosion in Queensland's rivers.[55] Moreover, mangroves in the coastal catchments (which currently occupy almost 4,000 km^2) are known to contribute significantly to the water purification process by effectively trapping the nutrients from farming land (in the dry season) and by trapping approximately 4.2% of all riverine sediments.[10]

The value of ES provided to the GBR

As noted earlier, the four examples discussed above are but a small subset of the full range of ES provided by, and to, the GBR from the adjoining catchment. The GBR catchment encompasses many different types of land use systems, including, but by no means limited to grazing (comprising 75% of the catchment area); tropical rainforests (13%); cropping (mainly sugarcane), horticulture, production forestry, and mining (which, together, comprise about 9% of the catchment area); and urban areas that comprise just 1% of the total land area.[10,56] A number of different habitats also exist in the coastal and marine zone (e.g., mud flats, salt flats, mangroves, coral reefs, seagrass, and openocean). Essentially, each of these land use and habitat types influence a range of ES—either positively or negatively.

It is not the intention of this article to provide a comprehensive review of literature relating to the ES, which these other systems provide to the reef (rather, our focus is on the value of ES that the reef provides to other systems). But it is worth noting that most studies of the ES provided by these different habitats and land uses have focused on the services provided within their immediate locale, with little investigation of the flow across land use and habitat types. Thorburn *et al.*,[57] for example, highlight the range of ES provided by the sugarlands in Australia, while Butler *et al.*[58] identify 32 ES provided by the Wet Tropics rainforests in Far

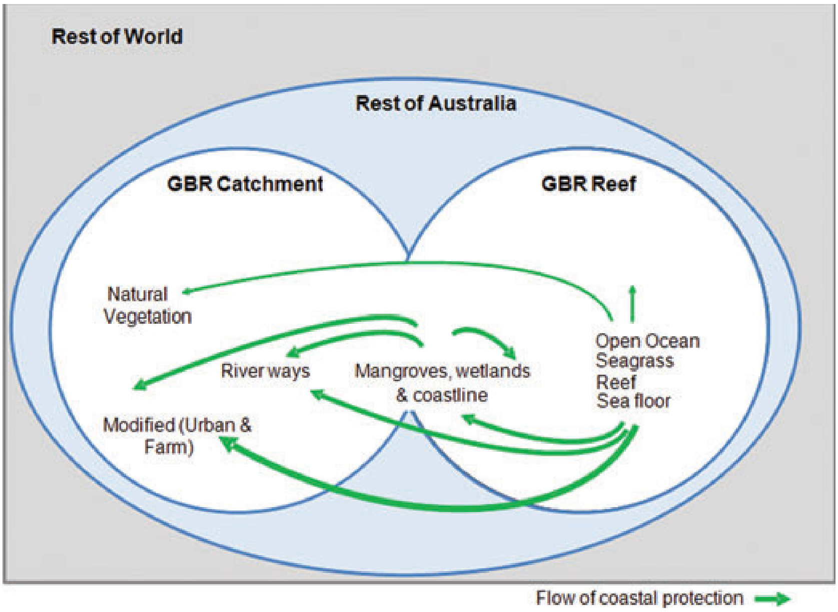

Figure 5. Conceptual flow of benefits from coastal protection. (In color in *Annals* online.)

North Queensland. Sangha[59] and Sangha *et al.*[60] documented that different land-management practices influence the quality of ES provided by grazing land use. Additionally, researchers at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (e.g., Bartley *et al.*[61] and Bramley *et al.*[62]) have conducted much research that establishes quantitative links between grazing management and water quality. Even so, none of these studies have examined the ES (or, most pertinent to this article, attempted to value the ES) that these land uses provide to ecosystems outside their own boundaries, such as the GBR. To the extent that at least some land uses (e.g., forests, coastal wetlands, and mangroves) provide ES that, in turn, enable the reef to provide its own ES, these single-system assessments may under- (or over-) value the contribution that some types of land uses make to human well-being.

Directions for the future

Four strong themes emerge from the preceding discussions. First, it is clear that historically, most GBR valuation studies have employed a relatively narrow range of valuation techniques (often IO) and have concentrated on a relatively narrow range of ES (typically fishing and recreation); see "The value of the GBR's ecosystem services" section. While more recent research has served to broaden both the range of techniques employed and the range of services investigated, significant gaps in our knowledge remain. These "gaps" are particularly evident when one compares the breadth of valuation research that has been done on the GBR with the breadth of information available on the biophysical processes that underlie valuation exercises (Table 3).

Moreover, since there are clear dangers associated with "benefit" transfer,[6] one cannot but come to the inevitable conclusion that it will be difficult to improve pricing and incentive mechanisms (as directed by the act) unless, or until, such information deficiencies are redressed. Most evident is the need for more research on the "value" of the reef's regulating services, and on some of its cultural services (e.g., its aesthetic, or iconic status).

Second, this review has also highlighted the fact that many of the GBR's valuation studies have sought to generate estimates of the "total" value of particular ES (to wit: the eight studies listed in column one of Table 1, using expenditure or IO analysis to estimate the contribution of recreation and/or fishing). However, it has not been until recently that researchers have begun to look at "marginal" values. This is an important trend, since each type of value provides a distinctly different type of information, for use in different contexts. Thus, researchers

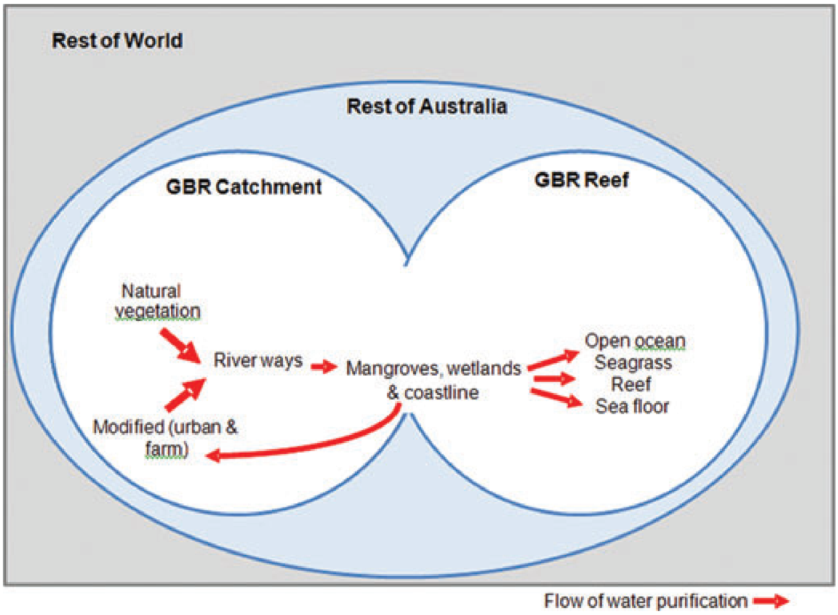

Figure 6. Conceptual flow of benefits from water purification. (In color in *Annals* online.)

need to be aware of what type of information is required by policy makers when designing research projects.[14]

To be more specific, estimates of total value are generally only of use if seeking to describe the current state of affairs (e.g., that tourism is a more significant generator of incomes in the GBR catchment than is fishing) or if seeking to address management/policy questions, such as What losses would the region suffer if the entire reef ceased to exist? We now have a reasonably good understanding of the relative contribution of different industries to the catchment's economy, and in most cases, managers are not faced with such all or nothing choices (reef or no reef). So methodological approaches that generate estimates of total value may be somewhat less relevant than they were when GBR valuation research was in an embryonic stage.

Instead, managers/policy makers are, nowadays, more likely to need answers to questions, such as What losses would the region suffer if reductions in water quality reduced the reef's ability to provide certain ES? Or would a relocation of resources from one sector to another improve overall welfare? Importantly, for questions like these, it is marginal, not total values that one needs. Specifically, one needs information about the value of changes.

As highlighted in the "*State of knowledge*" subsection, most GBR studies that have sought to estimate the value, or financial impact, of changes, have focused on (a) changes in water quality and (b) impact on the tourism sector (i.e., recreational aspects of cultural services). But there is relatively little information available on the likely impact of other (nonwater quality) changes to other (non-tourism/recreation) services. There is a clear need for research of this type, but given the vast array of potential "changes" that could affect any number of ES, it will be important to develop some mechanism for prioritizing the changes to be investigated. The Outlook Report has recently highlighted climate change, water quality, and loss of coastal habitats as the main threats to the reef.[10] A better understanding of changes to ES as a result of these drivers is critical, and such research is increasingly taking place. It will be important to extend investigations to cover all ES and not just focus on the recreational and provisioning services.

Third, it is clear that we do not just need information about total or marginal values, but we also need information about the social, temporal, and spatial distribution of those values.[63] The substantive body of IO work done by groups, such as Access Economics[25,26] has given us a reasonably good

Table 3. **Biophysical and economic research on the ES of the GBR by ES**

<table>
<tr><th colspan="2">Services</th><th>Background and/or biophysical studies</th><th colspan="3">Economic/valuation studies</th></tr>
<tr><td rowspan="5">Cultural services</td><td>Australian icon</td><td>Great Barrier Reef Marine Park Authority[93]</td><td colspan="2"></td><td rowspan="15">Windle & Rolfe[34]; investigated a subset of nonuse values, Alam et al.,[45] Oxford Economics[44]</td></tr>
<tr><td>Cultural heritage</td><td>Smith[94]</td><td colspan="2"></td></tr>
<tr><td>Cognitive/ Scientific research</td><td>Lucas et al.,[1] Wachenfeld et al.[95]</td><td colspan="2"></td></tr>
<tr><td>Aesthetic</td><td>Lucas et al.[1]</td><td colspan="2"></td></tr>
<tr><td>Recreation</td><td>Great Barrier Reef Marine Park Authority[10]</td><td>Hundloe et al.,[30] Knapman & Stoeckl,[31] Carr & Mendelsohn,[33] Kragt et al.,[38] Prayaga et al.[41]</td><td rowspan="2">Driml,[22,24,111] Access Economics,[25,26] PDP Australia,[29] KPMG[23]</td></tr>
<tr><td rowspan="4">Provisioning services</td><td>Fishing</td><td>Great Barrier Reef Marine Park Authority,[10] ABARE,[21] Queensland Department of Primary Industries and Fisheries[47]</td><td>Fenton & Marshall,[27] ABARE,[21] Grafton et al. (ongoing research), Delisle[40]</td></tr>
<tr><td>Ports and shipping</td><td>Great Barrier Reef Marine Park Authority,[96] Australian Maritime Safety Authority,[97] Australian Government Department of the Environment, Water, Heritage, and the Arts (p. 103)[82]</td><td colspan="2"></td></tr>
<tr><td>Aquarium and ornamental trade (e.g., for fish, shells, and live rock)</td><td>Harriott[28]</td><td colspan="2"></td></tr>
<tr><td>Oil reserves, medicinal products</td><td>Ettinger-Epstein et al.[98]</td><td colspan="2"></td></tr>
<tr><td rowspan="3">Regulating services</td><td>Protection from storms and tsunamis</td><td>Young and Hardy,[99] Knott,[85] Fabricius et al.,[51] UNEP-WCMC,[86] Massel et al.[52]</td><td colspan="2"></td></tr>
<tr><td>Water purification</td><td>McKergow et al.,[55] Lotze et al.,[100] Verhoeven et al.[101]</td><td colspan="2"></td></tr>
<tr><td>Climate regulation/carbon sequestration</td><td>Nellemann et al.[102]</td><td colspan="2"></td></tr>
<tr><td rowspan="4">Supporting services</td><td>Nutrient cycling/ food webs</td><td>Chisholm,[66] Hughes et al.,[72] Hoey & Bellwood,[103] Gattuso et al.,[65] Graham et al.,[69] Sandin et al.,[104] Hixon & Jones,[70] Johnson et al.,[67] Bellwood & Fulton[71]</td><td colspan="2"></td></tr>
<tr><td>Habitat provision</td><td>Wilson et al.,[74] Halford et al.,[75] Emslie et al.,[105] Graham et al.,[69] Sheaves[76]</td><td colspan="2">Watson et al.[32]</td></tr>
<tr><td>Coastal protection</td><td>Sheppard et al.,[106, a] Burke et al.[107, b]</td><td colspan="2"></td></tr>
<tr><td>Ecosystem health (resilience)</td><td>Nyström et al.,[81] Bellwood et al.,[68] Bruno et al.,[77] Harvell et al.,[78] Ainsworth & Hoegh-Guldberg,[79] Jones et al.,[80] Hughes et al.,[72] Wilson et al.,[74] Hernaman et al.[108]</td><td colspan="2"></td></tr>
</table>

[a] Seychelles study.
[b] Tobago study.

base of information about the way in which the financial benefits of the fishing and tourism sectors are distributed throughout other industries within the GBR catchment area. As such, we know something about the social distribution of a few specific values. Nonetheless, more detail about the relative importance of those values to different stakeholder groups (e.g., different types of households, or individuals) and/or about the distribution of impacts within smaller regions, would be useful.

One way of attempting to identify and compare the relative importance of absolute levels or changes in different ES to different individuals or stakeholder groups is via formal "valuation" work. However, willingness to pay (the basis of most valuation work) is, necessarily, a function of ability to pay. Consequently, monetary valuation methods produce estimates that are essentially weighted averages: the weights that are used are a function of income, so that the priorities (or values) of the wealthy are given more voice than the priorities of the poor. Other nonmonetary methods are available—but only a few have been trialed in the GBR catchment area (Hajkowicz[46] and Larson[64]). More work on these approaches in this region would be welcome—particularly given the vast disparities in incomes between, for example, indigenous and nonindigenous householders. Moreover, without information about the social, spatial,[q] or temporal distribution of values, it will be difficult to determine who (or what) is likely to "win" or "lose" from different policies and/or incentive mechanisms. As such, it will be difficult to design appropriate policy.

This issue is particularly important in the context of the rising popularity of "payments for environmental services:" one needs accurate information about the distribution of costs and benefits associated with environmental services if one is going to design equitable, and efficient, payment systems. Information on the temporal and spatial distribution of ES would also be beneficial when revisiting the 2003 GBR Zoning Plan. This would allow for a design that would try to optimally configure the zones on the basis of a variety of ES.

[q] Access Economics[25,26] explored the "contribution" of reef-based fishing and tourism to the GBR catchment, comparing that to both the Queensland-wide and Australia-wide impact.

Finally, the discussion of "The flow of ES between adjacent ecosystems" section highlighted the importance of taking a broader "systems" view when considering the value of ES. Just as the reef provides ES to humans and to other ecosystems that adjoin the GBR, so too does the reef receive a variety of services from adjoining systems. It was not the intention of this article to provide a comprehensive review of literature relating to the ES of these adjacent ecosystems. However, it is clear that the regionally relevant literature lacks information on the value of ES that are provided from systems adjacent to the GBR. Subsequent terrestrial investigations may therefore wish to extend this important avenue of investigation, since failure to acknowledge the external benefits of the services that these terrestrial ecosystems provide, serves to undervalue their status within a larger system, and may, in turn, lead to suboptimal allocations of such land uses.

That it is important to take such steps is clearly emphasized in the Great Barrier Reef Marine Park Authority's Outlook Report,[10] which notes that "the effectiveness of management is challenged because complex factors that have their origin beyond the GBR region, namely climate change, catchment runoff, and coastal development, cause some of the highest risks to the ecosystem" (p. i). If it were possible to explicitly incorporate assessments of the value of changes to ES delivered to the GBR by adjoining ecosystems into a decision support framework and if one were able to clearly identify "winners" and "losers" from activities and actions that seek to improve the flow and status of ES (as per Pagiola *et al.*'s examples in a rainforest setting),[63] then it would be possible to align economic incentives with conservation objectives.[112] In other words, one would be able to design systems that capitalize on, rather than fight against, economic incentives, thus increasing the chance of affecting positive change. That it is essential to progress beyond the realm of simply estimating the total value of individual ES and onto the process of assessing the impacts of potential changes to ES so that it is possible to alter incentives, is clearly argued by Heal.[113] That it is possible to design systems that are capable of affecting such changes across a broad range of ES spanning multiple ecosystems is illustrated by the Costa Rican system outlined in Turner and Daly.[112]

It must, however, be noted that effective management across marine and terrestrial systems requires institutional structures that are able to manage these multiple, linked ecosystems. Studies that help draw attention to the value of individual ES, to the "value" of entire ecosystems, or to the value of cooperative transsystem goals are but one part of the story. It is not possible to capitalize on the opportunities that such studies identify, if the institutions that govern our behaviors are unable to respond accordingly, for example, by altering incentives so as change behaviors. As such, more research on alternative institutional structures and on the costs of building up the supporting infrastructure for such institutions could be of significant benefit to this vitally important world heritage area.

Appendix A: supporting services of the GBR

As highlighted in the "The value of the GBR's ecosystem services" section, a substantive body of literature supports the argument that the ability of the GBR to provide a range of ES is being eroded. We identify, and briefly discuss, some of the research underpinning four key supporting services:

Nutrient cycling/foodwebs (including primary production, herbivory, predation, competition, and microbial processes)

One of the major features of the coastal zone is that part of its sea floor receives a significant amount of sunlight and can therefore sustain benthic primary production by seagrasses, macroalgae, microphytobenthos, and corals. The degree to which this primary production can occur is dependent on the amount of light penetration.[65] Numerous studies have been involved in calculating this primary production. For example, Chisholm[66] quantified the primary production of four species of crustose coralline algae and therefore their contribution to the organic production of reefs on the GBR, and Johnson *et al.*[67] calculated the effect of replacement of coral by algae on the carbon flux. Herbivory, predation, and competition are key processes responsible for maintaining coral reef ecosystem function, structure, and resilience.[68] Much of the research leading this field comes out of the GBR.[69–72] Carbon and nitrogen sediment storage and microbial activity has been investigated in the northern GBR.[73]

Habitat provision (including habitat, structural complexity, habitat refuge, and nursery grounds)

The role of structural complexity in providing community structure, in maintaining diversity, and in maintaining a productive fishery is gaining recognition.[74,75] Mangroves and the connection between them and the rest of the coral reef system are important nursery and feeding areas for fish. Their rich invertebrate faunas render them productive feeding areas, while their shallow waters and structural complexity provide sanctuary habitats at a variety of scales.[76]

Coastal protection of coastal habitats, such as mangroves and seagrass beds, as well as the formation of islands and maintenance of beaches

While coastal protection is often categorized as a regulating service (providing protection from storms to our coastal farms and properties),[50] it is also a supporting service in that it provides protection to coastal mangrove and seagrass ecosystems allowing them to provide us with continued provisioning services.[51]

Ecosystem health (including disease control, connectivity, resilience, diversity, and trophic composition)

These aspects of an ecosystem ensure the continued provision of nutrient cycling, habitat provision, and coastal protection, and are in turn maintained by those same services (i.e., a healthy system provides services and the maintenance of services ensures a healthy system). Coral disease is coming to the fore as a serious problem on the GBR, and has been shown to be correlated with warm temperature anomalies.[77,78] The natural bacterial communities of corals are severely altered during stress, which suggests a potential mechanism for the link between diseases and stresses arising from global warming.[79] A key question in understanding population dynamics and hence whether and how populations will be replenished is how far the larvae of marine organisms disperse. Considerable progress has been made within the GBR in understanding the role of connectivity in terms of self versus long distance recruitment.[80] Resilience refers to the ability of a system to endure a disturbance and retain its previous state; essentially it provides insurance against ecological uncertainty. Empirical indicators of the cornerstones of coral reef resilience have been put forward.[81] These indicators include functional group approaches, diversity, and trophic composition, which, while it may not be possible to measure or predict resilience, these process orientated metrics capture ecosystem dynamics improving marine stewardship.[72]

Conflicts of interest

The authors declare no conflicts of interest.

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